

# Energy Saving Opportunities in Residential Buildings: Insights from Technological and Building Energy Code Perspectives

Bo Li

B.Eng. (Energy & Power Engineering),  
University of Shanghai for Science and Technology, 1996

M.A.Sc. (Mechanical Engineering), University of Victoria, 2011

A Dissertation Submitted in Partial Fulfillment of the Requirements for the Degree of

DOCTOR OF PHILOSOPHY

In the Department of

MECHANICAL ENGINEERING

© Bo Li, 2020  
University of Victoria

All rights reserved. This dissertation may not be reproduced in whole or in part, by  
photocopy or other means, without the permission of the author.

# Energy Saving Opportunities in Residential Buildings: Insights from Technological and Building Energy Code Perspectives

Bo Li

B.Eng. (Energy & Power Engineering),  
University of Shanghai for Science and Technology, 1996

M.A.Sc. (Mechanical Engineering), University of Victoria, 2011

## SUPERVISORY COMMITTEE

---

Dr. Andrew Rowe, Co-supervisor  
(Department of Mechanical Engineering)

---

Dr. Peter Wild, Co-supervisor  
(Department of Mechanical Engineering)

---

Dr. Phalguni Mukhopadhyaya, Committee Member  
(Department of Civil Engineering)

## Supervisory Committee

Dr. Andrew Rowe, Co-supervisor  
(Department of Mechanical Engineering)

Dr. Peter Wild, Co-supervisor  
(Department of Mechanical Engineering)

Dr. Phalguni Mukhopadhyaya, Committee Member  
(Department of Civil Engineering)

## ABSTRACT

The residential building sector plays an important role in combating climate change in Canada. Many energy efficiency solutions along with new building energy standards have been implemented to improve building energy performance. However, their effects on energy saving and GHG emissions reduction vary due to the complexity of the building systems and the variability of their operational conditions. This work quantifies such variability in both energy efficiency devices and building energy standards implementation, respectively.

The first study in this dissertation assesses the energy savings from sensible heat recovery in a residential apartment suite in various locations across Canada. A series of detailed building energy performance models are developed in TRNSYS. The HVAC system's annual energy consumption is simulated and the results are compared with and without HRV for each climate zone. The results show the heating energy savings of employing the HRV vary from 17 to 34% depending on the winter climatic conditions;

while, the building cooling energy use can be increased due to the undesired thermal recovery occurring in the HRV during the cooling season.

The second study investigates the free cooling potential of outside air in various Canadian cities. A series of thermal models developed using BEopt 2.8 for a hypothetical single-family house with various window-to-wall ratios and building aspect ratios simulates hourly building cooling load profiles. The free cooling potential is analyzed by comparing the maximum available and the actual usable free cooling for various building features and different climates. The results indicate that, although free cooling is widely available in most areas of Canada during the summer and shoulder seasons, only 17-42% of such free cooling is usable without the use of thermal storage.

The last study examines the effects of two building energy standards - the BC Step Code and the Passive House criteria - on reductions in residential household space heating GHG emissions under different enforcement scenarios. The space heating energy and the GHG emissions are estimated using the forecast growth of single detached households for the period from 2020 to 2032. The results show that the space heating GHG emissions can be reduced by 77% and 89%, respectively if the BC Step Code or the Passive House criteria is implemented in Canada. It is also found the impacts of energy code on GHG emission mitigation are less significant in regions where the carbon intensity of the dominant heating fuels is low.

## TABLE OF CONTENTS

Supervisory Committee .....	ii
Abstract .....	iii
Table of Contents .....	v
List of Tables .....	viii
List of Figures .....	xi
Nomenclature .....	xvi
Acknowledgements .....	xix
Dedication .....	xx
1. Introduction .....	1
1.1 Previous work .....	3
1.1.1 Energy Saving Potentials of HRV .....	3
1.1.2 Energy Saving Potential of Air-side Economizer .....	4
1.1.3 Effectiveness of Residential Building Energy Codes .....	5
1.2 Objectives .....	6
1.3 Overview and Outline .....	9
2 Performance of A Heat Recovery Ventilator Coupled With An Air-to-Air Heat Pump For Residential Suites In Canadian Cities .....	13
2.1 Introduction .....	13
2.2 Literature Review .....	15
2.3 Objective .....	20
2.4 Methodology .....	20
2.4.1 Model Description .....	21
2.4.2 Parametric Analysis .....	29
2.5 Results and Discussion .....	30
2.5.1 Annual Heating and Cooling Energy Requirements .....	30
2.5.2 Heating Energy and Heating Degree Days .....	35
2.6 Limitations .....	36
2.7 Conclusions .....	37
3 Free Cooling Potential of Air Economizer In Residential Houses In Canada .....	39
3.1 Introduction .....	39

3.2	Literature Review.....	43
3.3	Objective.....	46
3.4	Methodology.....	47
3.4.1	System Configuration.....	47
3.5	Model Description.....	49
3.5.1	Simulation Tools.....	49
3.5.2	Residential House Description.....	49
3.5.3	Thermal Envelope Assemblies.....	51
3.5.4	Occupancy.....	52
3.5.5	Internal Heat Gains & HVAC Systems.....	52
3.5.6	Ventilation and Air Leakage.....	53
3.6	Metrics.....	53
3.6.1	Cooling Demand,.....	53
3.6.2	Maximum Available Free Cooling.....	54
3.6.3	Usable Free Cooling.....	55
3.6.4	Free Cooling Potential.....	55
3.7	Results and Discussion.....	56
3.7.1	Annual Sensible Cooling Demand.....	56
3.7.2	Annual Usable Free Sensible Cooling.....	58
3.7.3	Maximum Available Free Cooling.....	59
3.7.4	Annual Usable and Maximum Available Free Cooling Potentials.....	61
3.8	Limitations.....	64
3.9	Conclusions.....	64
4	Building Code Effectiveness For Climate Change Mitigation In Canada.....	66
4.1	Introduction.....	67
4.2	Objective.....	72
4.3	Methodology.....	73
4.3.1	New single-detached households.....	74
4.3.2	Allocation to climate zones.....	78
4.3.3	Adoption Scenarios.....	80
4.3.4	Annual space heating demand.....	83

	vii
4.3.5 Allocation to fuel types .....	83
4.3.6 Annual GHG emissions .....	84
4.4 Results and Discussion .....	85
4.4.1 Emissions .....	85
4.4.2 Regional emission reductions .....	87
4.5 Limitations .....	90
4.6 Conclusions.....	91
5 Contributions and Future Work .....	93
5.1 Contributions.....	93
5.2 Future Work .....	95
Reference .....	97
Appendix- A: Additional Tables and Figures for First Study.....	108
Appendix- B: Additional Tables and Figures for Second Study .....	119
Appendix- C: Additional Tables for Third Study.....	131

## LIST OF TABLES

Table 1.1: Varying Window to Wall and Aspect Ratios Considered in Chapter 3 Study	11
Table 2.1: Modeled heating and cooling energy savings of HRV compared to pressurized corridor system with intermittent exhaust fans in suites [3] .....	18
Table 2.2: Types of HVAC system being investigated in previous studies .....	19
Table 2.3: The operation status of heat pump and its electrical stage heaters under the control of the multi-stage suite thermostat.....	26
Table 2.4: Fifteen Canadian Cities Representing Three ASHRAE Climate Zones in Parametric Study.....	30
Table 2.5: Calculated Annual Heating Degree Days (HDDs) for the Fifteen Selected Canadian Cities .....	35
Table 3.1: Varying Design Schemes in Window to Wall Ratio and Aspect Ratio of a Typical Single-Family House .....	50
Table 3.2: Sixteen Canadian cities representing three ASHRAE climate zones .....	51
Table 3.3: Building envelope fabrics and thermal properties .....	52
Table 4.1: Provincial share of single detached housing stock, $rSDHp$ .....	75
Table 4.2: Forecasted overall residential housing stocks in British Columbia ( $\times 1,000$ ), 2016-2036 .....	76
Table 4.3: Average area of a typical household by province in Canada.....	78
Table 4.4: Canadian climate zones and the corresponding annual heating degree days [102].....	79
Table 4.5: The climate zone specific population ratio of each province and territories ...	80
Table 4.6: The climate-specific thermal energy demand intensity (TEDI) of each step in BC step code .....	81
Table 4.7: Assumed single detached household's space heating system thermal efficiency by heating fuel types .....	84
Table 4.8: The ratio of the involved population to the census population record by province.....	91
Table A-1: Properties of each layer and composition of hypothetical suite envelope in ASHRAE Climate Zone 5.....	108

Table A-2: Assumed lighting, cooking, computer and other miscellaneous design power .....	109
Table A-3: Manufacturer performance data of air-to-air heat pump serving the suite in cities within climate zone 5.....	109
Table A-4: The summary of the key performance data of the selected ventilation devices .....	110
Table A-5: The summary of the ventilation airflow of each space of the hypothetical condo unit.....	110
Table A-6: Properties of each layer and composition of hypothetical suite envelope in ASHRAE Climate Zone 6.....	111
Table A-7: Properties of each layer and composition of hypothetical suite envelope in ASHRAE Climate Zone 7.....	112
Table A-8: Key Performance Data of the Selected Air Source Heat Pump with the corresponding Electrical Supplemental Heater Serving the Suite in Different Climate Zones in Parametric Study .....	113
Table A-9: Main TRNSYS modeling components and the key parameter settings .....	116
Table B-1: Lighting, Appliance & Equipment and Miscellaneous Equipment Settings in the Model .....	119
Table B-2: Internal Heat Gains and HVAC System Settings in the Model.....	119
Table C-1: Forecasted overall residential housing stocks in Newfoundland ( $\times 1,000$ ), 2016-2036 [99].....	131
Table C-2: Forecasted overall residential housing stocks in Prince Edward Island ( $\times 1,000$ ), 2016-2036 [99] .....	131
Table C-3: Forecasted overall residential housing stocks in Nova Scotia ( $\times 1,000$ ), 2016-2036 [99].....	132
Table C-4: Forecasted overall residential housing stocks in New Brunswick ( $\times 1,000$ ), 2016-2036 [99].....	132
Table C-5: Forecasted overall residential housing stocks in Quebec ( $\times 1,000$ ), 2016-2036 [99].....	133
Table C-6: Forecasted overall residential housing stocks in Ontario ( $\times 1,000$ ), 2016-2036 [99].....	133

Table C-7: Forecasted overall residential housing stocks in Manitoba ( $\times 1,000$ ), 2016-2036 [99].....	134
Table C-8: Forecasted overall residential housing stocks in Saskatchewan ( $\times 1,000$ ), 2016-2036 [99].....	134
Table C-9: Forecasted overall residential housing stocks in Alberta ( $\times 1,000$ ), 2016-2036 [99].....	135
Table C-10: Forecasted overall residential housing stocks in Yukon ( $\times 1,000$ ), 2016-2036 [99].....	135
Table C-11: Forecasted overall residential housing stocks in Northwest Territories ( $\times 1,000$ ), 2016-2036 [99] .....	136
Table C-12: Forecasted overall residential housing stocks in Nunavut ( $\times 1,000$ ), 2016-2036 [99].....	136
Table C-13: Forecasted housing stocks in Newfoundland ( $\times 1,000$ ), 2020-2032.....	137
Table C-14: Forecasted housing stocks in Prince Edward Island ( $\times 1,000$ ), 2020-2032	138
Table C-15: Forecasted housing stocks in Nova Scotia ( $\times 1,000$ ), 2020-2032.....	139
Table C-16: Forecasted housing stocks in New Brunswick ( $\times 1,000$ ), 2020-2032.....	140
Table C-17: Forecasted housing stocks in Quebec ( $\times 1,000$ ), 2020-2032 .....	141
Table C-18: Forecasted housing stocks in Ontario ( $\times 1,000$ ), 2020-2032 .....	142
Table C-19: Forecasted housing stocks in Manitoba ( $\times 1,000$ ), 2020-2032 .....	143
Table C-20: Forecasted housing stocks in Saskatchewan ( $\times 1,000$ ), 2020-2032.....	144
Table C-21: Forecasted housing stocks in Alberta ( $\times 1,000$ ), 2020-2032.....	145
Table C-22: Forecasted housing stocks in British Columbia ( $\times 1,000$ ), 2020-2032.....	146
Table C-23: Forecasted housing stocks in Yukon ( $\times 1,000$ ), 2020-2032.....	147
Table C-24: Forecasted housing stocks in Northwest Territories ( $\times 1,000$ ), 2020-2032	148
Table C-25: Forecasted housing stocks in Nunavut ( $\times 1,000$ ), 2020-2032.....	149
Table C-26: The selected cities for the climate zone specific population ratio calculation .....	150
Table C-27: Main types of space heating fuels in each province and territories of Canada .....	162
Table C-28: Provincial GHG emissions factors by heating fuel types .....	162

## LIST OF FIGURES

Fig. 1.1: Schematic of air source heat pump with the HRV .....	10
Fig. 1.2: Schematic of air source heat pump without the HRV .....	10
Fig. 1.3: Four cases representing different rates for BC step code adoption .....	12
Fig. 2.1: The plan of the hypothetical top-floor corner condo suite (Azimuthal orientation is 0 degrees) .....	22
Fig. 2.2: Suite level weekday and weekend occupancy schedules .....	23
Fig. 2.3: Suite level weekday and weekend interior lighting schedules .....	24
Fig. 2.4: Suite level weekday and weekend miscellaneous load schedules .....	24
Fig. 2.5: Schematic of air source heat pump with the HRV .....	27
Fig. 2.6: Schematic of air source heat pump without the HRV .....	27
Fig. 2.7: Comparison of annual heating energy use per unit area by heat pump between non-HRV and HRV scenarios.....	33
Fig. 2.8: Comparison of annual cooling energy use per unit area by heat pump between non-HRV and HRV scenarios.....	33
Fig. 2.9: Reduction in heat pump annual heating and cooling energy use per unit area V.S. the reduction in heat pump annual heating only energy use per unit area due to the employment of HRV.....	34
Fig. 2.10: Percentage reduction in heat pump annual heating and cooling energy use with HRV and reduction in heating only energy use .....	34
Fig. 2.11: Relationship between the annual heating degree days and heat pump annual heating energy use per unit area when the suite is facing true south .....	36
Fig. 3.1: Basic form of an air-side economizer [74].....	41
Fig. 3.2: Conceptual residence with an air-side economizer and HVAC system .....	48
Fig. 3.3: The hypothetical single family house with aspect ratio of 1:1 and 3:1 .....	51
Fig. 3.4: The building annual cooling demand without the air-side economizer for the single-family house with varying aspect ratios for the Canadian cities in ASHRAE climate zone 5.....	57
Fig. 3.5: The annually usable free sensible cooling for the single-family house in the Canadian cities of ASHRAE climate zone 5 .....	58

Fig. 3.6: Comparison of Annual Cooling Demand, Annual Maximum Available Free Cooling and the Annual Usable Free Cooling of the Hypothetical Single-Family House in Kamloops .....	59
Fig. 3.7: Hourly profile of the sensible cooling demand, the maximum available free sensible cooling, the usable free sensible cooling and the outside air dry-bulb temperature for the case of 1:3 aspect ratio and 12% WWR for a typical summer day in Kamloops .	61
Fig. 3.8: The annually usable free sensible cooling potential in percentage of the annual building cooling demand for the Canadian cities in ASHRAE climate zone 5 .....	63
Fig. 3.9: Comparison of the Ranges of the Annual Usable and Maximum Available Free Sensible Cooling Potentials .....	64
Fig. 4.1: Four cases representing different rates for BC step code adoption .....	82
Fig. 4.2: Comparison of forecasted nationwide cumulative GHG emissions due to growth in single detached households for the BC step code adoption scenario .....	85
Fig. 4.3: Comparison of forecasted nationwide cumulative GHG emissions due to the single detached households growth of between the case 1 in BC step code adoption scenario and No-Action scenario, 2020-2032 .....	86
Fig. 4.4: Comparison of forecasted nationwide cumulative GHG emissions due to the single detached households' growth of between the case 4 in BC step code adoption scenario and Passive house standard adoption scenario, 2020-2032 .....	87
Fig. 4.5: Provincial GHG emission reductions per thousand square meters floor area growth of single detached households under various energy standard adoption scenarios/cases compared to the No-Action reference scenario in 2032 .....	88
Fig. 4.6: The share of main heating fuels of the single detached households in each province and territories. (Reproduced from dataset provided by [106]) .....	89
Fig. A1: Suite area normalized design heating loads for fifteen Canadian cities .....	114
Fig. A2: Suite area normalized design cooling loads for fifteen Canadian cities .....	115
Fig. A3: TRNSYS simulation model for the heat pump coupled with HRV .....	115
Fig. A4: TRNSYS simulation model for the heat pump coupled with balanced ventilation .....	116

Fig. B1: The building annual cooling demand without the air-side economizer for the single-family house with varying aspect ratio for the cities in climate zone 6 according to the window to wall ratios.....	120
Fig. B2: The building annual cooling demand without the air-side economizer for the single-family house with varying aspect ratio for the cities in climate zone 7 according to the window to wall ratios.....	120
Fig. B3: The annually usable free sensible cooling for the single-family house in the Canadian cities of ASHRAE climate zone 6 .....	121
Fig. B4: The annually usable free sensible cooling for the single-family house in the Canadian cities of ASHRAE climate zone 7 .....	121
Fig. B5: The annually usable free sensible cooling potential in percentage of the annual building cooling demand for the selected cities in ASHRAE climate zone 6 .....	122
Fig. B6: The annually usable free sensible cooling potential in percentage of the annual building cooling demand for the selected cities in ASHRAE climate zone 7 .....	122
Fig. B7: Comparison of Annual Cooling Demand, Annual Maximum Available Free Cooling and the Annual Usable Free Cooling of the Hypothetical Single-Family House in Vancouver .....	123
Fig. B8: Comparison of Annual Cooling Demand, Annual Maximum Available Free Cooling and the Annual Usable Free Cooling of the Hypothetical Single-Family House in Victoria .....	123
Fig. B9: Comparison of Annual Cooling Demand, Annual Maximum Available Free Cooling and the Annual Usable Free Cooling of the Hypothetical Single-Family House in Port Hardy.....	124
Fig. B10: Comparison of Annual Cooling Demand, Annual Maximum Available Free Cooling and the Annual Usable Free Cooling of the Hypothetical Single-Family House in Sandspit.....	124
Fig. B11: Comparison of Annual Cooling Demand, Annual Maximum Available Free Cooling and the Annual Usable Free Cooling of the Hypothetical Single-Family House in Summerland .....	125

Fig. B12: Comparison of Annual Cooling Demand, Annual Maximum Available Free Cooling and the Annual Usable Free Cooling of the Hypothetical Single-Family House in Toronto.....	125
Fig. B13: Comparison of Annual Cooling Demand, Annual Maximum Available Free Cooling and the Annual Usable Free Cooling of the Hypothetical Single-Family House in Montreal.....	126
Fig. B14: Comparison of Annual Cooling Demand, Annual Maximum Available Free Cooling and the Annual Usable Free Cooling of the Hypothetical Single-Family House in Ottawa.....	126
Fig. B15: Comparison of Annual Cooling Demand, Annual Maximum Available Free Cooling and the Annual Usable Free Cooling of the Hypothetical Single-Family House in Lethbridge.....	127
Fig. B16: Comparison of Annual Cooling Demand, Annual Maximum Available Free Cooling and the Annual Usable Free Cooling of the Hypothetical Single-Family House in Charlottetown.....	127
Fig. B17: Comparison of Annual Cooling Demand, Annual Maximum Available Free Cooling and the Annual Usable Free Cooling of the Hypothetical Single-Family House in Prince George.....	128
Fig. B18: Comparison of Annual Cooling Demand, Annual Maximum Available Free Cooling and the Annual Usable Free Cooling of the Hypothetical Single-Family House in Edmonton.....	128
Fig. B19: Comparison of Annual Cooling Demand, Annual Maximum Available Free Cooling and the Annual Usable Free Cooling of the Hypothetical Single-Family House in Winnipeg.....	129
Fig. B20: Comparison of Annual Cooling Demand, Annual Maximum Available Free Cooling and the Annual Usable Free Cooling of the Hypothetical Single-Family House in Regina.....	129
Fig. B21: Comparison of Annual Cooling Demand, Annual Maximum Available Free Cooling and the Annual Usable Free Cooling of the Hypothetical Single-Family House in Saskatoon.....	130

Fig. B22: Comparison of Annual Usable Free Sensible Cooling Potential in the Sixteen  
Canadian Cities ..... 130

## NOMENCLATURE

$A_y^p$	Overall floor area growth in each province, $p$ in year, $y$ .
$A_{y,z}^p$	Floor area of new single detached households allocated to a specific climate zone, $z$ in year, $y$ .
$ACa_y$	National floor area growth of single detached households in year, $y$ .
$ASDH^p$	Provincial specific average area of a typical single detached house.
$\beta_{vy}$	The replacement coefficient for the households of vintage, $v$ in the year, $y$ .
$C_{p,air}$	Specific heat capacity of air at constant pressure.
$E_y^p$	Allocated space heating fuel use for a specific province or territory, $p$ in year, $y$ .
$F_{fuel\ typ}^p$	GHG factor relating emissions per unit of specific type of heating fuel use in a specific province or territory, $p$ .
$GHG_y^p$	Annual GHG emissions from new single detached households in a specific province or territory, $p$ in year, $y$ .
$HDD$	Annual heating degree day.
$i$	Specific hour when the building requires the cooling.
$n$	Total number of hours for which the building has cooling needs.
$\eta_{free\ clg}$	Annual usable free cooling potential of the air-side economizer.
$\eta_{free.clg.available}$	Annual maximum available free cooling potential.
$\eta_{fuel\ typ}$	Space heating system's average thermal efficiency based on the heating fuel type.
$NHT_y^p$	Total residential housing stock of a province, $p$ in year, $y$ .

$NHT_{y+1}^p$	Overall residential housing stock of a province, $p$ in year $y + 1$ .
$NSDH_y^p$	Number of newly constructed single detached households due to population growth in each province or territory, $p$ in year, $y$ .
$\rho_{air}$	Air density.
$Pl_z^p$	Census population within a specific climate zone, $z$ .
$Q_{free.clg.available}$	Annual Maximum available free cooling.
$q_{free.clg.available}_i$	Hourly maximum available sensible free cooling.
$Q_{free.clg.usable}$	Annual usable free sensible cooling.
$q_{free.clg.usable}$	Hourly usable free cooling.
$Q_{sen.clg.demand}$	Annual sensible cooling demand.
$q_{sen.clg.demand}_i$	Hourly sensible cooling demand without an air-side economizer.
$q_y^p$	Annual thermal energy demand in a specific province or territory, $p$ in year, $y$ .
$Q_y$	National energy demand of space heating.
$r_{fuel\ typ}^p$	Share of heating fuel types for single detached households in a specific province or territory, $p$ .
$r_{RHT}^p$	Provincial share of the overall single detached housing stocks of old vintages being replaced in Canada
$r_{SDH}^p$	Relative share of single detached households.
$r_z^p$	Climate-specific population ratio the province or territory, $p$ in climate zone, $z$ .
$RHT_{vy}$	Nationwide single detached housing stocks of old vintage, $v$ in year $y$ .

$RSDH_y^p$	The number of existing households of vintage, $v$ to be replaced with the new single detached house in year, $y$ .
$T_{clg\ set-point}$	Indoor cooling set-point.
$T_{OA}$	Hourly outdoor air dry-bulb temperature.
$TEDI_z^{step,y}$	Thermal energy demand intensity target of a certain <i>step</i> required to comply with in year, $y$ within climate zone, $z$ .
$TSDH_y^p$	Total growth of single detached housing stocks in each province and territory, $p$ in year, $y$ .
$\mu$	Average single detached household's life expectancy.
$v$	Vintage.
$\dot{V}_{air}$	Rated volume flowrate of the air-conditioner circulation fan.
$y$	Year.
$z$	A specific climate zone.

## ACKNOWLEDGEMENTS

I owe my deepest gratitude to my supervisors, Professor Andrew Rowe and Professor Peter Wild for their valuable time, professional advice, helpful guidance, unstinting support and consistent motivation throughout the course of this work. Without them, the works in this dissertation would have never been completed.

I am also grateful to Mr. George Steeves, P.Eng., former President of Sterling Cooper Consultants Inc. for his help and guidance. He also provides the industrial part of NSERC Industrial Postgraduate Scholarships to support my research.

I am deeply grateful to my family, my mother, Pinlan Chen, my wife, Kitty and my daughters, Natalie and Vanessa for their support, patience and inspiration all the time.

## DEDICATION

To the memory of my father, Ruifeng Li, who encouraged me that I should never give up when facing the challenge. You are gone but your encouragement inspired me and will keep inspiring me in the new journey of exploration.

# 1. INTRODUCTION

Fostering economic growth while minimizing the environmental impacts of growth is a global challenge faced by humanity. To tackle this challenge, in 2016, Canada along with 194 member countries of United Nations Framework Convention on Climate Change (UNFCCC) signed the Paris Agreement, thereby committing to cut GHG emissions from all economic sectors, including the building sector, by 30% of 2005 level by 2030 [1, 2]. The GHG emissions from buildings are mainly associated with mechanical system energy use; therefore, developing and implementing appropriate energy saving strategies makes the GHG emissions mitigation target assigned to the building sector more feasible. These energy saving strategies include implementing more technological solutions and launching new building energy standards to encourage sustainable and high-performance building design.

Many technological solutions, including the heat recovery ventilator and air-side economizer, have been proposed and applied to minimize building heating and cooling needs. A heat recovery ventilator (HRV) is a device that recovers energy from the exhaust airstream to temper the incoming ventilation air resulting in less energy use for heating. The use of the HRV is gaining more popularity and many guidelines and/or standards regarding its performance, design, and implementation have been provided by different level jurisdictions [3, 4, 5, 6]. An air-side economizer uses cool outside air to reduce the mechanical cooling requirements of a building when outdoor climatic conditions are favorable for free cooling [7]. This device has been widely used in heating, ventilation and air-conditioning (HVAC) systems of many non-residential building.

Undoubtedly, the employment of HRV and air-side economizer can reduce building energy use. However, buildings are complex systems with many linked sub-systems. The energy performance of such a complex system can be dominated by various factors under different operational conditions. Therefore, the energy saving potential of utilizing a specific building energy saving technology varies due to many factors, including: climate; thermal insulation levels of building envelope system; space heating and cooling load profiles; and the detailed performance characteristics of building mechanical systems. Gaining insight into the effects of these factors on the energy saving potential of these devices is of interest to both building designers and energy policy makers.

Most regions of Canada fall into cold climate zones with mild weather in both summer and shoulder seasons – conditions in which free cooling is readily available for residential buildings. Despite this, air-side economizers are mainly found in commercial building HVAC systems and are rarely used in residential applications, possibly because there is lack of free cooling potential information to reference in the design process. Potential free cooling from outside air is commonly quantified as *Maximum Available Free Cooling* and *Usable Free Cooling*. The former is the maximum free cooling that is available and can be provided by the air-side economizer to the building whenever the cooling is required. The usable free cooling defines the portion of the free cooling that is actually utilized by the building to reduce mechanical cooling needs. This is because there are times where the available free cooling may be below or exceed actual building cooling needs. Knowledge of the location-specific maximum available and usable free cooling potential can encourage the building HVAC system designer to implement free cooling technology in the design.

While the implementation of various energy conservation measures in building mechanical systems design can lower the energy demand and GHG emissions, new building energy standards can also play an important role [8]. Implementing an appropriate building energy standard can help emission mitigation targets be more attainable. The impacts of a specific building energy standards on emissions mitigation vary depending on thermal efficiency, heating fuel carbon intensity, and code enforcement. Although different building energy standards which are implemented in different areas are not easily comparable, comparison of the energy and GHG emissions reduction effects of two different energy standards which target building energy efficiency and are potentially implemented within the same areas is significant to building energy policy makers.

## 1.1 Previous work

This section provides an overview of the previous studies regarding the research topics of Chapter 2, 3 and 4 and their limitations. The detailed reviews for these previous works are in the literature review section of Chapter 2 and 3 and in the introduction section of Chapter 4. Here we provide the summaries of the relevant studies which address: (1) HRV performance; (2) air-side economizer energy saving potentials; and, (3) the effectiveness of residential building energy codes on space heating energy and GHG emission reductions.

### 1.1.1 Energy Saving Potentials of HRV

There is a significant body of literature investigating building energy savings due to the deployment of HRVs [9-18]. However, many of these studies draw conclusions based on the building ventilation system without considering the balance of the HVAC building

system [9-13]. Other studies [14-16] do consider the balance of the entire HVAC system, but the HRV energy saving potential is evaluated based on relatively simple representations of the HVAC system. Only the seasonal energy efficiencies of HVAC system heating and cooling devices are used to simulate the energy performance; neither the type nor the sizing nor the associated performance characteristics of the heating and cooling devices are reflected in the models.

The energy saving potential of HRVs reported by previous works vary due to various influencing factors, including the type and configuration of the host HVAC system [9, 10, 11, 12]. Although the air-to-air heat pump is recognized as an energy-efficient alternative to traditional heating and cooling devices for residential buildings [13], only one study analyzing the impacts of HRV on the energy use of a residential building served with an air-to-air heat pump system has been identified.

The impacts of weather on the energy saving potential of HRVs is one of the key factors causing variations in performance results reported in previous works [14, 15, 16, 17, 10, 11]. In addition, these studies fail to adjust the envelope design to reflect each of the climates represented; thus, reported results may not capture actual impact.

### 1.1.2 Energy Saving Potential of Air-side Economizer

Many studies conclude that using an air-side economizer to bring the free cooling of cold outside air into the building during the cooling season can decrease the mechanical cooling needs. Most of these studies focus on commercial buildings and data centers [20-29]. Although several studies [18, 19, 20] do examine the possibility of using free cooling of outside air for residential buildings, these studies only consider the free cooling potential of night-time natural ventilation through the building openings. Only a few studies [21, 22,

23], were found that deal with an air-side economizer in residential buildings and, in these studies, only the night time performance of the air-side economizer is investigated. As a result, for areas in cold climate zones having relatively mild summer weather, the free cooling potential would be underestimated since the outdoor conditions may be favorable for cooling even during the daytime.

From the methodology perspective, many studies [24, 25, 26, 27, 22], draw conclusions based on the energy use of building cooling systems. The results are specific to the features of the building and the type of the HVAC systems studied and, therefore, are not generally applicable. Other studies provide more generalizable results for the free cooling potential due to the deployment of an air-side economizer, based on weather data analysis only [28], [29]. These results are not specific to a particular building and HVAC system and, thus, these studies neglect interactions between varying building cooling needs and the outdoor temperatures.

### 1.1.3 Effectiveness of Residential Building Energy Codes

The contribution of residential building energy codes and their effectiveness in generating space heating energy savings and GHG emissions reduction have been addressed and evaluated in many previous studies [30, 31, 32, 33, 34, 35]. However, results tend to have uncertainty due to a range of factors including climate variability. For example, some studies [30, 31, 32] estimate future annual heating demand as the product of the envelope transfer coefficient, the exposed area, and the annual HDD. Thus, energy demand can be in error due to uncertainties in future building envelope thermal requirements and the penetration rate of the envelope efficiency technology. These factors impact the results of previous studies [33, 34].

## 1.2 Objectives

Neither BC Energy Step Code nor Passive House criteria stipulates specific code-compliant mechanical, electrical and plumbing (M.E.P.) systems; however, the HRV and free cooling technologies somehow have become essential in compliance with the two standards. For example, the deployment of HRVs in new residential houses has been addressed in the city of Vancouver's by-law in addition to its Passive House standards requirement. Likewise, thermal comfort terms regarding the limited overheating hours have been added to the BC Energy Step Code Design Guide Supplement [36] for residential units without having full cooling systems. Although the range of energy saving potentials by using HRV under various weather and operational conditions is not clarified in the city of Vancouver's by-law; and the air-side economizer is not mentioned at all as the available potential means for free cooling in the aforementioned step code design guide supplement, heat recovery and free cooling technologies are considered by industry as an indispensable part in residential building's mechanical system design leading towards code-compliant building. The developers and the general public see the utilization of heat recovery and free cooling technologies as essential to a high-performance building. However, building systems are complex and the applicability of the HRV and free cooling can be affected by various runtime conditions.

The energy performance targets specified in the BC Energy Step code or the Passive House criteria may be adopted by jurisdictions in other climate zones within Canada. This is because the energy performance targets specified in the BC Energy Step code are climate specific and BC has all of the six distinct climate zones seen across Canada. The Passive House criteria has a fixed energy performance target regardless of the climate zone.

The ultimate purpose to implementing more stringent energy performance standards is to mitigate the GHG emissions level of the building; however, such targets are partially realized through certain energy saving technologies. Therefore, it is necessary to consider both code and technologies when assessing the potential reduction in GHG emissions. Considering both HRV and free cooling technologies are closely related to the compliance of both BC Energy Step code and Passive House criteria and either of them could be potentially adopted by other regions within Canada, the overarching objective of this dissertation is to examine their effects on energy use and GHG emissions under various runtime conditions for Canada's residential buildings.

Specifically, the first work in the study analyzes the variability of the energy saving potentials of HRVs under various operating conditions in a typical Canadian residential apartment suite; and correlate the corresponding heating energy savings to the heating degree days. The analysis is focused on residential apartment buildings due to the recent change in building code regarding ventilation system design. The traditional passive ventilation method (i.e. outside air is intake through in-slab ductwork via the negative indoor pressure caused by a washroom exhaust fan) in high-rise apartments is no longer code compliant. Balanced ventilation, coupled with heat recovery ventilator, has been widely applied in residential apartment building's ventilation system; however, many HVAC system designers tend to apply the HRV without fully understanding the applicability of such a device under different design and runtime conditions. Hence, the research questions addressed in this study are:

- Does the HRV help to reduce energy use in residential buildings in all locations across Canada?

- What is the energy reduction potential of HRV and how does it vary by climate zone in Canada?
- Can the ranges of the variation be quantified so that the results can be used by building designers and energy policy makers to support HRV implementation decisions and development of policy on HRV use?

The objective of the second work in this study is to quantify the available free cooling and usable potential of outside air for a typical single-family house in Canada. Although free cooling technology can be applied to different types of residential buildings, in practice, free cooling in apartment buildings is realized through natural ventilation instead of air-side economizer due to limited ceiling space. This study considers the free cooling potential resulted from using an air-side economizer; therefore, single-detached houses are the focus of this work. The research questions addressed in this study are:

- What is the maximum available and usable free cooling for residential houses in Canadian jurisdictions?
- To what extent can mechanical cooling needs be reduced by the usable free cooling?
- How does the free cooling potential vary under various building designs?

The third work in this study is to investigate the impacts of building energy standard's stringency on GHG emission reductions. The study is carried out by examining the effects of BC Step Code and the Passive House Criteria on energy uses and GHG emissions in new single-detached households of Canada under various scenarios of adoption and enforcement. The research questions addressed in this study are:

- How does the building energy standard stringency affect the building GHG emissions in different areas across Canada?

- What differences in the space heating GHG emission from new single-family households would be if BC Step Code or Passive House Criteria is implemented nationwide in Canada?

### 1.3 Overview and Outline

To address the research questions related to HRV performance, in Chapter 2 TRNSYS models are developed to simulate the energy use of an air-to-air heat pump serving a hypothetical top-floor corner residential apartment suite under two scenarios- with or without employing HRV under various operating conditions. TRNSYS allows the energy performance characteristics of each type of equipment to be modeled in detail. In addition, being able to acquire the hourly simulation results in terms of the energy performance profile of each major equipment in the system is critical. TRNSYS allows a variety of simulation results of each component to be easily output by simply connecting that component to a data output component. [Fig. 1.1](#) and [Fig. 1.2](#) show the schematic designs of an HVAC system with an air source heat pump with and without and HRV, respectively. The annual heating and cooling energy use for these systems are simulated and compared and the results are normalized by suite's floor area to generalize the finding from one suite to the entire floor.

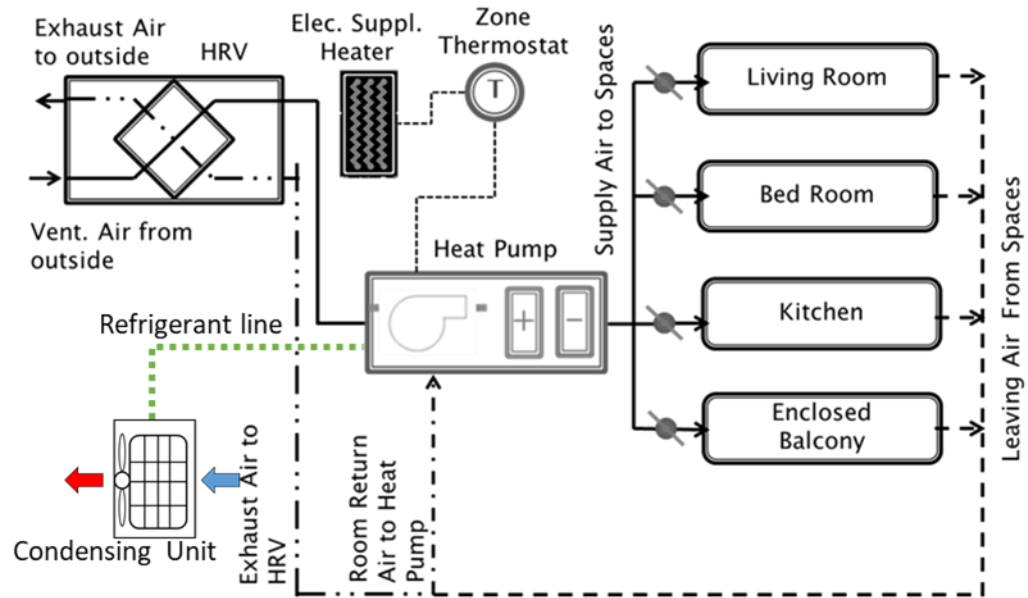


Fig. 1.1: Schematic of air source heat pump with the HRV

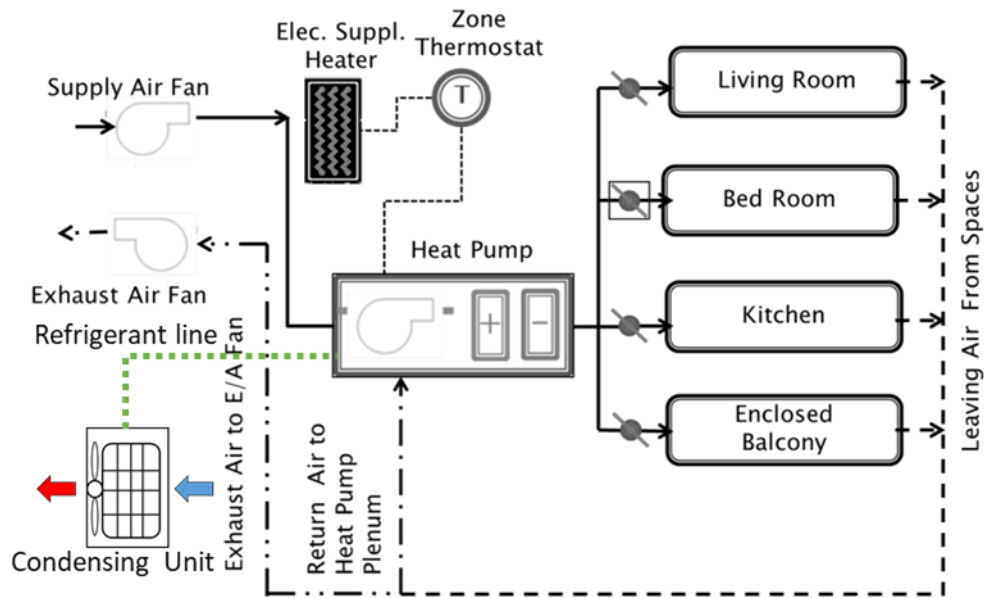
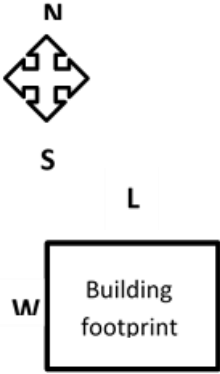


Fig. 1.2: Schematic of air source heat pump without the HRV

The research questions related to free cooling are addressed in Chapter 3. In this study, the ranges of the free cooling potential for a hypothetical single-family house of various configurations represented by different aspect and window-to-wall ratios in different climate zones are qualified. [Table 1.1](#) lists the aspect and window to wall ratios

considered in the study. As can be seen, 51 cases reflecting the permutation of different aspect and window to wall ratios are investigated for each selected Canadian city; therefore, a simulation tool with the capability of quickly and easily changing the shape of the footprint and the window area of the studied building is desirable. For this reason, a series of thermal models are developed using BEopt 2.8 to obtain the building hourly cooling needs based on which the corresponding annual usable free sensible cooling potential under each scenario is assessed. Details of the work are presented in Chapter 3.

Table 1.1: Varying Window to Wall and Aspect Ratios Considered in work of Chapter 3

Building Footprint & Orientation	Building Aspect Ratio (L:W)	Window to Wall Ratio		
		12%	15%	18%
	1:3	√	√	√
	1:2.75	√	√	√
	1:2.5	√	√	√
	1:2.25	√	√	√
	1:2	√	√	√
	1:1.75	√	√	√
	1:1.5	√	√	√
	1:1.25	√	√	√
	1:1	√	√	√
	1.25:1	√	√	√
	1.5:1	√	√	√
	1.75:1	√	√	√
	2:1	√	√	√
	2.25:1	√	√	√
	2.5:1	√	√	√
	2.75:1	√	√	√
	3:1	√	√	√

The research questions related to building energy standards are addressed in Chapter 4. In this study, we consider six levels of stringency for building energy performance code.

For each level, the space heating GHG emissions from new constructed single detached households are analyzed for the period from 2020 to 2032. The six levels of stringency are reflected by a reference (i.e., no-action) scenario, four scenarios representing different rates of BC Step Code adoption and one scenario of the Passive House criteria. [Fig. 1.3](#) shows the four BC Step Code adoption scenarios. Both regional and national emissions under different scenarios are generated and compared. The detailed work is presented in Chapter 4.

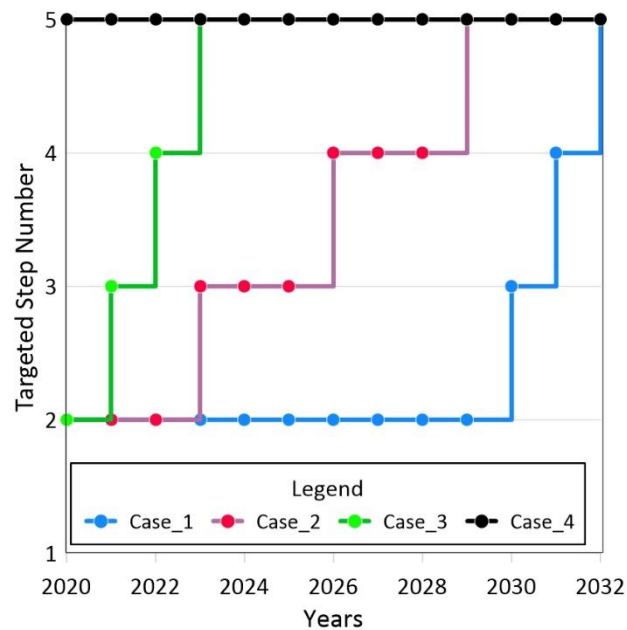


Fig. 1.3: Four cases representing different rates for BC step code adoption

Chapter 5 summarizes the contributions of the work presented in Chapters 2, 3 and 4 and recommends future research that would follow from the research presented here.

## 2 PERFORMANCE OF A HEAT RECOVERY VENTILATOR COUPLED WITH AN AIR-TO-AIR HEAT PUMP FOR RESIDENTIAL SUITES IN CANADIAN CITIES<sup>1</sup>

### **Preamble**

Heat recovery ventilation (HRV) technologies are used to satisfy indoor air quality requirements while reducing building energy consumption. In a typical installation, an HRV system is expected to decrease energy demand; however, the actual benefit depends on the mechanical system, climate conditions, and building design. Here, we assess the energy savings from sensible heat recovery in residential apartment buildings across Canada by modeling the building thermal demands and the HVAC system's energy use. We compare the annual performance of a commercial air-to-air heat pump coupled to a balanced ventilation system with and without the HRV. A hypothetical residential suite is modeled under eight different building orientations for fifteen Canadian cities. Results show that HRV use always reduces the annual heating energy consumption; however, energy consumption may increase in cooling seasons.

### 2.1 Introduction

Ventilation is the process of supplying air to a building [4]. Buildings must be appropriately ventilated to maintain acceptable air quality and temperature for human occupancy and to remove excess water vapor from occupied spaces. Although several types

---

<sup>1</sup> The body of this chapter was published in Bo Li, Peter Wild, Andrew Rowe, *Journal of Building Engineering*, vol. 21, page 343-354, January 2019.

of mechanical ventilation systems are available for the residential buildings, *balanced ventilation* is widely used in Canada. With balanced ventilation, the mechanical system manages both the flow of outdoor supply air and the exhaust air [37]. To minimize the negative impacts on thermal comfort, ventilation air is often conditioned to control temperature and humidity. The energy consumed during the process of conditioning can be significant. Studies show that conditioning of air can account for 18-35% of the total building energy consumption in non-industrial buildings [38]. The energy consumption of ventilation systems can be reduced by decreasing the flowrate of the ventilation air or by reducing the enthalpy difference between the ventilation air and indoor air [39]. Reducing the flowrate can place energy conservation in conflict with preserving indoor air quality if the amount of outdoor air supplied to the space is less than the minimum required by code. Therefore, HVAC design has focused on approaches that reduce the enthalpy difference between ventilation and indoor air. A solution to this problem is the *energy, or heat, recovery ventilator*, (ERV or HRV), a device that recovers part of the energy from the space exhaust air to temper the incoming ventilation air. An HRV harvests sensible heat from the exhaust air while an ERV recovers both sensible and latent heat.

The mechanical balanced ventilation system coupled with an HRV/ERV has become a preferred solution to satisfy the requirements of improving indoor air quality while reducing the building energy consumption. However, HRV systems are often simple heat exchangers with no ability to operate in an unbalanced mode. As a result, undesired thermal conditioning may result if the system is operated at times when energy recovery is not desired. Given the primary reason for HRV use is to reduce building energy consumption, it is important that ventilation systems are operated so as not to introduce unwanted thermal

loads. HRVs combined with heat-pumps are considered to be solutions for reducing residential energy consumption.

The following section provides a review of relevant studies quantifying HRV system performance. The limitations of previous work lead to the objectives of the current paper. Subsequently, the research methodology including the description of the simulation tool, the residential suite, the heating, cooling and ventilation systems, and the parametric analysis are described. The impacts of the variation in a number of outdoor climates, building orientation and building envelope thermal properties on annual heating and cooling energy uses of the suite are investigated.

## 2.2 Literature Review

Although there is a significant body of HRV/ERV literature [40, 7, 17, 41, 42, 11, 14, 9, 12], it is difficult for HVAC system designers to draw clear guidance because the energy saving potential is impacted by many factors, including: climate [17], [11], [14], [10], [15], [16]; building mechanical system type [11], [10], [12], [3]; ventilation air flowrate [17], [11], [15]; indoor cooling and heating temperature set-points [41], [43]; the energy performance of ERV/HRV blowers [17], [14], [10], [44]; the sensible and latent heat transfer effectiveness of ERV/HRV [17], [10]; the physical heat transfer area of the HRV/ERV core [45]; the control strategies [46], [11], [14], [43]; the building operation schedules [42]; the building envelope tightness [43], [47], [12]; and the parasitic leakage [43], [47]. A further complication is that the ventilation system type to which the HRV/ERV system is compared varies from study to study [12], [3].

Within this literature, many simulation-based studies draw conclusions based on models of the HRV/ERV alone, with no consideration of the balance of the HVAC system [14, 9, 15, 16, 43]. For example, Zhong et al. [16] study the applicability of HRVs with different heat exchanger cores for eight cities representing different climatic zones in China. It is found that the energy saving potential and the building heat recovery ventilation system efficiency are dominated by the temperature and humidity differences between the outdoor and indoor air. These conclusions result from the analysis of energy performance of the building ventilation system only.

Other simulation-based studies [17], [7], [10], [43], [45] investigate the energy saving potential of HRV/ERV systems in the context of the HVAC system but are based on relatively simple representations of the HVAC system. Typically, these models simulate the HVAC system energy performance based on the Seasonal Energy Efficiency Ratio (SEER) or Seasonal Coefficient of Performance (SCOP) of the major heating and cooling devices. Neither the specific type nor the sizing and the associated performance characteristics of these devices are represented in detail. For example, Fouih et al. [10] compare the energy performance of an HRV ventilation system with a range of heat exchanger efficiencies and specific fan powers to two other types of ventilation systems without an HRV. The study examines low energy residential and commercial buildings located in seven cities within two ASHRAE climate zones of France. The conclusions of their study are based on comparisons of annual heating and cooling energy use under various simulation scenarios which are developed to reflect different climates, ventilation system types, HRV heat exchanger efficiencies and blower energy performance. The annual HVAC system energy use is calculated based only on the equipment's rated SEER

(i.e. annual cooling use = annual cooling demand / SEER). The rated SEER does not provide an accurate evaluation of annual heating or cooling energy because it is determined for a single set of assumed operating conditions [48, 49, 50]. The accuracy of predicted annual cooling energy based on rated SEER has been shown to range from -30% to 15% of the actual annual cooling energy due to the impacts of climate and building/HVAC system characteristics [51]. To capture the complex interactions between the climate, building and the HVAC system, it is necessary to model the HVAC system in more detail.

The energy saving potential of an HRV/ERV depends upon the host HVAC system and climate conditions. The heat recovery ventilation guide for multi-unit residential buildings [3] issued by BC Housing presents simulated energy savings due to the deployment of an HRV, coupled with various HVAC system types, in a typical 10-storey MURB building for five Canadian cities. [Table 2.1](#) summarizes the modeled heating and cooling energy savings of HRV compared to the pressurized corridor system with intermittent exhaust fans in suites in Ref. [3]. For Vancouver, the annual energy savings of an HRV ventilation system is \$280 if the building heating and cooling are provided by the gas furnace and general air-conditioner, respectively. These savings increase to \$640 if the building is equipped with electrical baseboard heat and no cooling system. In Toronto, the energy savings of using HRV that operates with these two HVAC systems are \$300 and \$1,090, respectively. As can be seen, the reductions in system energy use due to the deployment of HRV/ERV are specific to the HVAC system type and climate zone.

Table 2.1: Modeled heating and cooling energy savings of HRV compared to pressurized corridor system with intermittent exhaust fans in suites [3]

Location	Annual Energy Cost Savings Per Suite and % Reduction in Ventilation Heating and Cooling Energy Due to an HRV	
	Gas Furnace & Generic AC	Electric Baseboard & No Cooling
Vancouver	\$280 (86%)	\$640 (81%)
Toronto	\$300 (81%)	\$1,090 (78%)
Montreal	\$200 (82%)	\$690 (80%)
Winnipeg	\$440 (85%)	\$960 (82%)
For McMurray	\$370 (85%)	\$1,800 (83%)

The applicability of HRV/ERV system to a variety of building HVAC systems has been described in many previous studies, as summarized in [Table 2.2](#). The air-to-air heat pump is considered an energy-efficient alternative to traditional heating and cooling devices for residential buildings [13]. Although these devices are growing in popularity [48, 13], only one study has been identified in which the performance of an HRV coupled with air-to-air heat pump system is assessed [12]. Dodoo et al. analyze the impacts of HRV on the source energy use in a case-study of a residential building located in Sweden with the building envelope designed to conventional and passive house standards. The analysis is performed for three types of heating systems: an air-to-air heat pump, electric baseboard and hydronic district heating system. The source energy supplied to the building is based on steam turbine or integrated gasification combine cycle technology using biomass fuel. The results show that using an HRV can reduce both building heating load and source energy use; however, reductions in source energy use strongly depend on the type of heating system, the electricity consumed by the HRV's blowers, and the air tightness of the building envelopes. Although the interactions between the HRV and the combination

of different building heating system type and different source energy supply technologies are investigated, the detailed heat pump sizing and performance characteristics and the interactions between the HRV and heat pump itself are not reflected in the study.

Table 2.2: Types of HVAC system being investigated in previous studies

Relevant Referred Studies	HVAC Systems	
	Heating	Cooling
[6]	Floor radiant heating	N/A
[7]	Radiator	DX Coil
[8]	District heating	DX Coil
[9]	Natural Gas-fired	DX Coil
[12]	Natural Gas-fired	DX Coil
[15]	DX Coil	DX Coil
[16]	Four-pipe fan coil	Four-pipe fan coil
	Gas-fired	DX Coil
[26]	Electric baseboard	N/A

Weather is a key factor influencing the energy saving potential of an HRV/ERV. Many studies [17], [7], [11] compare energy performance of an HVAC system with and without HRV/ERV in different climates/locations. Typically, however, the building envelope design is not adjusted to suit each of the climates represented in these studies. For example, Lam et al. [11] investigate the geographic applicability of ERVs and the associated economizer or bypass operation by conducting a series of Energy-Plus simulations of five different HVAC systems on a generic office building for sixty-two U.S. cities. Although the size of the HVAC system is adjusted for each city's climate, the same building envelope is used for all cities. In practice, building envelope requirements, as stated in ASHRAE 90.1-2010 [4], vary with climate and these requirements have been widely implemented in many government-issued energy standards and regulations.

## 2.3 Objective

Although many studies investigate the energy saving potential of an HRV, these studies typically consider a sub-set of key drivers of HRV performance. These drivers include: climate; the thermal properties of the building envelope required by local building code; and the detailed performance characteristics of the mechanical system to which the HRV is coupled.

The objective of the current study is to investigate the energy saving potentials of an HRV coupled with an air-to-air heat pump serving a residential apartment suite for three ASHRAE climate zones using detailed building and HVAC system models. The building envelope design regarding the thermal insulation tailored to suit each of the climate zones considered. The hourly heating, cooling and ventilation needs of a residential apartment suite are determined. A commercial heat pump and HRV are selected to meet the apartment demands in accordance with ASHRAE 90.1-2010 standard and the associated detailed performance characteristics are applied in the model. Energy savings are determined as a function of annual heating and cooling degree days.

## 2.4 Methodology

A TRNSYS model is developed and used to simulate the energy use of an HVAC system for a hypothetical top-floor corner residential apartment suite. In one scenario, a balanced ventilation system supplies the outside air to the suite using an HRV while, in a second scenario, there is no HRV. In both scenarios, an air-to-air heat pump of the same capacity is selected to provide heating and cooling. The simulated heating, cooling and fan energy use of the heat pump operating with and without HRV are then analyzed and

compared. The logic network diagram of the TRNSYS simulation models of the aforementioned two scenarios are illustrated in [Fig. A3](#) and [Fig. A4](#) in the Appendix. The TRNSYS components and the key parameters are explained in [Table A-9](#).

For each scenario, a parametric analysis is conducted to investigate the impacts of the variation in a number of outdoor climates, building orientation, and building envelope. Fifteen Canadian cities representing three ASHRAE climate zones are modeled. For each location, the building envelope is adjusted to be consistent with local building codes and the building azimuth angle is varied from 0 to 315 degrees at increments of 45. The annual heating and cooling energy use for each case are calculated and normalized by the suite area so that the findings can be generalized from one suite to the entire floor. The relationship between the annual heating degree days (10°C as reference point) and the annual heating energy savings due to the use of HRV are determined.

## 2.4.1 Model Description

### 2.4.1.1 Simulation Tools

The simulations in this study are conducted with TRNSYS (Thermal Energy System Specialists, LLC, Madison, USA) which is a complete and extensible simulation environment with modular structure for the transient simulation of systems, including multi-zone buildings and is widely used by both industry and academe [52]. The parametric study is conducted with jEPlus 1.6.3 (Energy Simulation Solutions Ltd., UK) which is able to perform complex parametric analysis of multiple parameters of simulation models [53]. The suite characteristics and representative data are explained in the following sections using Vancouver as the representative location.

### 2.4.1.2 Suite Description

The hypothetical apartment suite shown in [Fig. 2.1](#) is a one-bedroom, top-floor, corner unit, for two-person occupancy in a residential apartment building with an overall suite area is  $56 \text{ m}^2$  ( $604 \text{ ft}^2$ ).

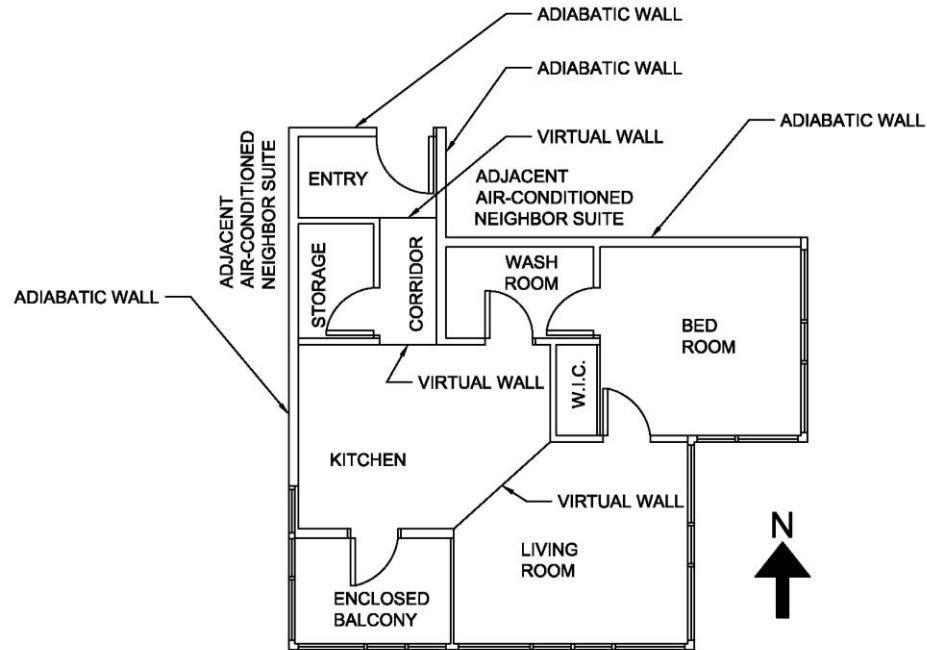


Fig. 2.1: The plan of the hypothetical top-floor corner condo suite (Azimuthal orientation is 0 degrees)

A 3-D model of the hypothetical apartment suite is created by Trnsys 3D plugin tool in SketchUp 2015. Each room is modeled as a thermal zone consisting of a single air-node which assumes that area of the suite that can be characterized by a single air temperature. The partitions between the living room and kitchen, kitchen and in-suite corridor, in-suite corridor and entry are virtual walls type since there is no physical partition wall in between. This building is assumed to have two adjacent air-conditioned suites, as shown in [Fig. 2.1](#). Therefore, the walls separating these suites are modelled as adiabatic

boundaries. All the interior partition walls within the unit are assumed to be adiabatic as well.

TRNSYS type 56 is used to model the thermal behavior of the residential suite. The thermal properties of the suite envelope are assumed to meet and/or exceed the requirements of ASHRAE Standard 90.1-2010 [4]. Detailed thermal properties of the suite envelope for the Vancouver location are provided in [Table A-1](#). [Figs. 2.2-2.4](#) present the weekday and weekend schedules for suite occupancy, interior lighting and the miscellaneous loads, respectively. The schedules are those used with the DOE2.2 based building energy simulation software- eQuest 3.65. [54].

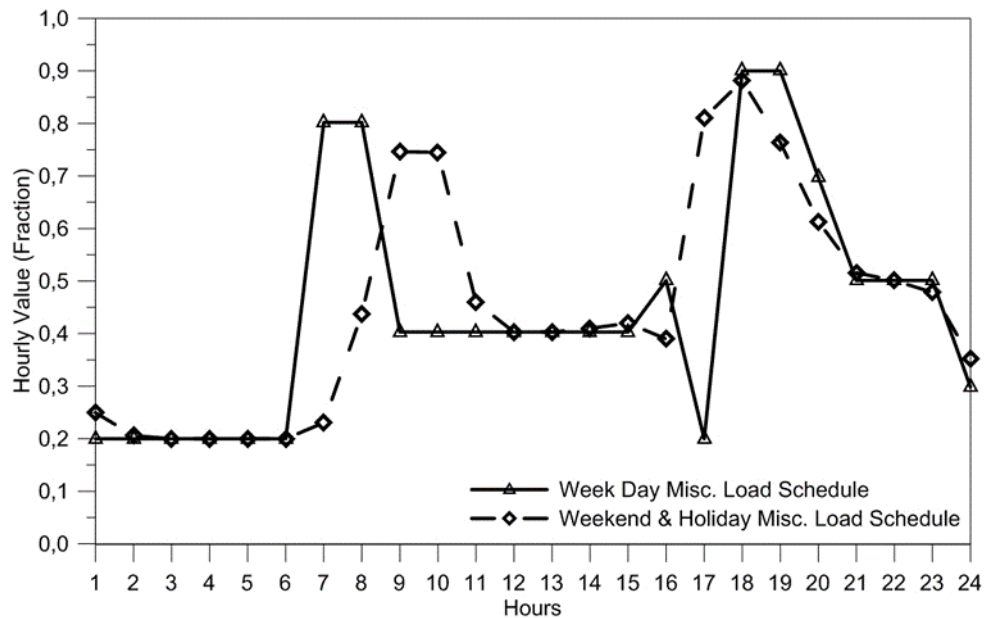


Fig. 2.2: Suite level weekday and weekend occupancy schedules

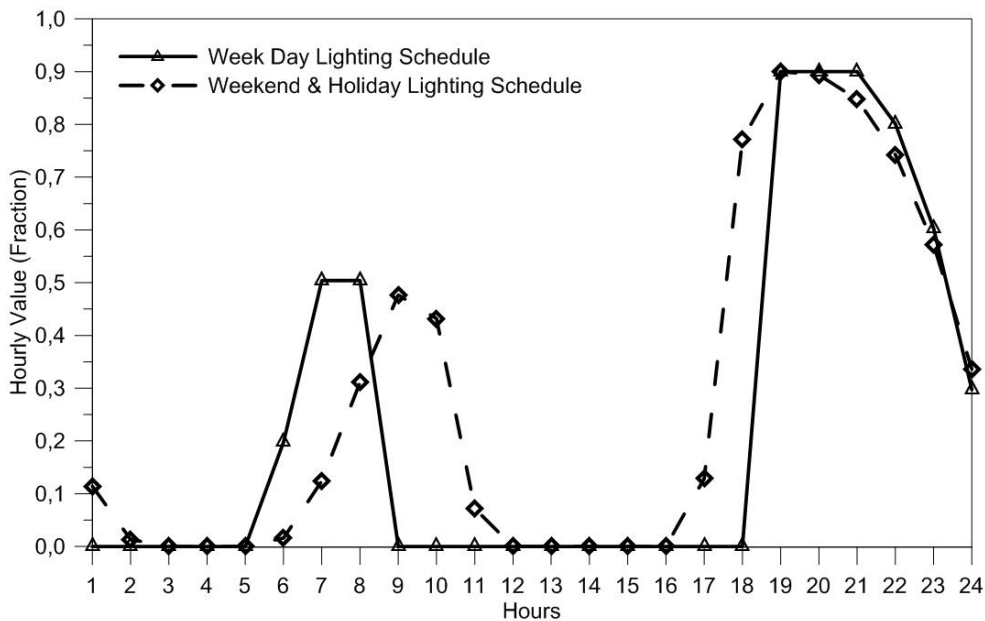


Fig. 2.3: Suite level weekday and weekend interior lighting schedules

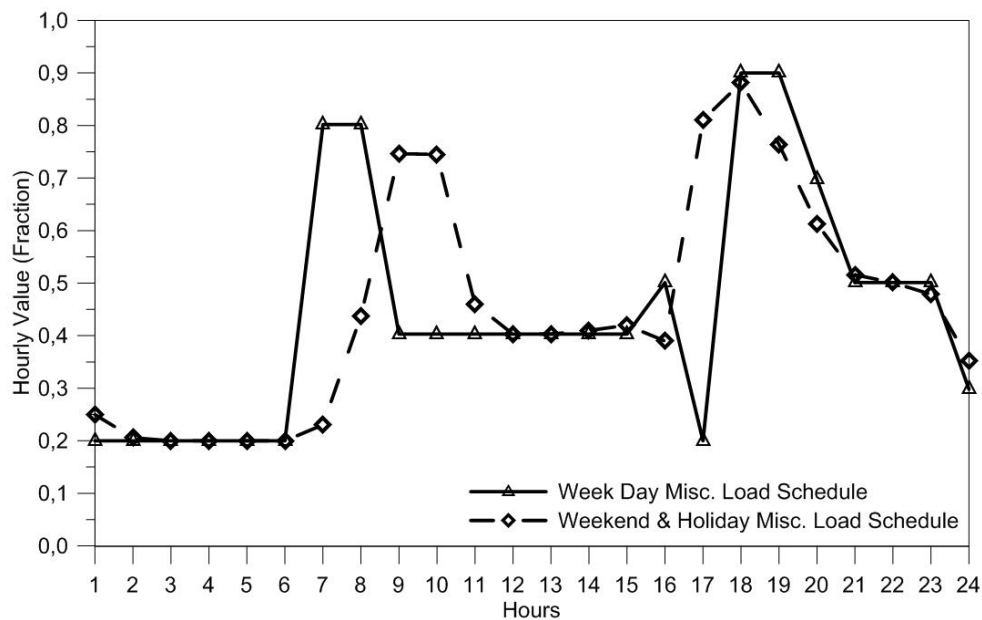


Fig. 2.4: Suite level weekday and weekend miscellaneous load schedules

The assumed lighting cooking, computer and other miscellaneous peak design powers are summarized in [Table A-2](#). No lighting or other equipment usage occurs in the storage room, bedroom walk-in closet, or the enclosed balcony.

The heating and cooling set-points are set to 20°C and 24°C, respectively. The heating and cooling loads are obtained from TRNSYS using the energy rate control method. This method enables the model to calculate the loads based only on the net heat gain or loss from the space to maintain the space heating and cooling set-points.

#### 2.4.1.3 Air-Conditioning Systems

The suite is heated and cooled by an air-to-air heat pump. [Fig. 2.5](#) shows the mechanical ventilation configured with and HRV, while [Fig. 2.6](#) shows the configuration in the non-HRV scenario. In both scenarios, the rate of ventilation air flow is 38 l/s. The conditioned air supplied by the heat pump is delivered to the living room, bedroom, kitchen, and enclosed balcony. The air returned from each of those rooms is collected and then mixed with the ventilation air which is either directly from the building exterior in non-HRV scenario or through the HRV in the HRV scenario. The mixed air is then heated or cooled by the heat pump before it is delivered back to the rooms. In order to balance the room air pressure, part of the return air is exhausted to the outside at the same flowrate of ventilation air brought to the suite.

According to the Natural Resources Canada guidelines for the air-source heat pumps sizing [55], the air-to-air heat pump shall be sized based on the design cooling load. Accordingly, a 5 kW (1.5 ton) ductable air source heat pump with the supplemental electric heater (Model: York YHJD18 S41S2 & AHE18B) is selected with its key performance parameters listed in Appendix [Table A-8](#). The heating capacity of the heat pump is limited since it is sized based on the suite design cooling load which is expected to be smaller than the design heating load. To accommodate the imbalance between the design heating load and the capacity of the heat pump, the heat pump is equipped with a built-in two-stage

electric supplemental heater. The capacity of the supplemental electric heater is based on the difference between the suite design heating and cooling loads and the available electric heater size published in manufacturer's manual. The TRNSYS Type 954a [56] is chosen to model the air-to-air heat pump and the manufacturer's data are applied to the TRNSYS model (see Appendix [Table A-3](#)). The TRNSYS type 108 [56] is chosen to model the multi-stage thermostat which controls the heat pump. [Table 2.3](#) shows the how the staged use of electrical heating under the control of a suite multi-stage thermostat. As indicated in the table, when the first stage electrical heater is activated, the heat pump keeps running; similarly, when the second stage electrical heater is triggered, both heat pump and the first stage electrical heater keep running.

Table 2.3: The operation status of heat pump and its electrical stage heaters under the control of the multi-stage suite thermostat

Set-points [°C]	Heat Pump	1 <sup>st</sup> Stage Electrical Heater	2 <sup>nd</sup> Stage Electrical Heater
20	ON	OFF	OFF
18	ON	ON	OFF
16	ON	ON	ON

In practice, the conditioned air provided by the HVAC system is not delivered to each of the rooms inside the suite; instead, it is delivered to the rooms which are occupied by people most time in a day. Those rooms are air-conditioned directly; while the rest rooms are in-directly air-conditioned through heat and mass transfer in between. In this study, the living room, bedroom, kitchen and the enclosed balcony are assumed to be direct air-conditioned rooms. The ratio of flowrate of the air supplied to each direct air-conditioned room to the overall flowrate of the heat pump supply air is assumed to be fixed

in the model, and is calculated by dividing the sensible cooling load of each individual room into the corresponding overall suite sensible cooling load under design conditions.

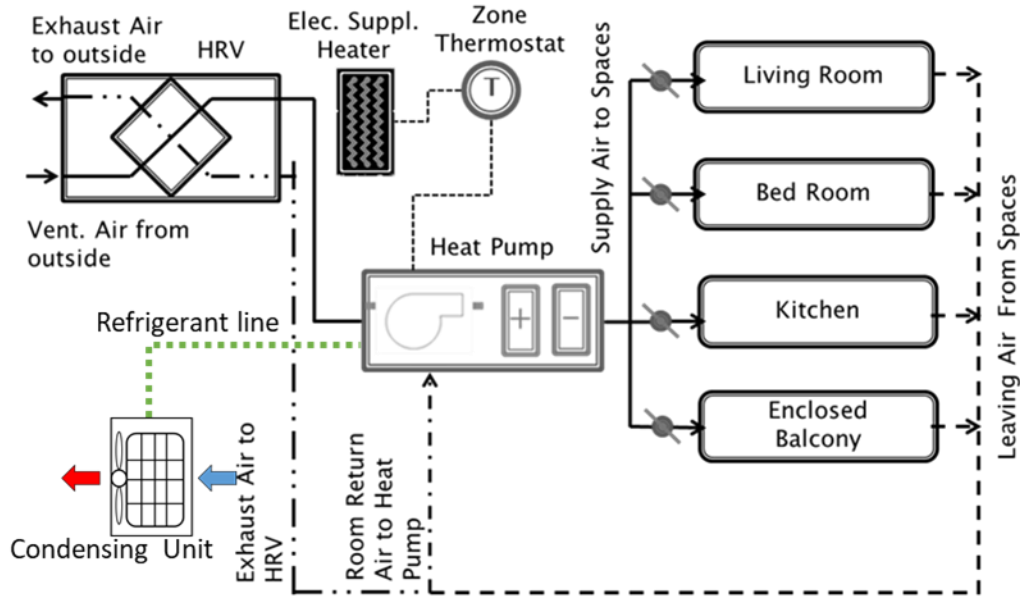


Fig. 2.5: Schematic of air source heat pump with the HRV

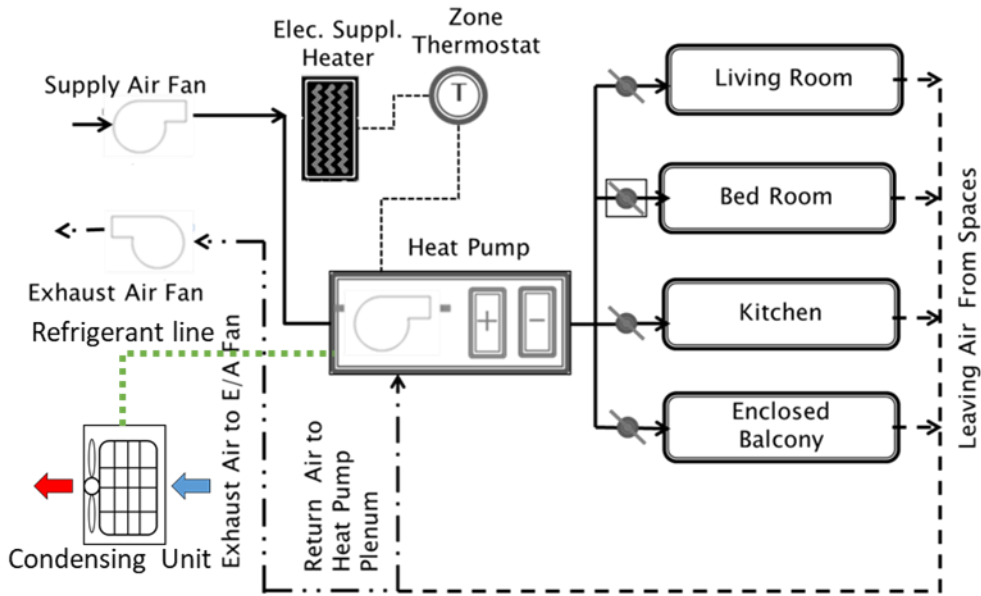


Fig. 2.6: Schematic of air source heat pump without the HRV

#### 2.4.1.4 Suite Ventilation Systems Description

Based on a suite area of 56.2 m<sup>2</sup> with two occupants, according ASHRAE 62.1-2010 [57], the minimum required ventilation airflow is 27.3 l/s. This value closely matches the minimum ventilation capacity requirements specified in the BC Building Code (BCBC) 2012 [58] for a one bedroom residential dwelling. However, a typical high-rise MURB building also has two- and/or three-bedroom suites requiring a ventilation system with higher capacity. To be consistent with common design practice in industry, the operating ventilation air flowrate for the modeled suite is set to 35.4 l/s, approximately 23% higher than the minimum requirement as per ASHREAE 62.1-2010 [57].

As shown in [Fig. 2.5](#) and [Fig. 2.6](#), the ventilation air is drawn from outside and delivered to each room through ductwork, as is the suite exhaust air. The total pressure drop of the air in the ventilation and exhaust air ductwork is assumed to be 75 Pa (0.3” Water Column), respectively, for both non-HRV and HRV scenarios. In order to simulate the actual fan’s operating power and the corresponding energy consumption, the corresponding published manufacturer’s data of the fan including the rated airflow and the rated fan power are applied to TRNSYS Type. The Type 760 is chosen to model the sensible heat recovery ventilator and the manufacturer’s data are applied to the HRV model. A sensible effectiveness of 71% is used in accordance with manufacturer’s data. Appendix [Table A-4](#) lists the key performance data of the supply/exhaust fans and the HRV published by manufacturer. Meanwhile, the coefficients of the fan power curve polynomial which Type 744 uses to simulate the operating fan power are derived based on affinity law of fan.

The flow of the ventilation air to each room within the suite is allocated proportionally based on floor area (see Appendix [Table A-5](#)). For rooms which are not directly air-conditioned (i.e., bedroom's closet, corridor, suite entry area, bathroom and storage room), the calculated ventilation airflow is added to the ventilation airflow of the adjacent air-conditioned room so that the overall suite ventilation airflow remains unchanged.

#### 2.4.2 Parametric Analysis

To assess the energy performance for a range of climate types, a series of TRNSYS simulations of the annual heating and cooling energy uses of this residential apartment suite are conducted. The suite is set to face eight different azimuth angles (i.e. 0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°) for each of the fifteen Canadian cities representing three ASHRAE climate zones (i.e. climate zone 5, 6, and 7) [4]. Fifteen Canadian cities are simulated in the parametric study (see [Table 2.4](#)). The minimum envelope thermal requirement for the appropriate climate zone, based on ASHRAE 90.1-2010 [4], is applied to each simulation. Thus, in total, 120 cases are simulated for each of the HRV and non-HRV scenarios.

The hourly weather information for each location is generated by TRNSYS component type 15 which reads the TMY 2 weather data from taken from the external weather data file. Due to the difference in outdoor conditions and building envelope design for the different climate zones, the designed heating and cooling loads differ from city to city. For each city, the capacity of the heat pump and the built-in supplemental electric heater are independently determined as described earlier. Appendix [Table A-8](#) lists the key specifications of the selected heat pumps and supplemental electric heaters. The thermal properties of the envelope are in compliance with the residential building envelope

thermal property requirements for ASHRAE climate 5, climate 6 and 7 zones in this study.

Envelope details are summarized in [Table A-1](#), [A-6](#) and [A-7](#).

Table 2.4: Fifteen Canadian Cities Representing Three ASHRAE Climate Zones in Parametric Study

Climate Zone	Climate Zone 5	Climate Zone 6	Climate Zone 7
City Name	Vancouver	Lethbridge	Prince George
	Nanaimo	Charlottetown	Edmonton
	Port Hardy	Montreal	Winnipeg
	Sandspit	Ottawa	Kapuskasing
	Summerland	Toronto	Saskatoon

## 2.5 Results and Discussion

In order to focus on the impacts of HRV on energy performance under different climatic conditions, results reflecting the difference of the annual heating and cooling energy are analyzed and presented here. Additional details can be found in the Appendix describing other results related to residence envelope and climate zone impacts (e.g. suite design heating and cooling loads.)

### 2.5.1 Annual Heating and Cooling Energy Requirements

The annual heating energy with and without HRV is presented in [Fig. 2.7](#). The heat pump energy use is normalized by suite area. The range of values for each city due to orientation effects are shown by the box-whisker plot. As can be seen, in climate zone 7, the annual heating energy use without-HRV ranges between 110 kWh/m<sup>2</sup> and 175kWh/m<sup>2</sup> while for the with-HRV scenario, this value ranges between 64 kWh/m<sup>2</sup> and 85 kWh/m<sup>2</sup>. The least heating energy is needed in climate zone 5, ranging between 60-79 kWh/m<sup>2</sup>

without-HRV and 50–64 kWh/m<sup>2</sup> with-HRV. As indicated by the range of the bars, the energy use varies with the building orientation. For example, in Edmonton, the annual heating energy use is 122 – 140 kWh/m<sup>2</sup> for non-HRV case and 86 – 100kWh/m<sup>2</sup> with HRV. As the suite position is varied to face different orientations, the exposed area and the architectural component materials of the building's façade result in changes in the solar heat gain. [Fig. 2.7](#) implies that employing HRV always reduces the annual heating energy consumptions of the heat pump system in all three climate zones. Also, even with an altered envelope, more heating energy is consumed in colder climate zones; however, more heating energy saving potentials can be achieved in colder weather by utilizing HRV.

[Fig. 2.8](#) shows the annual cooling energy use per unit area of the system with and without HRV. Again, bar ranges reflect the impacts of orientation in each city. The annual cooling degree days (CDDs) for each location are indicated at the top of the plot. As can be seen, during the cooling season, more cooling energy is consumed by the air-to-air heat pump when operated with the HRV. This is due to the undesired heat recovery that occurs in the HRV. When the outdoor air dry-bulb temperature is lower than the indoor temperature set-point, the building cooling demand (mainly due to the solar and space internal heat gains) can be met partially, or entirely, by the free cooling of outdoor air. However, the potential of such free cooling is reduced if the cold outdoor air passes through the HRV so that it recovers the undesired heat from the exhausted air of the space at higher temperature. That means the building cooling demand which could have been met by the free cooling of outdoor air will be handled by the air-source heat pump resulting in more cooling energy consumption.

Although the heat pump's annual cooling energy consumption is small compared to its annual heating energy use, the energy performance of the entire building HVAC system coupled with the HRV can be negatively impacted by such undesired heat recovery in the HRV during the cooling and/or even shoulder season. [Fig. 2.9](#) compares the annual heat pump energy reductions with HRV (including both heating and cooling) to the energy use reductions for heating only. As can be seen, the combined heat and cooling reductions are smaller than when the system is providing heating only. For example, using HRV in Vancouver, the annual heating energy consumption reductions range between 12-14.4 kWh/m<sup>2</sup>; while, the reductions when both heating and cooling demands are met range between 8.0-9.9 kWh/m<sup>2</sup>. [Fig. 2.10](#) shows the same results as [Fig. 2.9](#), but as a percentage of the energy demands without HRV. These results show that deployment of HRVs can lead to increased energy consumption in the building HVAC systems during the cooling season if they are used blindly. This effect may be more significant if building thermal resistance is higher, but solar gain is also large. One possible solution to minimize such undesired heat recovery is implementing an air-side economizer to the ventilation system. The economizer is interlocked with the HRV. Whenever the outdoor condition is favorable for providing the free cooling, the economizer is on and the HRV shuts down and vice versa. Another possible method is to have the required ventilation air circumvented the HRV core through an internal bypass damper whenever the undesired heat recovery occurs. More studies are needed to develop a strategy to appropriately control the flowrate of the air either through the economizer or bypassing the HRV core.

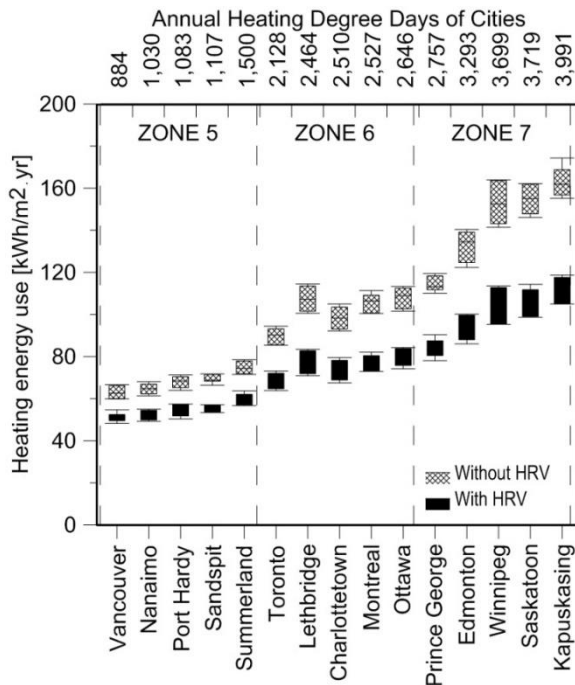


Fig. 2.7: Comparison of annual heating energy use per unit area by heat pump between non-HRV and HRV scenarios

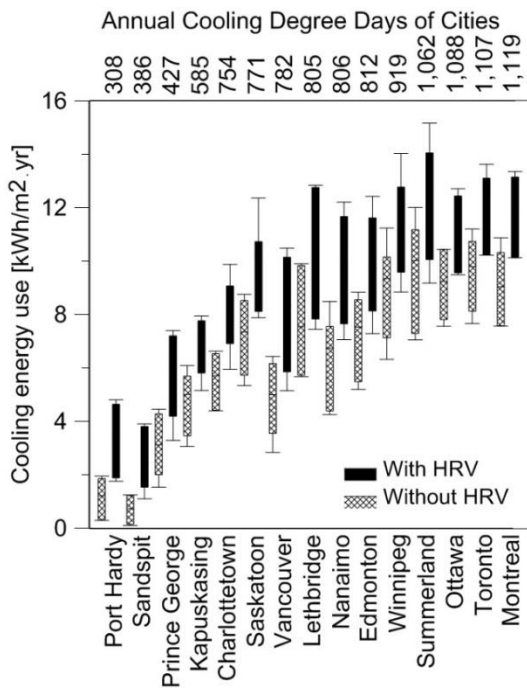


Fig. 2.8: Comparison of annual cooling energy use per unit area by heat pump between non-HRV and HRV scenarios

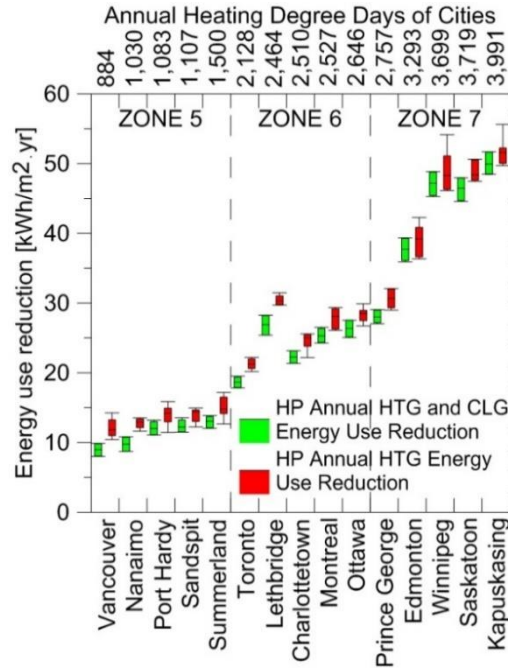


Fig. 2.9: Reduction in heat pump annual heating and cooling energy use per unit area V.S. the reduction in heat pump annual heating only energy use per unit area due to the employment of HRV

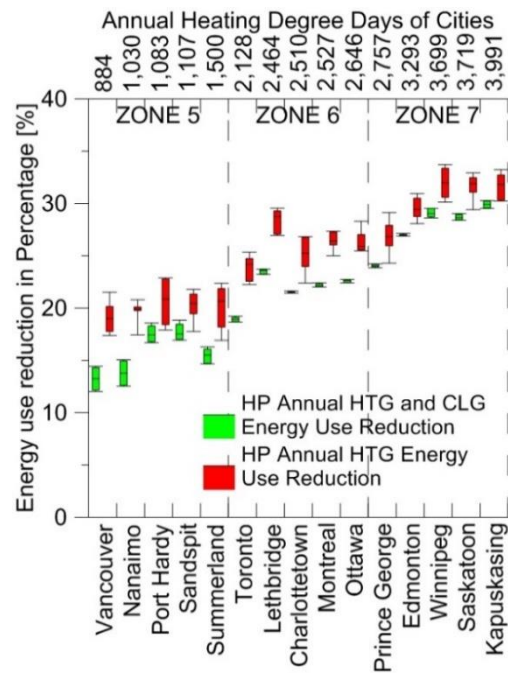


Fig. 2.10: Percentage reduction in heat pump annual heating and cooling energy use with HRV and reduction in heating only energy use

## 2.5.2 Heating Energy and Heating Degree Days

The relationship between the annual heating degree days and the corresponding heating energy use of the heat pump is summarized in [Table 2.5](#) and [Fig. 2.11](#). These results are for a south facing suite and a reference point temperature of 10°C. The reference point temperature for annual heating degree day calculation is set to be 10°C because simulation results show that this is approximately the thermal neutral point and, above this temperature, the heat pump is no longer needed for heating. Only the results for a south orientation are presented due to the similarity among the results for other orientations. As can be seen in [Fig. 2.11](#), the curve representing the HRV scenario is always below the scenario without HRV which means the HRV reduces annual heating energy use. The heating energy reduction per unit area with HRV is approximately 10 kWh/m<sup>2</sup> at 850 HDDs and increases to 50 kWh/m<sup>2</sup> at 4000 HDDs. A similar trend is observed for other suite orientations.

Considering the initial investments including the installation of an HRV are similar across Canada, buildings located in colder climates can benefit more from employing HRV from the perspective of both heating energy reduction and payback time. As observed from the results in [Fig. 2.11](#), implementing HRV in apartment building HVAC systems reduces the sensitivity of heating energy consumptions to climate.

Table 2.5: Calculated Annual Heating Degree Days (HDDs) for the Fifteen Selected Canadian Cities

Zone 5			Zone 6			Zone 7		
City	HDDs	CDDs	City	HDDs	CDDs	City	HDDs	CDDs
Vancouver	1,194	781.8	Toronto	2,450	1106.7	Prince George	3,156	426.6
Nanaimo	1,349	805.6	Lethbridge	2,808	805.3	Edmonton	3,660	812.3
Port Hardy	1,468	308.2	Montreal	2,851	1118.7	Winnipeg	4,049	919.1
Sandspit	1,483	385.6	Charlottetown	2,870	753.6	Saskatoon	4,078	771.0
Summerland	1,808	1061.8	Ottawa	2,974	1087.8	Kapuskasing	4,387	585.3

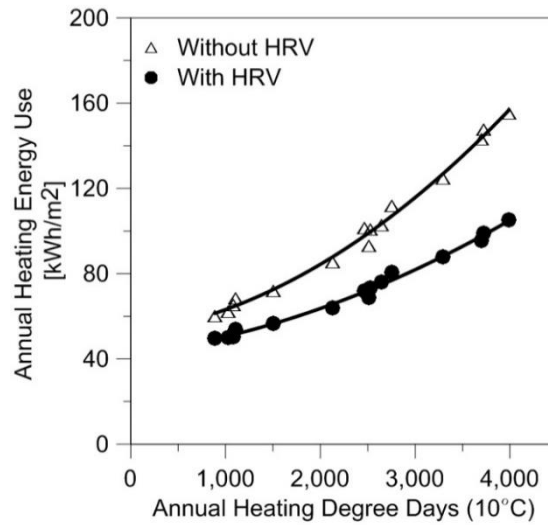


Fig. 2.11: Relationship between the annual heating degree days and heat pump annual heating energy use per unit area when the suite is facing true south

## 2.6 Limitations

The energy saving potential of HRV is limited by the mechanical system's heating and/or cooling efficiencies. Here, we have considered a specific commercial air-to-air heat pump. Savings might be more significant for cases where HVAC systems with lower efficiency are combined with HRV. Results for HRV energy savings as a function of heating degree days are specific to the assumed suite characteristics and the specific HVAC configuration. The TRYNYSYS component-Type 954a's (i.e. air-air heat pump) built-in heating and cooling performance curves are used due to the lack of data available from the real-life product; however, this is acceptable as the focus of the study is to investigate the tendency of change in energy saving potential of using the HRV, not to predict the actual energy consumptions of the heat pump. Although the findings are generalized from a single residential suite to the entire floor by normalizing the results simulated based on the hypothetical suite model under different orientations, the findings consider a top floor

scenario only. Future works should evaluate the benefits of HRV when it combined with other types of HVAC systems commonly used in residential buildings. In doing so, the undesired heat recovery in HRV during the cooling season should be quantified. Another consideration for cold climates is freezing in the HRV resulting in reduced performance. A detailed HRV configuration, operating profile and location would need to be considered to adequately address this phenomenon. This is beyond the scope of the present paper.

## 2.7 Conclusions

This study investigates the energy performance of an air-to-air heat pump system with and without a heat recovery ventilation system (HRV) in a residential application in three Canadian climate zones. TRNSYS simulations for an air-to-air heat pump's annual heating and cooling energy use are conducted using detailed HVAC system energy models for a residential apartment. The impacts of climatic conditions on the energy saving potential of utilizing the HRV are analyzed and their relationships are correlated. Key findings include:

- Utilizing the HRV always reduces the annual heating energy consumption of the HVAC system in climate zones 5, 6 and 7.
- Residential buildings located in colder weather consume more heating energy but have higher heating energy saving potential if the HRV is employed; therefore, payback times are shorter for apartments in colder climates.
- The use of HRV can increase energy consumption in residential building's HVAC systems during the cooling season in Canada.

- The sensitivity of heating energy requirements to heating degree days is reduced by the deployment of the HRV.

### 3 FREE COOLING POTENTIAL OF AIR ECONOMIZER IN RESIDENTIAL HOUSES IN CANADA<sup>2</sup>

#### **Preamble**

An air-side economizer uses outside air to reduce building cooling system energy demand. In Canada, air economizers are widely applied in non-residential building cooling systems but are rarely implemented in residential single-family houses. This study investigates the free cooling potential of the outside air through a temperature controlled air-side economizer in a hypothetical single-family house for sixteen cities across Canada. A series of thermal models with different aspect and window-to-wall ratios are developed to simulate the hourly and annual building cooling demand for each simulation case. The impacts of climatic conditions and building geometry on the potential annual usable and maximum available free sensible cooling are investigated. Results show that the available free cooling potential ranges from 50% up to 325% of the building cooling needs due to the mild summer weather in most areas of Canada; however, a majority of available free cooling is not able to be utilized. Further studies focused on finding the solutions to maximize the outside air free cooling usage to minimize the building HVAC system cooling energy use is necessary.

#### 3.1 Introduction

A substantial portion of global energy consumption is attributed to residential buildings. In 2017, residential buildings consumed 87.5 EJ energy which accounts for 22%

---

<sup>2</sup> The body of this chapter was published in Bo Li, Peter Wild, Andrew Rowe, *Building and Environment*, vol. 167, page 106460, January 2020.

of the global final energy use and 17% of the energy related carbon-dioxide emissions [59]. In Canada, residential buildings account for 17% of national secondary energy use [60]. Although residential space cooling accounts for a relatively small fraction of residential energy demand, it has increased by 95% compared to that of 1990. In absolute terms, this represents 5,061 million kWh of energy use and 800,000 tons of CO<sub>2</sub> emissions [61]. Minimizing energy demand for buildings is needed to facilitate the development of net zero emissions buildings.

A considerable amount of work has been done to reduce or eliminate the need for mechanical cooling in residential buildings. Strategies to reduce energy demand include: improving the air tightness level and the thermal resistance of the building envelope [62, 63]; employing more efficient mechanical and electrical systems [64]; integrating passive cooling techniques in the building design [65, 66, 67] adopting innovative technology for air-conditioning systems [68] and utilizing the renewable energy available on site [67].

The use of air-side economizers is an energy saving strategy that has attracted considerable interest. An air-side economizer uses cool outside air to reduce the mechanical cooling requirement of a building [7]. It can reduce overall cooling energy consumption 20 to 30 percent when properly sized, installed, commissioned, and maintained [69]. In general, the longer the period during which the outdoor air is cooler than the indoor air, the higher the free cooling potential is, and the opportunity to reduce cooling energy consumption. [Fig. 3.1](#) illustrates a basic form of an air-side economizer and the corresponding components integrated with a constant air volume (CAV) air handling unit (AHU). When the outdoor conditions are favorable for free cooling, the economizer sets the outside air flowrate based on the building cooling needs, making this a variable air volume (VAV)

ventilation system during the warm season. The outside air flowrate is determined by the motorized outside air damper opening. The return air flowrate is determined by the motorized return air damper which is interlocked with the outside air damper so that the AHU supply air flowrate is fixed. The excess air (i.e. the outside air less the space exhaust air) entering the space is released through the motorized relief damper (refer to [Fig. 3.2](#)) which is interlocked with both outside and return air dampers. When outdoor conditions are not suitable for free cooling (i.e. too cold in the winter or too hot and humid in the summer), the outside air damper reduces its opening to meet the minimum code requirement. Under such a scenario, the relief air damper is fully closed and the space air pressure is balanced by the exhaust air fan.

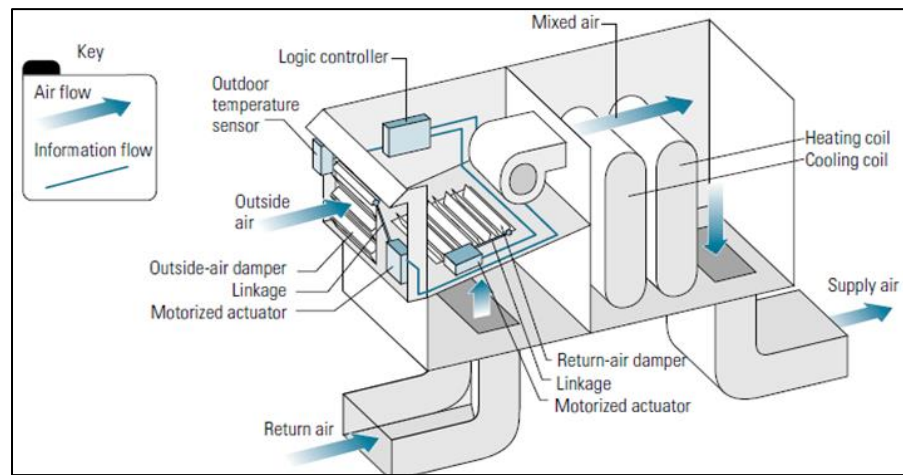


Fig. 3.1: Basic form of an air-side economizer [69]

Although such a configuration can be widely found in AHUs serving commercial buildings, it is seldom applied in mechanical systems serving residential buildings in Canada because, due to the relatively short and mild cooling season. For fully air conditioned buildings, the outside air intake duct is sized based on the code compliant ventilation air inflow and, therefore, the smaller sized duct is not able to provide sufficient

outside air required by economizer. Canada is considered as a heating dominant country with most areas falling in ASHRAE climate zones 5 to 8, namely cool, cold, very cold and subarctic zone [4]. One favorable climatic condition in these zones is the mild outdoor air temperature during the summer and shoulder seasons. For this reason, it is presumed there is potential to utilize the air-side economizer to provide cooling for a large fraction of the year. Although the air-side economizer is theoretically a cost-effective solution to reduce the need for mechanical cooling, achieving expected performance requires an adequate design strategy, sturdy and reliable components, conducting a thorough commissioning of Heating, Ventilation and Air Conditioning (HVAC) systems, and performing adequate periodic maintenance [69]. This additional investment must be justified by suitable free cooling potential resulting from the implementation of an air-side economizer under different weather conditions.

The purpose of this paper is to quantify the potential of free cooling from the outside air through an air-side economizer for a typical residential dwelling in different climates across Canada. A simple rectangle-shaped single-family house with varying building aspect ratios and window to wall ratios is studied. The following section provides a review of relevant studies quantifying the air-side economizer cycle performance. The limitations of previous work are identified and used to refine the objectives of the current paper. Subsequently, the research methodology including the description of the simulation tool, the residential dwelling house, the mechanical systems, and the key metrics of the study are presented. Finally, the impacts of the outdoor climate and building structure on the free cooling potential of using outside air through an air-side economizer in a residential dwelling are quantified.

## 3.2 Literature Review

A number of studies have investigated the efficiency improvement of building cooling systems with the implementation of an air-side economizer. Results suggest that air-side economizers can reduce the building cooling energy demand; however, most studies focus on commercial buildings and data centers.

Yiu et al. [24] conducted an on-site measuring and performance verification of an air-side economizer in the air handling unit serving a three-floor commercial building located in the suburban area of Hong Kong. It was found that 41.7% of the building cooling energy consumption in the winter can be reduced by running the air-side economizer, which is equivalent to a 12.1% reduction in the annual cooling energy use of that building. Yao et al. [25] developed a year-round energy simulation program to explore the potential energy savings of the air-side economizer of two different control methods, namely temperature- and enthalpy- based control in a six-story office building. The cooling energy consumptions of HVAC systems with and without the air-side economizer were simulated and compared for six climatic zones in China. The results indicate that, in northern Chinese cities, the dry bulb temperature control based economizer has shorter running time compared to that of the enthalpy controlled economizer but achieves higher energy saving ratio; while, in southern cities, the temperature controlled economizer has longer economizer cycle time but has less energy saving than enthalpy control based economizer. Lee et al. [26] explored the potential energy savings resulting from the implementation of the enthalpy control based air economizer for a data center with the indoor temperature and humidity maintained within the allowable range of IT equipment operating conditions for seventeen ASHRAE climate zones. It was found that the data center located in climate zone

4A, 3C and 4C can achieve the highest cooling energy savings by using the air-side economizer. Other examples of the studies that investigate the performance of the air-side economizer are Son et al. [27], Budaiwi [70], Tom et al. [71], Jin-Hyun et al. [72] for commercial buildings; and Siriwardana et al. [73], Wang et al. [74], Gözcü et al. [75] for data centers.

Although utilizing the free cooling of outside air for the residential building has been proposed and examined by some previous studies, most of them explored the free cooling potential of the night-time natural ventilation through the building openings [18, 19, 20] and only a few deal with the air-side economizer in residential building applications. In these studies, the free cooling potential of utilizing the air-side economizer was evaluated only based on its performance at nighttime. For example, Santamouris et al. [21] investigated and quantified the free cooling contribution of the mechanical ventilation systems operating at night time based on the data collected from two hundred and fourteen air conditioned residential buildings. William et al. [22] evaluated the performance of the night ventilation air-side economizers for a typical new home with ASHRAE Standard 62.2 compliant ventilation, in fifteen U.S. Climates and Kensek et al. [23] conducted a theoretical analysis and an experimental verification on the feasibility of using air-side economizer as a primary cooling source for a residential building in Southern California. For areas having mild summer weather, the free cooling potential of the air-side economizer would be underestimated if the analysis were only based on the economizer's night-time performance since the free cooling may also be achieved by running the air-side economizer during the daytime.

Many of the aforementioned studies draw conclusions from the perspective of the cooling energy use in the building air conditioning systems. The results are not generalizable since they are specific to the characteristics of the chosen building and the configurations of the host HVAC systems. For example, Yiu et al. [24] studied free cooling contributions of the air economizer to a constant air volume (CAV) air handling unit with the chilled water supplied by the air-cooled chillers. Both Yao et al. [25] and Son et al. [27] investigated the cooling energy savings of a Variable Air Volume (VAV) system by using the air-side economizer. The data center selected by Lee et al. [26] is served by an air handling unit coupled with the water-cooled chiller. The chosen building in Turner et al.'s [22] study is based on the California State Energy Code Title 24 one story prototype residential building served by an 80% Annual Fuel Utilization Efficiency (AFUE) natural gas furnace and a Seasonal Energy Efficiency Ratio (SEER) of 13 split air conditioner, respectively. Cooling system energy reduction due to the deployment of an air-side economizer is limited by the efficiencies of the air conditioning systems being coupled with. Savings might be more significant for cases where the air-side economizer is coupled with the air-conditioning systems of lower efficiency. Thus, to objectively quantify the free cooling potential of an air-side economizer, the evaluation should consider the reduction in building cooling demand, not the resulting energy consumption of the particular mechanical cooling system.

Some studies examined the free cooling potential of the air-side economizer for a specific city by analyzing the local key climatic data such as dry-bulb temperature. These results are more generalizable since they are not specific to a particular building and HVAC system; however, the cooling energy saving potentials due to the deployment of the air-

side economizer might be underestimated since the result is solely based on the weather data analysis without taking into account of the varying building cooling needs with the outdoor temperature. For example, Bulut et al. [28] and Palmiste et al. [29] evaluated the free potential of temperature control based air-side economizer in Istanbul, and Estonia, respectively by analyzing the outdoor dry-bulb temperature from a long-term weather measurements. The results of their studies suggest, the building mechanical cooling needs can be completely eliminated by taking the advantage of the free cooling from the outside air whenever the outdoor dry-bulb temperature is equal to or below the typical air-conditioning system's supply air temperature which is usually set to be 12.7°C (55°F). However, when outdoor air temperature is in between the typical mechanical cooling supply air temperature, and the building cooling set point (i.e. 24°C), the building's instant cooling load is less than the designed cooling load and can possibly be completely covered by the free cooling of the outside air through an air-side economizer.

### 3.3 Objective

Although many studies investigate the energy saving potentials of the air-side economizer, the majority are focused on non-residential building applications. Of those that study the air-side economizer in residential building applications, they all focus on the performance of the air-side economizer operating at night-time only. The value of these systems in providing free cooling for household in cold climate zones is unclear. The objective of this study is to systematically evaluate the free cooling potential of air-side economizer in a typical single-family house for sixteen cities across Canada. According to Natural Resources Canada's research report [76], there is no pronounced improvement in

energy performance when using an enthalpy control based economizer in seven major Canadian cities. Also, enthalpy control requires a humidity sensor to be installed both outside and inside of the building. Most mechanical cooling systems in residential houses are controlled by the thermostat instead of a humidistat; therefore, we consider an air-side economizer using temperature control.

### 3.4 Methodology

A series of thermal models for a hypothetical single-family house used to simulate the hourly building cooling demand for sixteen cities across Canada. The house configuration is varied in terms of aspect and window to wall ratios. For each configuration, the capacity of the mechanical cooling system circulation fan is determined based on the simulated peak cooling demand. The hourly maximum available free sensible cooling is then calculated and the hourly *usable* free sensible cooling is determined. Annual usable free sensible cooling is calculated by summing up the hourly usable free sensible cooling. Details of the building configurations and cooling calculations are given in the following sections.

#### 3.4.1 System Configuration

A schematic of a residential single-family house with an air-side economizer coupled to a mechanical HVAC system is shown in [Fig. 3.2](#). As can be seen, conditioned supply air is delivered to the indoor space of the building. Return air from the space is mixed with outside air which is directly drawn through the outside air duct. The mixed air is then heated or cooled by the system's heating or cooling coil before it is delivered back to the indoor space. In order to balance the indoor pressure, part of the return air is either released as

relief air or exhausted by the exhaust fan to the outside at the same flowrate of outside air is brought to the building.

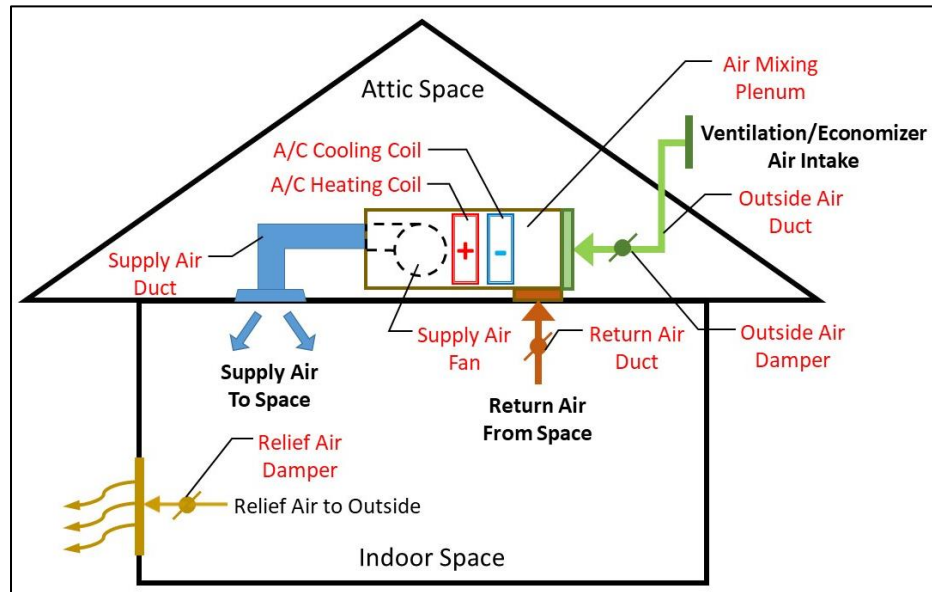


Fig. 3.2: Conceptual residence with an air-side economizer and HVAC system

Unlike traditional residential HVAC systems where the outside air duct is sized based on the minimum code compliant outside airflow, the outside air duct shown in [Fig. 3.2](#) is larger to accommodate the needs of the air economizer operation. Whenever the outdoor conditions are favorable for free cooling (i.e. economizer mode), the outside air flowrate is set somewhere between the minimum code requirement and the supply air fan's rated capacity depending on the building cooling needs. The outside air flowrate is adjusted by the outside air damper; meanwhile, the return air flowrate is adjusted to maintain the fixed supply airflow. When the outside air damper is fully open and the return air damper is fully closed, 100% of the outdoor air free cooling is utilized. When this occurs, the relief air damper is fully opened to balance the indoor air pressure. When the outdoor air dry-bulb temperature reaches the high limit of the economizer, the outside air damper is adjusted to

the minimum opening position which allows the minimum code required ventilation air for the building. Under such a scenario, the opening of both return air and relief air dampers is adjusted correspondingly.

## 3.5 Model Description

### 3.5.1 Simulation Tools

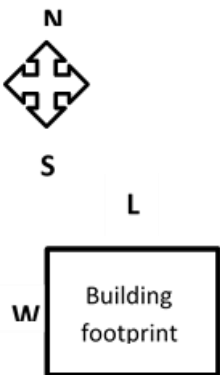
Building thermal behavior is simulated using BEopt 2.8 (National Renewable Energy Laboratory, Golden, USA). BEopt is an Energy-Plus engine-based computer simulation tool designed to develop and evaluate the optimal designs for high-performance residential buildings based on discrete building envelope and equipment options reflecting realistic construction materials and practices [77, 78]. Although BEopt 2.8 can provide a comprehensive analysis and evaluation for residential buildings, here, it is only used to simulate the hourly building cooling demand based on which the free cooling contribution of an air-side economizer is then evaluated.

### 3.5.2 Residential House Description

The hypothetical single-family house is assumed to be a wood structure with three bedrooms and two bathrooms. The overall building's construction area is assumed to be  $193\text{m}^2$  ( $2,077\text{ft}^2$ ), which reflects the average area of a typical residential house in British Columbia, Canada [79]. The house is assumed to have two above-ground floors with an un-finished attic between the pitched roof and the second floor's ceiling. The floor to floor height is assumed to be 2.45m (8ft) and the height of the house up to the eaves is 4.9m (16 ft). The house is assumed to be rectangular with a realistic range of building aspect and

window to wall ratios. The aspect ratio varies between 1:3 to 3:1 with an increment of 0.25 and the window to wall ratio (WWR) varies among 12%, 15% and 18%. [Table 3.1](#) lists the aspect and the window to wall ratios considered in the study. The simulation cases for each city are the permutations of the building aspect and the window to wall ratios. [Fig. 3.3](#) shows the 3-D models of the house with the aspect ratios of 1:1 and 3:1, respectively. The arrows in [Fig. 3.3](#) point North. In total, there are fifty-one cases investigated for each city listed in [Table 3.2](#).

Table 3.1: Varying Design Schemes in Window to Wall Ratio and Aspect Ratio of a Typical Single-Family House

Building Footprint & Orientation	Building Aspect Ratio (L:W)	Window to Wall Ratio		
		12%	15%	18%
	1:3	√	√	√
	1:2.75	√	√	√
	1:2.5	√	√	√
	1:2.25	√	√	√
	1:2	√	√	√
	1:1.75	√	√	√
	1:1.5	√	√	√
	1:1.25	√	√	√
	1:1	√	√	√
	1.25:1	√	√	√
	1.5:1	√	√	√
	1.75:1	√	√	√
	2:1	√	√	√
	2.25:1	√	√	√
	2.5:1	√	√	√
	2.75:1	√	√	√
	3:1	√	√	√

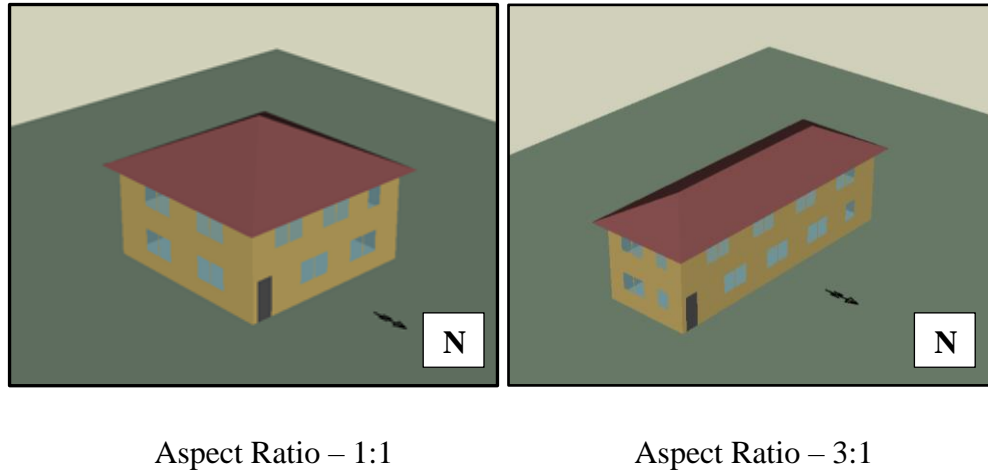


Fig. 3.3: The hypothetical single family house with aspect ratio of 1:1 and 3:1

Table 3.2: Sixteen Canadian cities representing three ASHRAE climate zones

	Climate Zone 5	Climate Zone 6	Climate Zone 7
City Name	Vancouver	Lethbridge	Prince George
	Victoria	Charlottetown	Edmonton
	Port Hardy	Montreal	Winnipeg
	Sandspit	Ottawa	Regina
	Summerland	Toronto	Saskatoon
	Kamloops		

### 3.5.3 Thermal Envelope Assemblies

The thermal insulation of the building envelope is assumed to represent a typical single-family house that meets and/or exceeds the wood-structure building envelope insulation requirements of ASHRAE Standard 90.1-2010 [4] for climate zones 5-7. ASHRAE 90.1-2010 instead of its counterpart for low-rise building standard- ASHRAE 90.2-2007 - is used as reference in this study because the thermal requirements of wood-framed wall in 90.2-2007 is lower than those in 90.1-2010. [Table 3.3](#) lists the thermal properties and the configurations of the building envelope modelled with the BEopt 2.8 software.

### 3.5.4 Occupancy

The number of occupants of the building is estimated implicitly by the BEopt 2.8 software based on the number of the bedrooms using the equations in [80]. The sensible and latent heat from the occupants and the corresponding occupancy schedule are modelled implicitly by the BEopt 2.9 software as well. Refer to [80] for the detail.

Table 3.3: Building envelope fabrics and thermal properties

Envelope Systems	Exterior Wall	Ceiling/Roof	Foundation/Floor	Windows
Configurations	<ul style="list-style-type: none"> <li>• 38mm x 140mm Wood Studs c/w 610 mm O.C.</li> <li>• RSI-6.34 closed cell cavity insulation</li> <li>• OSB wall sheathing</li> <li>• Medium/Dark closed stucco</li> </ul>	<ul style="list-style-type: none"> <li>• Ventilated attic c/w RSI-5.28 cellulose ceiling insulation</li> <li>• Asphalt shingles roof</li> </ul>	<ul style="list-style-type: none"> <li>• 610mm RSI-0.88 XPS perimeter insulation</li> <li>• 0.12 m concrete slab/foundation</li> </ul>	<ul style="list-style-type: none"> <li>• Low-E double pane</li> <li>• Non-metal frame</li> <li>• Air filled</li> </ul>
Assembly RSI values	RSI-4.09	RSI-5.49/RSI-0.41	RSI-0.88	N/A
Assembly U factors	U-0.244	U-0.182/2.439	U-1.136	U-2.083 SHGC-0.3

### 3.5.5 Internal Heat Gains & HVAC Systems

Although obtaining the simulated hourly cooling demand is the only purpose of using the BEopt 2.8 software, the building HVAC system is specified in detail to ensure the building thermal behavior is simulated appropriately. The lighting, appliance fixtures and other miscellaneous equipment are modeled to represent the commonly used household equipment and their typical use profile (See Appendix [Table B-1](#)). The single-family house is assumed to be fully air-conditioned with the cooling provided by a typical air-cooled split air conditioner through the duct system. The heating is provided by a typical gas fired furnace through the same duct system. The indoor heating and cooling set-points are 22°C

(72°F) and 24°C (75°F), respectively. (Refer [Table B-2](#) in the Appendix for the detailed HVAC system set in the BEopt 2.8 software for the study).

### 3.5.6 Ventilation and Air Leakage

An ASHRAE Standard 62.2 [81] compliant exhaust-only system is assumed to provide the ventilation for the house. The exhaust air flowrate is calculated to be 43 l/s (91cfm) by the BEopt software based on the finished floor area and the total number of bedrooms. The infiltration rate is set to be seven air changes per hour at 50 Pascal (7ACH50).

## 3.6 Metrics

In total, there are eight hundred and sixteen (816) different cases representing a single-family house of varying geometries and window to wall ratios under sixteen (16) climatic conditions. The key metrics characterizing thermal performance are described in the following sections and are calculated based on the simulation results of the BEopt2.8 software.

### 3.6.1 Cooling Demand,

The *hourly* cooling demand,  $q_{sen.clg.demand}$ , is calculated in BEopt for each building configuration and climate zone. The cooling demand includes two parts – the sensible cooling and latent cooling. Since the current study considers a temperature control based air-side economizer, only the simulated minimum hourly sensible cooling demand is used.

The *annual* sensible cooling demand,  $Q_{sen.clg.demand}$ , is the total amount of the sensible cooling handled by the mechanical cooling system for the entire cooling season:

$$Q_{sen.clg.demand} = \sum_{i=1}^n q_{sen.clg.demand_i} \quad (1)$$

where  $q_{sen.clg.demand}$  is the hourly sensible cooling demand without an air-side economizer [kJ/hr],  $i$  is the specific hour when the building requires the cooling, and,  $n$  is the total number of hours for which the building has cooling needs.

### 3.6.2 Maximum Available Free Cooling

The *hourly* maximum available sensible free cooling,  $q_{free.clg.available}$ , is defined as the steady-state maximum sensible free cooling that is available and can be provided by the air-side economizer to the building whenever cooling is required. It is calculated by:

$$q_{free.clg.available} = 3.6 \times \dot{V}_{air} \times \rho_{air} \times C_{p,air} \times (T_{clg.set-point} - T_{OA})^+ \quad (2)$$

where  $\dot{V}_{air}$  is the rated volume flowrate of the air-conditioner circulation fan, [l/s],  $\rho_{air}$  is the air density, [1.2kg/m<sup>3</sup>],  $C_{p,air}$  is the specific heat capacity of air at constant pressure, [1.005 kJ(kg · °C)],  $T_{clg.set-point}$  is the indoor cooling set-point, [°C], and,  $T_{OA}$  is the hourly outdoor air dry-bulb temperature, [°C] (exported from the weather database of BEopt 2.8). The superscript ‘+’ indicates  $q_{free.clg.available}$  only takes positive value calculated from Equation 2.

The rated volume flowrate  $\dot{V}_{air}$  of the air-conditioner circulation fan is fixed and based on the HVAC system cooling capacity and the air conditioner indoor fan rated airflow rate calculation routine [48], i.e., 12,660 kJ/hr (12,000 Btu/hr) of cooling capacity = 188 l/s (400 cfm). The hourly outdoor dry-bulb air temperature,  $T_{OA}$  is exported from the weather database of BEopt 2.8 software.

The *annual* maximum available free cooling  $Q_{free.clg.available}$  is the sum of the hourly maximum available sensible free cooling during the cooling season in one year:

$$Q_{free.clg.available} = \sum_{i=1}^n q_{free.clg.available_i} \quad (3)$$

where  $i$  is the the specific hour when the building requires the cooling, and,  $n$  is the total hours for which the building has cooling needs.

### 3.6.3 Usable Free Cooling

The *hourly* usable free cooling is the sensible cooling that can be provided by the air-side economizer. Because there are times where the available free cooling may exceed the cooling demand, the hourly usable free cooling  $q_{free.clg.usable}$ , is defined by the minimum of the hourly cooling demand and the maximum available cooling:

$$q_{free.clg.usable} = \min\{q_{sen.clg.demand}, q_{free.clg.available}\} \quad (4)$$

The *annual* usable free sensible cooling,  $Q_{free.clg.usable}$ , is the sum of the hourly usable free cooling during the cooling season in one year:

$$Q_{free.clg.usable} = \sum_{i=1}^n q_{free.clg.usable_i} \quad (5)$$

where  $i$  is the specific hour when the building requires the cooling, and,  $n$  is the total hours for which the building has cooling needs.

### 3.6.4 Free Cooling Potential

The annual usable free cooling *potential* of the air-side economizer,  $\eta_{free\ clg}$ , is defined as the ratio of annual usable free cooling to the annual sensible cooling demand:

$$\eta_{free\ clg} = \frac{Q_{free.clg.usable}}{Q_{sen.clg.demand}} \times 100\%. \quad (6)$$

The *annual maximum available* free cooling potential,  $\eta_{free.clg.available}$ , is defined as the ratio of annual maximum free sensible cooling available from the outside air to the annual cooling demand:

$$\eta_{free.clg.available} = \frac{Q_{free.clg.available}}{Q_{sen.clg.demand}} \times 100\%. \quad (7)$$

The usable free cooling potential  $\eta_{free\ clg}$  represents the fraction of cooling demand that can be provided by outside air using an economizer, whereas, the maximum available potential,  $\eta_{free.clg.available}$ , indicates the theoretical maximum fraction of cooling demand that may be provided by outside air.

### 3.7 Results and Discussion

In total, eight hundred and sixteen (816) different cases are formed by the permutations of seventeen (17) aspect ratios and three (3) window to wall ratios of the hypothetical single-family house for sixteen (16) Canadian cities. The hourly cooling demand is simulated for each case. A series of post-process calculations based on the simulated results are conducted to investigate the annual usable free sensible cooling potentials. Key results are analyzed and presented here with a more complete set of results given in the Appendix.

#### 3.7.1 Annual Sensible Cooling Demand

[Fig. 3.4](#) shows the annual sensible cooling demands of the single-family house with varying aspect ratios for the cities in ASHRAE climate zone 5. As can be seen, the higher the window to wall ratio (WWR) is, the larger the building annual sensible cooling demand.

For example, in Vancouver, the building's annual sensible cooling demand ranges between 3,690 MJ and 1,583 MJ in the case of 18% WWR; however, cooling demand varies between 2,374 MJ and 1,055 MJ in the case of 12% WWR. This is because the larger window area allows more solar heat to transmit through the glazing resulting in increased cooling demand. Fig. 3.4 also indicates that the annual sensible cooling demand decreases with the building aspect ratio varying from 1:3 to 3:1. In order to maintain the fixed finished area of the single-family house, the length of the northern and southern building facades become longer and length of the eastern and western building facades become shorter with the building aspect ratio changing from 1:3 through 3:1. Correspondingly, the area of the windows on both east and west facing walls becomes smaller resulting in a reduction in the annual sensible cooling demand. (Refer to Fig. B1 and B2 for the building annual sensible cooling demands for the cities in ASHRAE climate zone-6 and -7 in the appendix.)

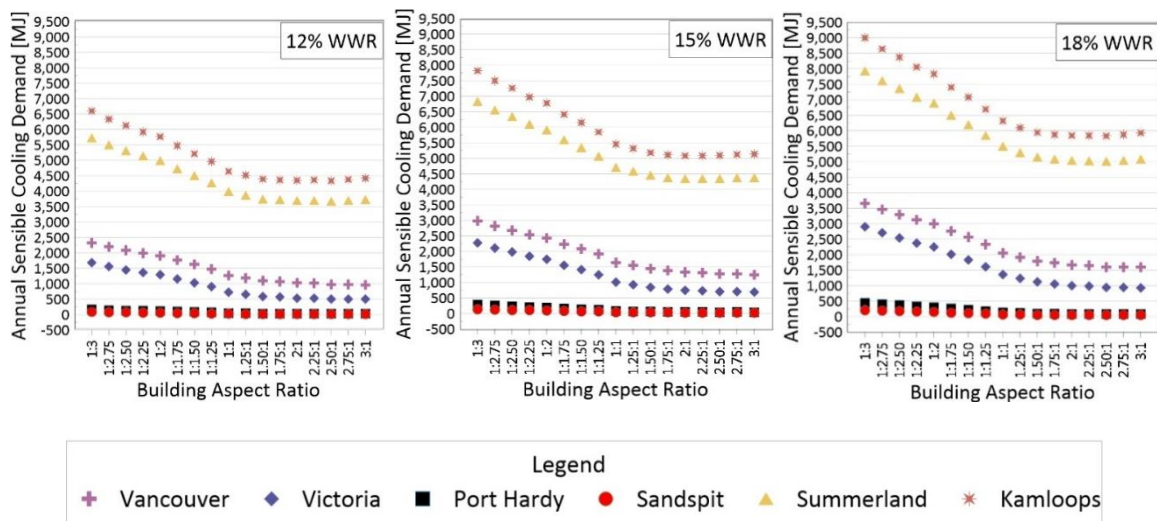


Fig. 3.4: The building annual cooling demand without the air-side economizer for the sing-family house with varying aspect ratios for the Canadian cities in ASHRAE climate zone 5

### 3.7.2 Annual Usable Free Sensible Cooling

The annual usable free sensible cooling for the ASHRAE climate zone 5 cities is presented in [Fig. 3.5](#) for the cases of 12%, 15% and 18% WWR. As can be seen, Vancouver has the highest annual usable free sensible cooling; while, both Port Hardy and Sandspit have the lowest annual usable free cooling in absolute values. For each city, the annual usable free sensible cooling decreases with the building aspect ratios varying from 1:3 through 3:1. In the context of [Fig. 3.4](#), [Fig. 3.5](#) reveals that a building with higher sensible cooling demand can benefit more by employing the air-side economizer under a specific climate condition. This result is similar to a finding reported by Santamouris [21]. (Refer to [Fig. B3](#) and [B4](#) for the annual usable free sensible cooling for the cities in ASHRAE climate zone-6 and -7 in the Appendix)

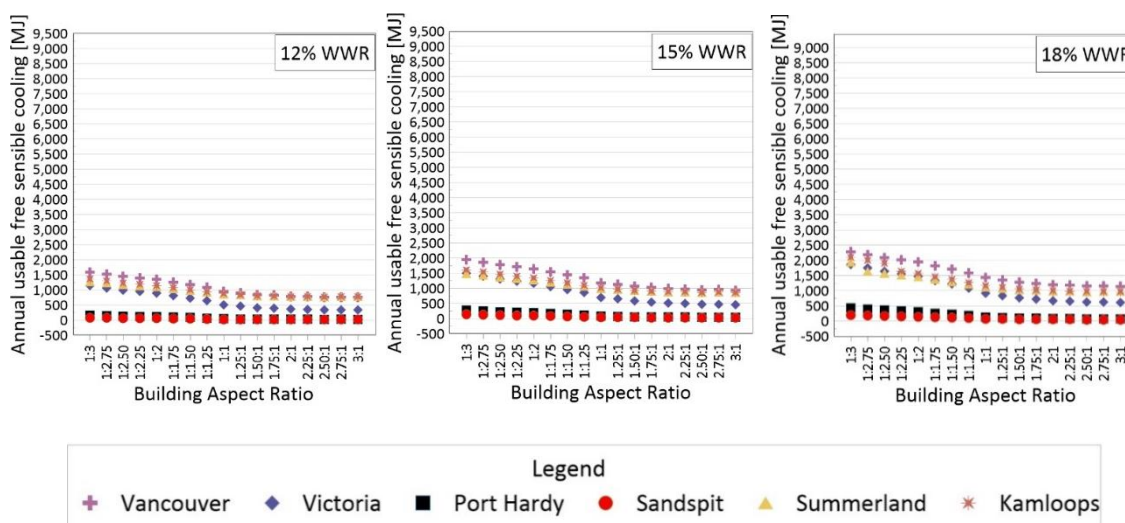


Fig. 3.5: The annually usable free sensible cooling for the single-family house in the Canadian cities of ASHRAE climate zone 5

### 3.7.3 Maximum Available Free Cooling

[Fig. 3.6](#) shows the annual sensible cooling demand, the annual maximum available free sensible cooling and the annual usable free sensible cooling of the single-family house for Kamloops climate. As can be seen, the maximum available free sensible cooling is much higher than the annual usable free cooling. For example, in the case of 12% WWR and 1:3 aspect ratio, the annual maximum available free sensible cooling is about 4,164 MJ; while, the annual usable free sensible cooling is 1,360 MJ. The results obtained for other cities are of the similar pattern and can be referred to [Fig. B7](#) to [B21](#) in the Appendix.

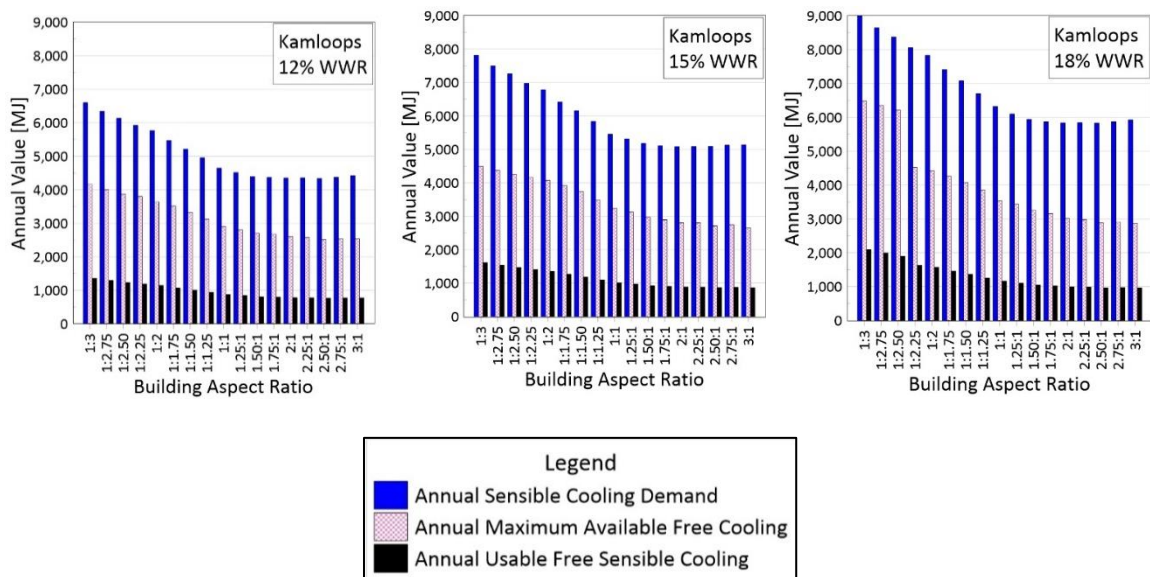


Fig. 3.6: Comparison of Annual Cooling Demand, Annual Maximum Available Free Cooling and the Annual Usable Free Cooling of the Hypothetical Single-Family House in Kamloops

The difference between the available and usable free cooling can be explained by considering the hourly profiles of the above mentioned metrics. [Fig. 3.7](#) shows the hourly profiles of the outside air dry-bulb temperature, the sensible cooling demand, the maximum

available free sensible cooling, and the usable sensible free cooling for the case of 1:3 aspect ratio and 12% WWR during a typical summer day (July 14<sup>th</sup>) in Kamloops. As can be seen, the free cooling from the outdoor air is available both daytime and nighttime whenever the outdoor dry-bulb temperature is below the indoor cooling set-point of 24°C; this free cooling is utilized by the cooling system as long as there is a cooling demand. As indicated by *Equation (4)*, the hourly usable free sensible cooling (i.e. the pink hatched area) is either the hourly sensible cooling demand or the hourly maximum available sensible free cooling, whichever is lesser. That means whenever the maximum available sensible free cooling of outdoor air is less than the building sensible cooling needs (i.e. from 1:00am to 3:00am, 8:00am to 10:00am and 11:00pm to 12:00am), the maximum available sensible free cooling will be utilized to minimize the mechanical cooling needs. Under this scenario, the remaining portion of the building cooling demand is provided by the building mechanical cooling system. When the maximum available free cooling exceeds the cooling demand (i.e. from 3:00am to 8:00am), only portion of the maximum sensible free cooling is utilized; thereby, the free cooling utilized by the building cooling system is the same as the building instant sensible cooling demand. The results suggest that cooling system energy savings could be potentially improved by storing some of the available free cooling (i.e. the green hatched area) for use several hours later when the outdoor air dry-bulb temperature is higher than the indoor cooling set point.

[Fig. 3.7](#) also indicates that the usable free sensible cooling can completely cover the building sensible cooling demand during a specific period of the time (i.e. from 3:00am to 8:00am) when the outdoor air temperature is higher the typical mechanical cooling system's supply air temperature of 13°C but below the indoor cooling set-point of 24°C.

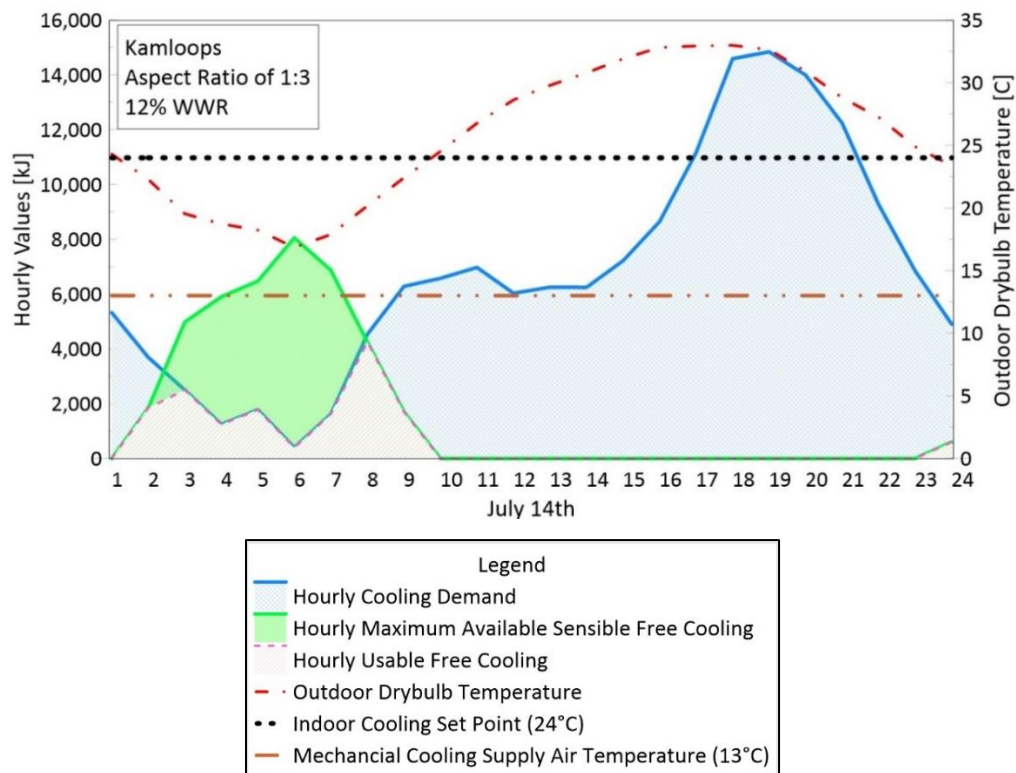


Fig. 3.7: Hourly profile of the sensible cooling demand, the maximum available free sensible cooling, the usable free sensible cooling and the outside air dry-bulb temperature for the case of 1:3 aspect ratio and 12% WWR for a typical summer day in Kamloops

### 3.7.4 Annual Usable and Maximum Available Free Cooling Potentials

[Fig. 3.8](#) shows the annual usable free cooling as a percentage of the annual building sensible cooling demand for the selected Canadian cities within ASHRAE climate zone 5. ([Fig. B5](#) and [Fig. B6](#) in the Appendix can be referred for the cities in climate zone-6 and -7.) In [Fig. 3.8](#), the Y-axis represents the annual usable free sensible cooling as a percentage of the building's annual sensible cooling demand (sensible cooling requirements without assistance of the air-side economizer) and the X-axis represents the building aspect ratios varying from 1:3 through 3:1 with the increment of 0.25. As can be seen, the range and the trend of variation of these values differ based on the climatic conditions, the building aspect



Fig. 3.8: The annually usable free sensible cooling potential in percentage of the annual building cooling demand for the Canadian cities in ASHRAE climate zone 5

[Fig. 3.9](#) shows the range of the annual usable and maximum available free cooling potentials for the cities in the current study (except for Sandspit and Port Hardy) due to the effects of the building aspect ratio and the window to wall ratio. Investigating the difference between the annual usable and the annual maximum available free cooling for the cities of Sandspit and Port Hardy are meaningless since 100% of the building annual cooling demand can be met by free cooling for almost all the cases as indicated in [Fig. 3.8](#).

As can be seen in [Fig. 3.9](#), although there is no clear trend for the annual usable free cooling potential across the different climate zones, employing an air-side economizer can help reduce the mechanical cooling needs for most areas in Canada and the free cooling can be utilized more effectively in the areas with mild summer weather. For example, in Vancouver, the air-side economizer can meet 62-78% of the annual building cooling demand; while, in Summerland and Kamloops which are both are located in the same ASHRAE climate zone 5, the air-side economizer can only meet 19-24% and 16-23% of the annual cooling demand, respectively. Similar situations are observed for the cities in ASHRAE climate zone 6 and 7.

As shown in [Fig. 3.9](#), the annual maximum available free cooling (i.e. blue colored bar) is much higher than the annual usable free sensible cooling (red colored bar) for all the cities across the three ASHRAE climate zones. This suggests that in most Canadian cities there is significant free cooling available from the outside air during the cooling season; however, the majority of free cooling is currently not able to be utilized by the air-side economizer. The building HVAC system's cooling energy could be reduced if

potential free cooling could be stored and utilized later during the same day when the outdoor air dry-bulb temperature is higher than the indoor cooling set point.

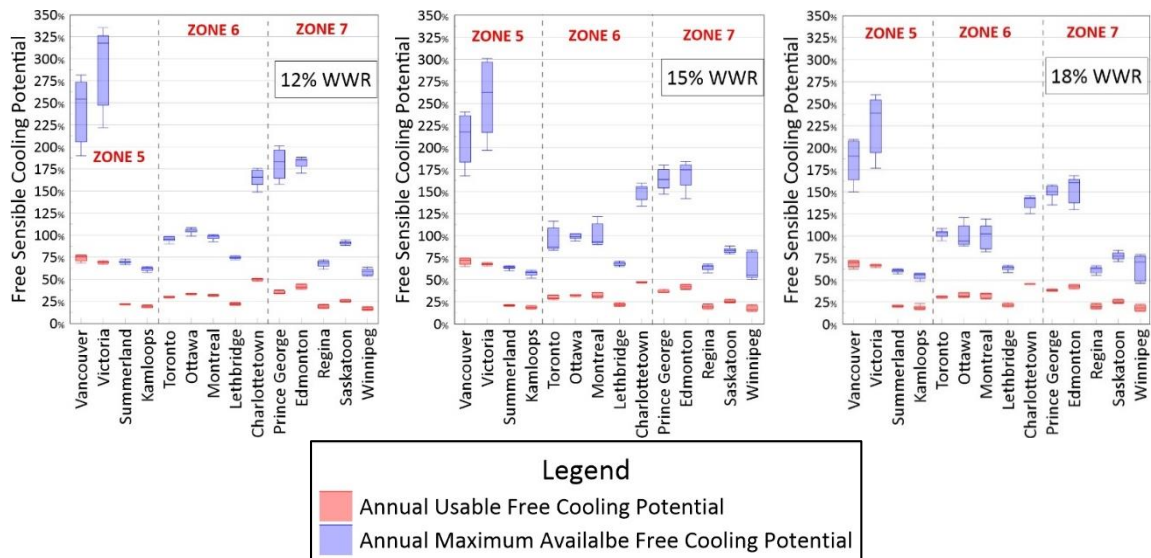


Fig. 3.9: Comparison of the Ranges of the Annual Usable and Maximum Available Free Sensible Cooling Potentials

### 3.8 Limitations

In the current study, although free cooling potential is considered for varying aspect ratios and window to wall ratios, it is assumed that the window to wall ratio is the same for each building façade and no external overhang of the window is applied. Future work should evaluate the benefit of utilizing the air-side economizer when different window to wall ratio is applied to the walls with different orientation.

### 3.9 Conclusions

This study investigates the free cooling potential of a temperature controlled air-side economizer in a single-family house for sixteen cities across Canada. The impacts of

climatic conditions, the building geometry, and the window to wall ratios on the building cooling demand as well as the annual usable free sensible cooling contributed by an air-side economizer are analyzed. Key findings include:

- An air-side economizer always reduces the cooling needs for residential houses in Canada.
- It is most effective to employ the air-side economizer in the cities with mild summer weather conditions in ASHRAE climate zone 5.
- Houses with higher cooling demand can benefit more by utilizing an air-side economizer than those in the same climate zone with lower cooling demand.
- Cooling demand can completely be met by free cooling for a specific period of the time even if the outdoor air temperature is not as low as the typical mechanical cooling system's supply air temperature of 13°C by increasing the outdoor air inflow rate.
- Although sufficient available free cooling is available in most areas of Canada, a majority of free cooling cannot be utilized because the usable free cooling is limited by the instantaneous building cooling load. Thermal storage may offer a way to increase usable free cooling.

## 4 BUILDING CODE EFFECTIVENESS FOR CLIMATE CHANGE MITIGATION IN CANADA

### **Preamble**

The building sector is a significant source of GHG emissions and has great potential for emission reductions. The effectiveness of building energy codes on energy savings and emission mitigation is of a primary concern to policy makers, but uncertainty in cost and benefit in different regions complicates code selection and implementation. The impacts of a specific building energy standard vary depending on the heating system's thermal efficiency and the heating fuel's carbon intensity. This paper examines the GHG emissions due to space heating for new construction single-detached households in Canada under different building energy codes and enforcement scenarios. The two codes considered are the BC step code and Passive House criteria where the TEDI values specified in both are used to determine the annual thermal energy demand. As codes and standards are only effective when enforced, three scenarios are examined reflecting different levels of stringency of performance standards for the period 2020 to 2032. The modeled energy and emissions due to forecasted growth of single detached households show both the BC step code and passive house criteria can help mitigate the space heating GHG emissions. There is no significant difference between the BC step code and the passive house criteria from the perspective of GHG emission reduction per floor area in the province of British Columbia; however, when implemented nationwide, the passive house criteria is 12% more effective in abating space heating GHG emissions levels than the BC step code.

## 4.1 Introduction

Increasing Greenhouse Gas (GHG) concentrations in the atmosphere due to the anthropogenic activities is the dominant cause of global climate change [82]. The majority of GHG emissions are carbon dioxide (CO<sub>2</sub>) associated with energy consumption and deforestation [83]. In 2017, the world's total final energy consumption was ~400 EJ with the emission of ~33 billion metric tons of CO<sub>2</sub>. Compared to 1990, energy demand and CO<sub>2</sub> emissions have increased by 5.4 and 1.6 times, respectively [84]. If no energy efficiency policies and measures are taken, annual global energy consumption and the associated CO<sub>2</sub> emission are expected to grow by nearly 50% and 33% respectively between 2018 and 2050 [85] resulting in ~1.75°C warming above pre-industrial level in average surface temperature by 2050 [1]. In order to tackle the climate change challenge, Canada along with 194 member countries of United Nations Framework Convention on Climate Change (UNFCCC) signed the Paris Agreement in 2016 under which Canada committed to cutting down its GHG emissions by 30% of 2005 level by 2030 [1, 2]. To achieve this nationally determined target, the GHG emissions from all the Canadian economic sectors, including the building sector, need to be mitigated [1].

The building sector plays a vital role in reducing GHG emissions. In 2017, globally, the residential component of the building sector consumed 86 EJ final energy (accounting for 21% of the world's final energy use (406 EJ) [84]), and was responsible for 17% of the world's total energy-related carbon dioxide emissions [86]. In Canada, 12% of national GHG emissions are attributable to the building sector, making it the third largest GHG emitter among seven economic sectors [2]; there is great potential for GHG emission reduction if appropriate efficiency measures and instruments are implemented. In 2007,

Diana et.al [87] estimated that globally, 29% of the building related CO<sub>2</sub> emissions can be cost effectively reduced by 2020. Yoshiyuki et.al [88] predicted that 20.4% CO<sub>2</sub> emission from the residential building in Japan can be reduced from 2005 to 2025 by improving the energy efficiency of both building envelope and the major appliances, and decreasing the electric grid CO<sub>2</sub> emission factors. In Canada, the building sector is expected to reduce ~22 million tons of CO<sub>2</sub> equivalent emission by 2030 with the plans described in the Pan-Canadian Framework for Clean Growth and Climate Change [1].

Direct GHG emissions from buildings are associated with energy consumption; therefore, reducing energy demand and improving the energy efficiency can make a mitigation target more attainable [89, 90]. Options to improve building energy efficiency include increasing the building envelope thickness, reducing the heat loss or gain through windows, improving the HVAC system's thermal efficiency, and optimizing the building mechanical, electrical and plumbing (M.E.P.) control systems [91]. Many of these energy conservation measures have proven cost effective and, as a result, adopted in building energy codes.

While variations in building energy codes lead to differences in energy consumption and the GHG emissions reduction, the timing and penetration rate of performance targets are also important. We use the term *stringency* to describe the efficiency of a performance standard and the timing of required compliance (or, *enforcement*.) A code with ambitious targets, but a long period for implementation, may be less effective than a lower efficiency, but faster penetration into the building stock. The effectiveness of implementing a building energy code of certain level of stringency on building energy savings and GHG emission mitigation is of interest to policy makers.

This paper compares the space heating GHG emissions from new construction single-detached households between 2020 and 2032 under different building code adoption and enforcement scenarios. Considering the large amount of GHG emissions from residential buildings in Canada (i.e. 41 Mt.CO<sub>2</sub> Equivalent in 2017 [2]), the majority of which is attributable to space heating in single-detached households [92, 93], the scope of the study is focused on detached single-family dwellings.

Previous studies address the effectiveness of residential building energy codes on space heating energy savings and GHG emissions reduction. Many use a detailed bottom-up approach; however, results tend to have significant uncertainty due to limited knowledge of change in future building stocks and the resulting thermal energy demand. One factor causing the uncertain annual thermal energy demand is future annual heating degree days (HDD) which drives heat losses across the building envelope. Mady et.al [30] studied the impacts of four combined factors including three climate warming trends on the GHG emissions projected for the German residential building sector until 2060. The results show that the percentage change in annual heating energy demand between periods of 1961-1990 and 2031-2060 under 1% future renovation rate and high building stock scenario is 53% and 64% (20% difference in the results) for 1°C and 3°C warming trends, respectively. Other studies use a similar method to determine the heating energy demand resulting in similar uncertainties in the results [31, 32].

Other factors impacting future energy demand are the envelope thermal insulation efficiency and the penetration rate of envelope technology. For example, Yu et.al [33] studied the long-term impacts of building energy codes on energy demand and associated GHG emissions of Chinese buildings. Four types of building energy codes were

investigated with differences in envelope insulating requirements, compliance rate, existing building retrofit rate, improvement of the existing building insulation after retrofit, and coverage for rural buildings. While the study's performance rating for the building envelope's thermal insulation from 2012 onwards are in line with expected envelopes, achieving the desired performance outcome remains uncertain without sufficient enforcement of code.

Veena et.al [34] investigated the long-term impacts of seventeen energy efficiency measures including the R-2000 envelope efficiency standard [35] for the residential building sector in Alberta, Canada. Two scenarios representing fast and slow technology penetration rates for selected measures are considered. In the fast scenario, the assumed final penetration of the R-2000 building envelope option is 15%, which is assumed to be achieved by 2030 while, in the low penetration rate scenario, the same final penetration is achieved by 2050. Their results show by implementing the thermal insulation requirements specified in the R-2000 standard, the attendant cumulative GHG emission reductions are 3.3 and 5.6 million tons of CO<sub>2</sub> equivalent in the fast and low penetration rate scenario, respectively; this represents 41% difference in the results. This shows that the benefit of an efficiency standard can differ significantly due to rate of adoption.

Uncertainties in projected GHG emission mitigation for future building stocks are intrinsically associated with variability in demand, standards and enforcement. As an alternative to estimating building thermal energy demand by a bottom-up approach, such as calculating the envelope performance and the HDD involved, the impacts of future heating demand may be examined by specifying the maximum thermal energy demand intensities (i.e. TEDI – annual thermal energy demand per unit area of the heated space

inside building). The uncertainties in the efficiency of future building stocks and the penetration of the corresponding technology are ignored when specifying TEDI requirements; however, it allows for a direct comparison of building energy codes for a prescribed level of penetration. Moreover, TEDI takes into account effects beyond envelope design such as infiltration, which is often neglected or poorly treated in bottom-up studies. There are only a few countries utilizing performance-based building energy codes [94]; hence, the use of TEDI to estimate annual thermal energy demand is novel.

As a front-runner in developing and implementing higher performance building energy code in Canada, the government of British Columbia (BC) introduced the BC Energy Step Code in 2017 to achieve a “net-zero energy ready” target by 2032 [95]. BC Step Code is a dynamic, performance-based, building energy code that sets a series of increasingly stringent climate-specific targets of TEDI through five increments, or, steps. The higher the step number, the more stringent the required TEDI. The most stringent level of TEDI specified in the code is step 5 for a single-detached family house. Buildings compliant with step 5 energy efficiency requirements are considered *net-zero-energy-ready* and are comparable to those following the passive house criteria [96]. Passive house criteria defined by the Passive House Institute (PHI) is another type of performance-based building energy standard and has been adopted by City of Vancouver’s Green Buildings Policy for rezoning by-law starting in 2015 [97]. Different from the BC step code, passive house specifies a set of fixed building energy performance standards including the maximum allowed space heating energy use intensity (TEDI) of  $15kWh/(m^2 \cdot year)$ . Such energy performance requirements are the same for all climate zones [98].

The BC step code and the passive house criteria are of different stringency although both of them target a net-zero-energy-ready building. The BC step code represents a more flexible approach to achieving the target (through increments), whereas the passive house criteria reflects a discrete approach. Analyzing and comparing residential building's space heating GHG emissions mitigation by implementing these two building energy codes in Canada can provide valuable insights for policy makers in other regions considering similar approaches for the design of future building stocks.

## 4.2 Objective

The purpose of this paper is to examine the impact of energy code adoption and enforcement on space-heating GHG emissions of new single-detached households (SDH) in Canada. The TEDI values specified in both BC step code and Passive house criteria determine annual thermal energy demand under three stringency scenarios for building energy performance. Each Canadian province is considered for the period consisting of 2020 to 2032. The scope of the study is limited to detached single-family dwellings since they are the largest thermal energy consumer within the residential building sector according to the 2015 Survey of Household Energy Use Data [93].

The remaining sections of the paper describe methods, data and results. The next section describes the methodology applied in the study. The key results are presented and discussed in Section 4. The limits of the study and the potential uncertainties in the results are analyzed in Section 5 followed by Section 6, where the main findings are summarized.

### 4.3 Methodology

The space heating GHG emissions due to the forecasted growth of single detached households from 2020 to 2032 are analyzed under three building performance scenarios: (1) No-Action, (2) BC step code adoption, and, (3) Passive-House adoption. In addition, four variations of the BC step code scenario examine different timeframes in which a net-zero-energy-ready building performance target is achieved. The stringency level of building energy code reflects both energy performance targets and the timeframe of their enforcement. We consider six levels of stringency for building energy performance code.

The forecasted annual growth of single-detached household floor area (i.e. the increased floor area due to the new construction) is estimated for each province and territory in Canada. The increase in floor area is allocated to different climatic zones within each jurisdiction based on the population in each climate zone. Floor area is combined with a climate-specific TEDI value to calculate the yearly code-allowed maximum space thermal energy demand of the new SDH stock. This calculation is repeated for all climate zones within each province; aggregating results gives the annual provincial energy demand for residential space heating.

Due to regional variations in heating fuel mix across Canada, the annual provincial thermal energy demand is allocated to different heating systems based on the types of heating fuel used. The annual heating fuel consumption for each type of space heating system is calculated by the average thermal efficiency specified by the type of fuel being used. Annual GHG emissions are calculated based on the corresponding heating fuel's carbon intensity. Regional results are summed to give the nationwide results. The following sections describe the data processing and the corresponding calculations.

### 4.3.1 New single-detached households

The annual regional growth in floor area of SDH stock is the product of the number of new homes and the average floor area of a typical SDH typically built in a region. The growth of single detached housing stock in the year ‘y’ consists of two portions: (1) new SDH due to population growth and, (2) retirement and replacement of existing households.

The number of newly constructed single detached households due to population growth in each province and territory in year ‘y’, is denoted as  $NSDH_y^p$  and estimated using Eq.8:

$$NSDH_y^p = (NHT_{y+1}^p - NHT_y^p) \times r_{SDH}^p \quad (8)$$

where,  $NHT_y^p$  is the total residential housing stock (including single-detached, single-attached, low-, mid-, and high-rise apartment buildings) of a province or territory in year ‘y’,  $NHT_{y+1}^p$  is the overall residential housing stock of the same province or territories in year ‘y + 1’, and,  $r_{SDH}^p$  is the relative share of SDHs. The superscript ‘p’ denotes the region in Canada (i.e. BC, AB, and SK etc.) The share of the single detached housing stocks,  $r_{SDH}^p$ , varies from province to province as summarized in [Table 4.1](#) [99].

Table 4.1: Provincial share of single detached housing stock,  $r_{SDH}^p$ 

<b>Regions</b>	<b>Single-detached housing stock share [%]</b>
Newfoundland and Labrador	73.3
Prince Edward Island	69.2
Nova Scotia	65.5
New Brunswick	69.3
Quebec	45.4
Ontario	54.3
Manitoba	67.8
Saskatchewan	72.7
Alberta	61.9
British Columbia	44.1
Yukon	62.0
Northwest Territories	57.6
Nunavut	44.3

$NHT_y^p$  is the forecasted overall residential housing stocks from 2020 until 2032 and are acquired from Canada Mortgage and Housing Corporation's (CMHC) data set- *Numbers of households: Canada and provinces and territories 1976-2036* [100]. The residential housing stocks in the dataset are forecasted numbers under twenty-one scenarios permuted by seven population growth scenarios and three headship rates of each household. The original data table of forecasted housing stocks in British Columbia from 2016 to 2036 are reproduced in [Table 4.2](#) as an example. Similar tables of the forecast housing stock in Canadian provinces and territories can be found in [Tables C-1-C-12](#) in the Appendix. As can be seen in [Table 4.2](#), the time resolution of the forecasted residential housing stocks is five years. The data are linearly interpolated to create a yearly forecast. The resulting housing stocks forecasted under different headship rate scenarios in each province and territories are summarized in [Tables C-13-C-25](#).

Table 4.2: Forecasted overall residential housing stocks in British Columbia ( $\times 1,000$ ), 2016-2036

Headship rate scenario	Population growth scenario							
	Year	High growth	Medium growth 1	Medium growth 2	Medium growth 3	Medium growth 4	Medium growth 5	Low growth
High	2016	1,967	1,956	1,962	1,936	1,958	1,949	1,939
	2021	2,152	2,107	2,127	2,047	2,115	2,088	2,054
	2026	2,343	2,248	2,283	2,142	2,261	2,216	2,144
	2031	2,539	2,387	2,441	2,229	2,407	2,340	2,224
	2036	2,744	2,526	2,600	2,307	2,552	2,462	2,293
Medium	2016	1,924	1,913	1,920	1,894	1,916	1,907	1,897
	2021	2,082	2,038	2,057	1,981	2,046	2,021	1,987
	2026	2,248	2,158	2,191	2,057	2,171	2,127	2,059
	2031	2,422	2,278	2,328	2,128	2,297	2,233	2,123
	2036	2,601	2,395	2,465	2,188	2,420	2,334	2,175
Low	2016	1,925	1,914	1,921	1,895	1,917	1,908	1,898
	2021	2,081	2,038	2,057	1,980	2,045	2,020	1,987
	2026	2,246	2,156	2,189	2,055	2,169	2,125	2,057
	2031	2,419	2,275	2,326	2,126	2,295	2,231	2,120
	2036	2,595	2,390	2,459	2,184	2,415	2,330	2,170

The number of existing households of vintage ‘ $v$ ’ (i.e built in year ‘ $v$ ’) to be replaced with the new SDHs in year ‘ $y$ ’ is denoted as  $RSDH_y^p$  and is estimated using the *Housing Stock Over Time* equation described in Doluweera et al. [101] and reproduced here as Eq. 9:

$$RSDH_y^p = \sum_v^y RHT_{vy} \times \beta_{vy} \times r_{RHT}^p \quad (9)$$

where, the subscript ‘ $y$ ’ denotes the years from 2020 to 2032.  $RHT_{vy}$  is the nationwide single detached housing stocks of old vintage ‘ $v$ ’ in year ‘ $y$ ’.  $\beta_{vy}$  is the replacement coefficient for the households of vintage ‘ $v$ ’ in the year ‘ $y$ ’ and is determined assuming a Poisson distribution:

$$\beta_{vy} = e^{-\mu} \times \frac{\mu^{y-v+1}}{(y-v+1)!} \quad (10)$$

where,  $\mu$  is the average single detached household's life expectancy which is assumed to be 50 years in the study. Due to the limited available data, only the single detached houses built after 1990 are considered for replacement during the period of 2020 to 2032; therefore, the subscript ' $v$ ' denotes the house vintages from 1990 to the investigated year ' $y$ '. The  $RHT_{vy}$  can be recursively calculated based on the previous year's replacement coefficient,  $\beta_{vy-1}$  and the housing stock of vintage ' $v$ ' in the previous year denoted as  $RHT_{vy-1}$ ,

$$RHT_{vy} = (1 - \beta_{vy-1}) \times RHT_{vy-1} \quad (11)$$

Using the above, only the houses built during the period between 1990 and 1997 have the positive values of the replacement coefficient,  $\beta_{vy}$  starting from 2020 onward. The last term,  $r_{RHT}^p$  in Eq. 9 denotes the provincial share of the overall single detached housing stocks of old vintages being replaced in Canada.  $r_{RHT}^p$  is calculated as the ratio of provincial housing stock growth to the national housing stock growth between 1990 and 1996 [100].

The total growth of the single detached housing stocks in each province and territories in year ' $y$ ' is denoted as  $TSDH_y^p$  which is the sum of population induced growth and replacements:

$$TSDH_y^p = NSDH_y^p + RSDH_y^p \quad (12)$$

The provincial specific average area of a typical single detached house,  $ASDH^p$  is based on the average household energy use provided by Households and the Environment Energy Use 2011 [102], and summarized in [Table 4.3](#). The data for typical household area

in the territories (i.e. YT, NT and NU) are not available, so the national average household area of 133 m<sup>2</sup> is assumed for these regions.

Table 4.3: Average area of a typical household by province in Canada

Regions	Area per household [m <sup>2</sup> ]
Canada	133
NL	139
PE	163
NS	136
NB	112
QC	113
ON	145
MB	110
SK	116
AB	130
BC	148
YT	133
NT	133
NU	133

The overall floor area growth in each province and territory,  $A_y^p$  in year ‘y’ is:

$$A_y^p = TSDH_y^p \times ASDH^p \quad (13)$$

The national floor area growth of the singled-detached households in year ‘y’ is denoted as  $ACa_y$  and can be calculated by Eq. 14. Again, the superscript ‘p’ denotes the province or territories in Canada (i.e. NL, BC, AB, etc.).

$$ACa_y = \sum_p A_y^p \quad (14)$$

#### 4.3.2 Allocation to climate zones

Canada is divided into six distinct climate zones according to the annual heating degree days (HDD) [103]. [Table 4.4](#) lists all six Canadian climate zones with corresponding annual HDD.

Table 4.4: Canadian climate zones and the corresponding annual heating degree days [103]

Climate Zone	Annual HDDs
4	<3,000
5	3,000 to 3,999
6	4,000 to 4,999
7A	5,000 to 5,999
7B	6,000 to 6,999
8	>7,000

The annual growth in the floor area in each region is proportionally allocated to regional climate zones based on the specific population ratio of that region,  $r_z^p$ . The subscript ‘z’ denotes the climate zone number (i.e. 4, 5, 6, 7A, 7B and 8), so.

$$r_z^p = \frac{Pl_z^p}{\sum_z Pl_z^p} \quad (15)$$

where,  $Pl_z^p$  is the census population within a specific climate zone ‘z’ in the province or territory; while,  $\sum_z Pl_z^p$  is the sum of populations of all the climate zones defined in that province. The population of a specific climate zone is the sum of the census population in each city and/or town that is located within that climate zone. Each city’s census population is from the results of Canadian census 2016 [104] and the corresponding annual heating degree days are from [103]. Only the cities and/or towns listed in both datasets provided by [103] and [104], are considered since the census areas listed in [43] do not necessarily have the corresponding annual heating degree days in [103] and vice versa. Thus, the cities which meet these criteria are chosen for the climate zone specific population ratio calculation in each province and territories listed in [Table C-26](#). The regional climate zone

specific population ratios are summarized in [Table 4.5](#). The zero percent in the table indicates there is no such a climate zone defined in that province.

Table 4.5: The climate zone specific population ratio of each province and territories

Province/Territories	Climate Zones					
	4	5	6	7A	7B	8
	climate zone specific population ratio [%]					
NL	0.0%	0.0%	81.9%	11.4%	3.3%	3.4%
PE	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%
NS	0.0%	2.0%	98.0%	0.0%	0.0%	0.0%
NB	0.0%	0.0%	87.0%	13.0%	0.0%	0.0%
QC	0.0%	0.0%	87.0%	13.0%	0.0%	0.0%
ON	0.0%	72.4%	24.3%	2.8%	0.5%	0.0%
MB	0.0%	0.0%	0.0%	96.8%	1.6%	1.5%
SK	0.0%	0.0%	0.3%	88.0%	11.7%	0.0%
AB	0.0%	0.0%	6.8%	90.6%	2.6%	0.0%
BC	78.1%	16.7%	4.0%	1.1%	0.1%	0.0%
YT	0.0%	0.0%	0.0%	0.0%	88.9%	11.1%
NT	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
NU	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%

The floor area of new SDHs allocated to a specific climate zone in year ‘y’ is denoted as  $A_{y,z}^p$ , and is given by:

$$A_{y,z}^p = A_y^p \times r_z^p \quad (16)$$

where, the subscript ‘z’ denotes the climate zone.

### 4.3.3 Adoption Scenarios

Three scenarios of building energy code (standard) adoption considered are: (1) No-Action, (2) BC Step Code and, (3) the Passive House criteria.

The No-Action scenario is a reference case. Under this scenario, the annual space heating energy use intensity (i.e. space heating energy use per floor area) of new SDHs is

assumed to be unchanged compared to the year 2016 as determined by the total space heating energy and corresponding total floor area in 2016 [105]. The 2016 SDH average space heating energy use intensity is calculated to be  $166 \text{ kWh}/(\text{m}^2 \cdot \text{year})$ . Multiplying by the annual growth in floor area,  $ACa_y$  gives annual space heating energy consumptions if no action to improve energy performance is taken.

In the BC Step Code scenario, we assume the code is adopted across Canada. The five steps for building energy efficiency include two major climate specific indexes, namely, the Mechanical Energy Use Intensity (MEUI) and the Thermal Energy Demand Intensity (TEDI). The MEUI includes all the mechanical system energy use including the space heating, domestic water heating, pumps and fans; while, the TEDI measures the annual heat loss across the building envelope [106]. In the study, the stepwise targets of TEDI values specify the maximum allowed thermal energy demand served by the space heating systems ([Table 4.6](#)).

Table 4.6: The climate-specific thermal energy demand intensity (TEDI) of each step in BC step code

TEDI [kWh/(m <sup>2</sup> /year)]						
Step	Zone 4	Zone 5	Zone 6	Zone 7A	Zone 7B	Zone 8
2	35	45	60	80	100	120
3	30	40	50	70	90	105
4	20	30	40	55	65	80
5	15	20	25	35	50	60

Step one (1) is not included in the Table since there is neither MEUI nor TEDI requirements specified in the energy code. Although the BC step code requires all the

buildings in British Columbia to be net-zero energy ready by 2032, the rate of adoption is not prescribed. So, we explore four cases representing different rates at which the energy-zero ready target are achieved are assumed as illustrated in [Fig. 4.1](#).

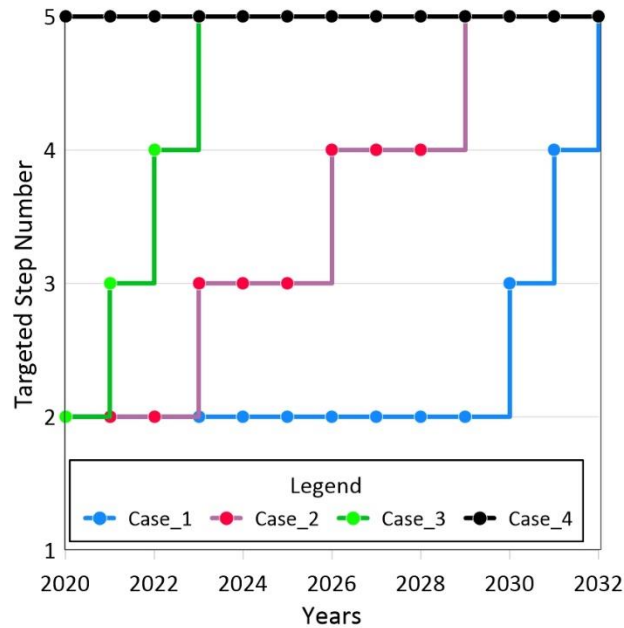


Fig. 4.1: Four cases representing different rates for BC step code adoption

All cases require new construction to comply with Step 5 in 2032; however, the stringency level varies in time. The TEDI values of existing households are assumed to remain the same as when they were built. Case 1 represents the longest deferral of Step adoption, with a rapid change at the end of the period. The remaining cases represent alternative adoption rates, with Case 4 representing an extreme case where Step 5 is required immediately.

The passive house scenario assumes all new single detached households meet the space heating energy use intensity of  $15 \text{ kWh}/(\text{m}^2 \cdot \text{year})$  according to the passive house criteria [98]. Similar to the No-Action scenario, this one-value-fits-all number is multiplied

by the annual growth of the floor area,  $ACa_y$ , to estimate the national annual space heating energy consumption.

#### 4.3.4 Annual space heating demand

The provincial annual thermal energy demand,  $q_y^p$  for a BC step code scenario is determined by the specified TEDI value in Table 6 and the floor area,

$$q_y^p = \sum_z (TEDI_z^{step,y} \times A_{y,z}^p) \quad (17)$$

where,  $TEDI_z^{step,y}$  is the climate (zone) specific TEDI target of a certain step which is required to comply with in year 'y' according to the timeframes shown in [Fig. 4.1](#). The subscript 'z' denotes the climate zone. The national energy demand,  $Q_y$  is the sum of regional annual space thermal energy demands

$$Q_y = \sum_p q_y^p \quad (18)$$

Both the No-Action and Passive-house scenarios use space heating energy use intensity instead of TEDI to calculate the annual space heating energy consumption. The TEDI does not capture the space heating system's thermal efficiency; therefore, thermal demand is allocated to fuel demand based on the average system thermal efficiency.

#### 4.3.5 Allocation to fuel types

The share of heating fuel types for SDH buildings,  $r_{fuel\ typ}^p$  are reproduced in Appendix [Table C-27](#) [107]. The national average is assumed for the three territories (i.e. YT, NT, and NU). The subscript 'fuel typ' denotes the heating fuel type (i.e. electricity,

natural gas, oil, and wood). The allocated space heating fuel use for each region in year ‘y’ under BC step code adoption scenario,  $E_y^p$  is,

$$E_y^p = q_y^p \times r_{fuel\ typ}^p / \eta_{fuel\ typ} \quad (19)$$

where,  $\eta_{fuel\ typ}$  is a particular space heating system’s average thermal efficiency based on the heating fuel type. The assumed thermal efficiencies of heating systems are listed in [Table 4.7](#).

Table 4.7: Assumed single detached household’s space heating system thermal efficiency by heating fuel types

Heating System Thermal Efficiency [%]			
Electricity	Natural Gas	Oil	Wood
100	90	85	50

#### 4.3.6 Annual GHG emissions

The provincial annual GHG emissions,  $GHG_y^p$  from new single-detached households are:

$$GHG_y^p = E_y^p \times F_{fuel\ typ}^p \quad (20)$$

where,  $F_{fuel\ typ}^p$  is the GHG factor relating emissions per unit heating fuel use. The nationwide annual GHG emissions,  $TGHG_y$  is the sum of all the provincial annual GHG emissions. Carbon intensity for electricity varies by province due to the different generation mixes. Regional GHG factors of heating fuels are summarized in [Table C-28](#) [108].

## 4.4 Results and Discussion

In total, there are one hundred and twenty-six (126) different cases formed by the permutation of twenty-one (21) growth projections in floor area and six (6) code scenarios. Key results are analyzed and discussed in the following sections. Detailed data summaries are provided in the Appendices.

### 4.4.1 Emissions

[Fig. 4.2](#) shows the national impacts of high headship and population growth under BC step code scenarios. The left axis shows cumulative space heating GHG emissions in million tons per year, while the right represents the cumulative growth of SDH floor area in million square meters. The 'x' axis indicates the years from 2020 to 2032.

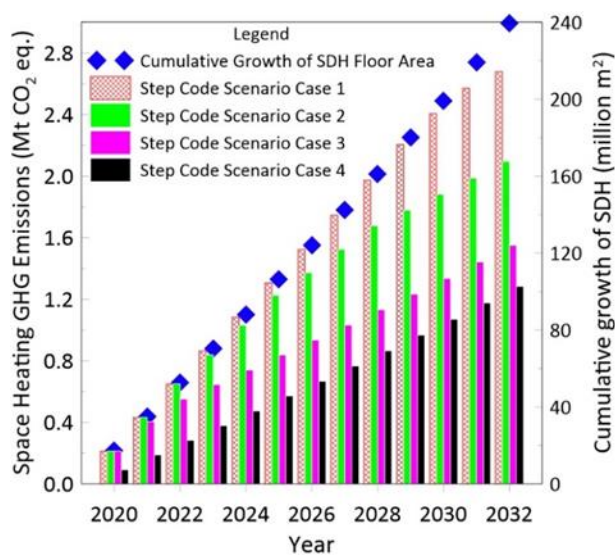


Fig. 4.2: Comparison of forecasted nationwide cumulative GHG emissions due to growth in single detached households for the BC step code adoption scenario

As can be seen, cumulative GHG emissions due to space heating in Case 4 are 1.28 Mt to year 2032, while in Case 1 emissions reach 2.68 Mt which is two times of that of

Case 4. The space heating GHG emissions associated to Case 2 and Case 3 are 2.10 Mt. and 1.55 Mt., respectively. The variation in cumulative emissions between each case represents the effect of timing of step enforcement with Case 1 being late adoption and Case 4 being the more aggressive scenario for increase in step adoption.

While Step code Case 1 is the least beneficial of those shown in [Fig. 4.2](#), it does represent a significant improvement over No-Action. [Fig. 4.3](#) compares Case 1 of the BC step code scenarios to the No-Action scenario. To year 2032, the GHG emissions associated with the No-Action scenario are 5.57 Mt., as compared to 2.68 Mt for Case 1 of BC step code adoption - 50% of the No-Action scenario value.

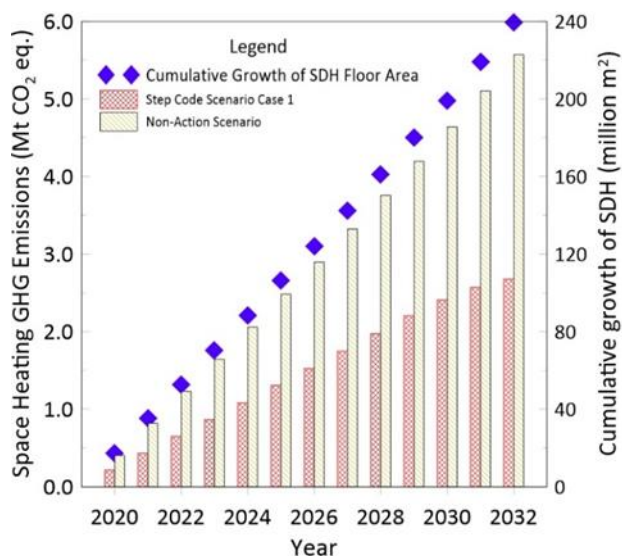


Fig. 4.3: Comparison of forecasted nationwide cumulative GHG emissions due to the single detached households growth of between the case 1 in BC step code adoption scenario and No-Action scenario, 2020-2032

[Fig. 4.4](#) compares the most aggressive BC Step Code scenario (Case 4) and the Passive house scenario. Although a Step 5 building represents the net-zero-energy performance level [95], Case 4 results in approximately two times more emissions than the

passive house scenario. Together, results in [Fig. 4.2](#) and [Fig. 4.3](#) show compared to No-Action scenario, space heating GHG emissions from new single-detached households can be reduced up to 77% and 89%, respectively if the BC Step Code or the Passive-House criteria is adopted nationwide. Therefore, from the perspective of the effects on national SDH emissions, the passive house criteria is 12% more effective.

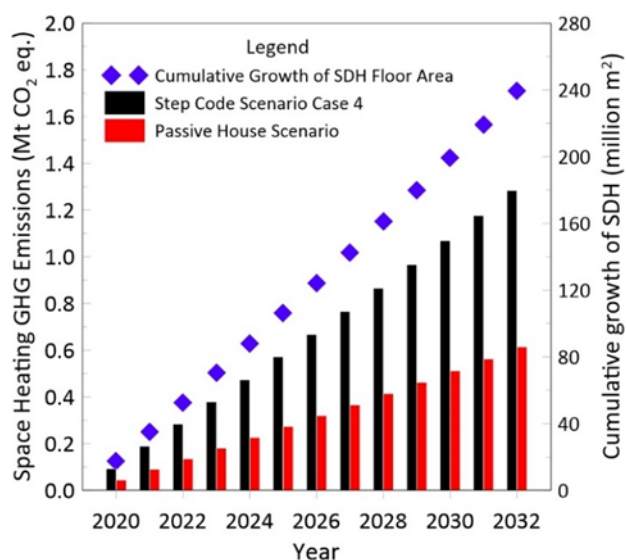


Fig. 4.4: Comparison of forecasted nationwide cumulative GHG emissions due to the single detached households' growth of between the case 4 in BC step code adoption scenario and Passive house standard adoption scenario, 2020-2032

#### 4.4.2 Regional emission reductions

[Fig. 4.5](#) shows the regional space heating GHG emission reductions per cumulative floor area of SDH households at the end of the study period under the high headship and medium population growth scenario. Reductions in emissions are determined by the difference with respect to No-Action scenario.

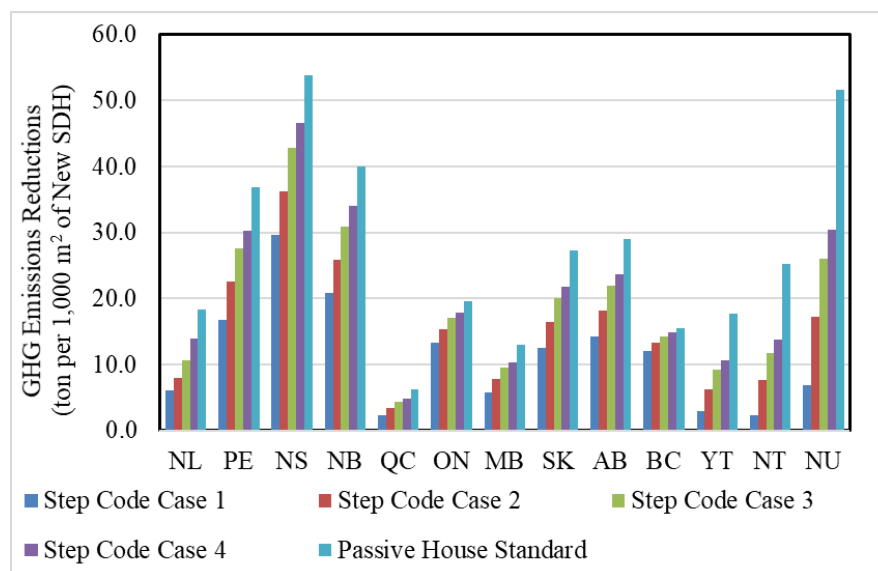


Fig. 4.5: Provincial GHG emission reductions per thousand square meters floor area growth of single detached households under various energy standard adoption scenarios/cases compared to the No-Action reference scenario in 2032

While there are regional variations in absolute reductions, results in [Fig. 4.5](#) show the passive house scenario having a higher impact than the other scenarios. For example, in Nova Scotia (NS), the passive house scenario reduces emissions by approximately 54 tons/1,000m<sup>2</sup> versus 29.6, 36.2, 42.8 and 46.7 tons/1,000m<sup>2</sup> respectively for Step code Cases 1-4. Although, in general, more stringent energy efficiency targets lead to greater reduction in GHG emissions from space heating in all regions, the magnitude of reductions is small for some regions like QC and BC. In terms of GHG emission reduction per floor area, in BC, there is no difference between the Step 5 (Case 4) standard and the passive house criteria. This is consistent with other studies [96].

The regional variations seen in [Fig. 4.5](#) reflect the heating fuel mix. For example, in Case 1 of the BC step code scenario, the cumulative emissions reduction is 2.3 t/1,000 m<sup>2</sup> for Quebec (QC), whereas the same scenario delivers a reduction of 29.6 tons/1,000 m<sup>2</sup> in

Nova Scotia. This difference is explained by variations in the heating fuel, technology mix, and carbon intensity of fuel. Regional fuel shares are shown in [Fig. 4.6](#).

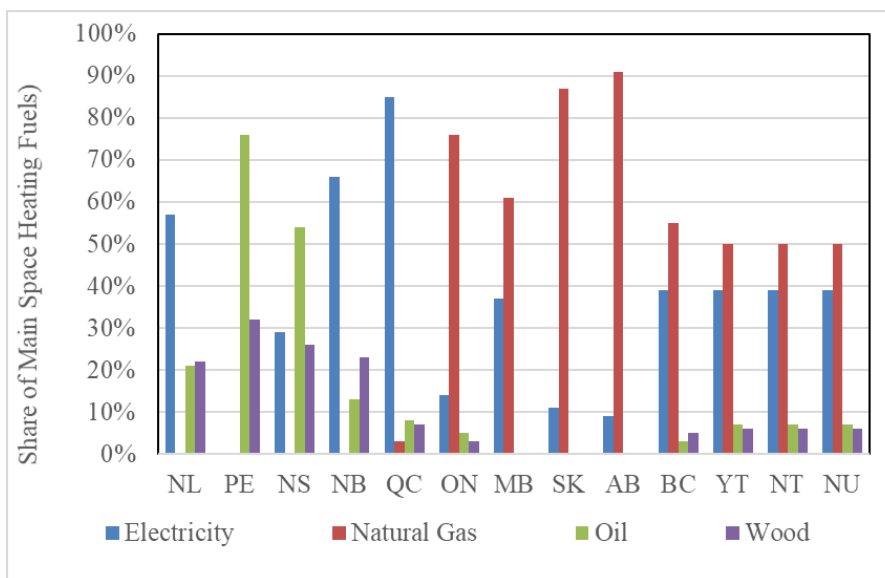


Fig. 4.6: The share of main heating fuels of the single detached households in each province and territories. (Reproduced from dataset provided by [107])

The reduced impact of building code stringency in QC is because 85% of heating energy comes from electricity produced from hydroelectric supplies. The carbon intensity of electricity in QC is 1.8g/kWh. In the case of New Brunswick (NB), although electricity accounts for 67% of heating fuel, the carbon intensity of electricity is 330g/kWh. In addition, the balance of heating fuel used (i.e., 13% oil and 23% wood) are for lower thermal efficiency space heating systems. For example, the thermal efficiencies of oil burning and wood burning heating system are approximately 85% and 50%, respectively. Together, the results shown in [Fig. 4.5](#) and [Fig. 4.6](#) show the effect of a specific building energy standard is more pronounced in regions where larger fractions of space heating are delivered using lower thermal efficiency systems and heating fuels with higher carbon intensity.

## 4.5 Limitations

In the current study, the future space heating GHG emissions assessed under the BC step code scenario may be under-estimated due actual heating demand exceeding the prescribed TEDI values. In both No-Action and Passive House criteria adoption scenarios, the space GHG emissions are calculated using space heating energy use intensity instead of using TEDI values. A key difference is that space heating energy use intensity includes the energy for both space heating and ventilation, whereas the TEDI values specified in the BC step code reflect the building envelope thermal performance only. According to [95] and [106], the heating load of the space ventilation airflow is included in the TEDI values if the ventilation is supplied through a heat recovery ventilator (HRV). Considering that HRV use is becoming more common in new construction, the TEDI predicted heating demand for BC step adoption should reflect future code compliant homes.

Future SDH stock and heating demand depends on population growth and the distribution of new households amongst climate zones. Hence, the climate zone specific population ratio in each province,  $r_z^p$  is uncertain. The climate zone distribution assumed for future SDHs is based on census data where HDD data is also available. [Table 4.8](#) lists the ratio of the population involved to the overall census population in each province and territory. As can be seen, in general, the majority of the population of each province and territories is included in the climate zone ratio calculation.

Table 4.8: The ratio of the involved population to the census population record by province

	Provinces and Territories												
	NL	PE	NS	NB	QC	ON	MB	SK	AB	BC	YT	NT	NU
Population Involved	254,793	70,610	489,094	327,629	5,570,946	11,241,134	856,957	636,249	2,932,545	3,848,600	28,211	37,396	10,825
Census Populatoin	301,728	72,310	529,969	368,118	6,315,598	11,846,034	935,372	721,606	3,411,127	4,016,279	30,447	39,416	27,192
% of Coverage	84.4%	97.6%	92.3%	89.0%	88.2%	94.9%	91.6%	88.2%	86.0%	95.8%	92.7%	94.9%	39.8%

The forecasted growth of the floor area for single-detached households may be underestimated. Replacement of homes built before 1990 is not considered in the projection; however, this will only effect the absolute emissions not GHG emission reduction per floor area.

Finally, the thermal energy demand projection assumes that all the new SDHs meet the minimum code-compliant energy performance requirements (i.e. TEDIs in BC step code and heating energy demand intensity of  $15kWh/(m^2 \cdot year)$  for the passive house criteria). In reality, the actual space heating energy use of any single-detached house could be higher or lower depending on many factors such as behaviour and owner modification not included in the current study. For this reason, this work does not provide predictions of actual energy consumption or GHG emissions for new, single-detached houses in the future. Instead, it compares the potential effectiveness of the building energy performance targets on GHG emission reductions.

## 4.6 Conclusions

This study estimate the space heating GHG emissions of new single-detached households under different building energy standards and enforcement scenarios. A regional analysis for Canada is performed based on climate zone population ratios and

stock change between 2020 and 2032. BC Step Code adoption and Passive-House criteria are compared to current stock performance. Key findings include:

- Nationwide, the passive house criteria is more effective in abating the space heating GHG emissions levels than BC step code does in Canada.
- Space heating GHG emissions from new single-detached households can be reduced up to 77% and 89%, respectively if the BC Step Code or the Passive House criteria is implemented nationwide.
- The effects of adopting a specific building energy standard on GHG emission reduction vary depending on the thermal efficiency of the heating system and the carbon intensity of the heating fuels. Building performance standards are less impactful in regions where carbon intensity of fuels are low.
- Because of the above, there is no notable difference between the BC step code and the passive house criteria from the GHG emission reduction per floor area point of view in British Columbia, Canada.

## 5 CONTRIBUTIONS AND FUTURE WORK

Energy saving technologies and energy standards (codes) should always work in parallel to contribute towards solving the building GHG emissions mitigation problems. To ensure appropriate implementation, understanding of the variations in their applicability due to the complexity of building systems and varying runtime conditions is imperative. This dissertation highlights the significance of scrutinizing the effects of building energy saving technologies and energy standards by taking account into the runtime conditions before implementation. Although only two selected technologies (i.e. the HRV and free cooling) and two building energy codes (i.e. the BC Energy Step Code and Passive House criteria) are investigated, the results suggest HVAC system designers and energy policy makers should undertake a more detailed analysis before implementing a new energy saving technology and/or adopting a specific building energy standard. This is because the performance of any building energy saving technology varies over the range of operational conditions due to the complexity of the building system; and higher energy performance target doesn't necessarily result in significant reductions in GHG emissions since the carbon intensity of the energy also plays important role.

### 5.1 Contributions

In the first study, the energy saving potential is investigated for a sensible heat recovery ventilator coupled with an air-to-air heat pump system serving a residential apartment suite facing different orientations in different climate zones. The contributions from the first study in this work are:

- The savings in annual space heating energy use of residential building by implementing a HRV is guaranteed since Canada is a heating dominant country.
- Higher heating energy saving potential is expected resulting in relatively shorter payback times of the investment for the HRV in colder climate zones.
- However use of HRV can increase energy consumption in residential building's HVAC systems whenever the outdoor air free cooling is available during the cooling and shoulder seasons in Canada. Appropriate inter-lock control strategy should be applied to coordinate the operations between the HRV and the air-side economizer.

In the second study, the free cooling potentials are evaluated by comparing the available and usable free cooling in these areas. The contributions from this study in this work are:

- When outdoor conditions are favorable for free cooling, use of the air-side economizer always reduces the cooling needs for residential houses in Canada.
- Employing the air-side economizer for free cooling should be highly encourage in the cities located in ASHRAE climate zone 5.
- Houses having higher cooling demand can benefit more by utilizing an air-side economizer than those in the same climate zone having lower cooling demand.
- Cooling demand can still be met completely by free cooling for a specific period of the time by increasing the outdoor air inflow rate when the outdoor air temperature is higher than 13°C which is the typical mechanical cooling system's supply air temperature.

The third study compares the GHG emissions mitigation effectiveness on space heating systems in new single-detached households in Canada for the period from 2020 to 2032 under different enforcement scenarios between the BC Step Code and Passive House criteria. The specific contributions of this study in this work are:

- Nationwide, the passive house criteria is more effective in abating the space heating GHG emissions levels than BC step code does in Canada.
- Space heating GHG emissions from new single-detached households can be reduced up to 77% and 89%, respectively if the step 5 requirement of BC Step Code or the Passive House criteria is implemented nationwide.
- The effects of adopting a specific building energy standard on GHG emission reduction vary depending on the thermal efficiency of the heating system and the carbon intensity of the heating fuels. Building performance standards are less impactful in regions where carbon intensity of fuels are low.

## 5.2 Future Work

Based on the results of this work, recommendations for future work and improved results are made.

In first study, conclusions are drawn based on a suite located on top floor. The results are, therefore, generalizable only for suites located on the top floor. In order to have a more comprehensive knowledge of the applicability of the HRV in residential apartment buildings, a similar study needs to be conducted for a suite located on a middle floor. Furthermore, the energy saving potential of utilizing the HRV would be reduced due to possible defrosting process during severe winter weather. Therefore, the models developed

in the first study need to be refined by taking into account the detailed HRV configuration, operating profile and installation location so that the impacts of this phenomenon on the HRV's performance can be addressed adequately.

In the second study, the window to wall ratio is assumed to be the same for each building façade and no external overhang of the window is applied. Investigating the benefit of utilizing the air-side economizer in the residential building with various window to wall ratio applied to each façade would provide a more complete picture of free cooling potential for residential buildings of various features. The results also indicate although the building peak cooling load is much smaller than the maximum free cooling that is available from outside air, only a small portion is usable since the maximum free cooling is not synchronous with the building peak cooling needs. Therefore, studies focusing on thermal storage for the free cooling may offer a way to increase the usable portion.

Finally, in the third study, the replacement of single-detached homes of older vintages (before 1990) is not considered in the projection and, as a result, the forecast growth of the floor area for the households is underestimated. Although this will only affect the absolute emissions, not GHG emission reduction per floor area, inclusion of the households built before 1990 in future studies would provide more complete results.

## REFERENCE

- [1] "Pan-Canadian Framework on Clean Growth and Climate Change, Canada's Plan to Address Climate Change and Grow the E".
- [2] "2019 National Inventory Report 1990-2017: Greenhouse Gas Sources and Sinks in Canada. Canada's Submission to the United Nations Framework Convention on Climate Change. Part 1," Environment and Climate Change Canada, Gatineau, QC, 2019.
- [3] "BC Housing, Heat Recovery Ventilation Guide for Multi-unit Residential Buildings," BC Housing, Burnaby, 2015.
- [4] ANSI/ASHRAE/IES Standard 90.1-2010, Energy Standard for Buildings Except Low-Rise Residential Buildings., Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 2010.
- [5] "Heat Recovery Ventilators," Natural Resources Canada's Office of Energy Efficiency, Ottawa ON, 2012.
- [6] *Information Bulletin- 9.32 Ventilation*, Victoria, B.C.: Government of British Columbia-Building and Safety Standards Branch, 2014.
- [7] 2012 ASHRAE Handbook of HVAC Systems and Equipment, Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 2012.
- [8] E. Vaughan and J. Turner, "The Value and Impact of Building Codes," Environmental and Energy Study Institute, 2013.
- [9] L. Zhang and J. Niu, "Energy Requirements for Conditioning Fresh Air and the Long-term Savings with a Membrane-based Energy Recovery Ventilator in Hong Kong," *Energy*, vol. 26, pp. 119-135, 2001.
- [10] Y. E. Fouih, P. Stabat, P. Riviere, P. Hoang and V. Archambault, "Adequacy of Air-to-Air Heat Recovery Ventilation System Applied in Low Energy Buildings," *Energy and Buildings*, vol. 54, pp. 29-39, 2012.

- [11] K. P. Lam, S. R. Lee, G. M. Dobbs and C. Zhai, "Simulation of the Effect of An Energy Recovery Ventilator on Indoor Thermal Conditions and System Performance," in *Ninth International IBPSA Conference*, Montreal, Canada, 2005.
- [12] A. Dadoo, L. Gustavsson and R. Sathre, "Primary Energy Implications of Ventilation Heat Recovery in Residential Buildings," *Energy and Buildings*, vol. 43, pp. 1566-1572, 2011.
- [13] "An Examination of the Opportunity for Residential Heat Pumps in Ontario," Ministry of Energy, 2017.
- [14] K. Zhong, S. Chen, Y. Kang and L. Yuan, "Analysis of Outdoor Temperature Ranges for the Operation of Different Ventilating Modes in Commercial Buildings of China," *Energy and Buildings*, vol. 55, pp. 174-182, 2012.
- [15] Y. Kang, Y. Wang, K. Zhong and J. Liu, "Temperature Ranges of the Application of Air to Air Heat Recovery Ventilator in Supermarket in Winter, China," *Energy and Buildings*, vol. 42, pp. 2289-2295, 2010.
- [16] K. Zhong and Y. Kang, "Applicability of Air to Air Heat Recovery Ventilators in China," *Applied Thermal Engineering*, vol. 29, pp. 830-840, 2009.
- [17] J. Liu, J. Liu and B. Wang, "Efficiency of Energy Recovery Ventilator with Various Weathers and Its Energy Saving Performance in a Residential Apartment," *Energy and Buildings*, vol. 42, pp. 43-49, 2010.
- [18] T. Kubota, D. T. H. Chyee and S. Ahamd, "The effects of night ventilation technique on indoor thermal environment for residential buildings in hot-humid climate of Malaysia," *Energy and Buildings*, vol. 41, pp. 829-839, 2009.
- [19] M. Macias, A. Mateo, M. Schuler and E. Mitre, "Application of night cooling concept to social housing design in dry hot climate," *Energy and Buildings*, vol. 38, pp. 1104-1110, 2006.
- [20] A. Michael, D. Demosthenous and M. Philokyrou, "Natural ventilation for cooling in mediterranean climate: A case study in vernacular architecture of Cyprus," *Energy and Buildings*, vol. 144, pp. 333-345, 2017.

- [21] M. Santamouris, A. Sfakianaki and K. Pavlou, "On the efficiency of night ventilation techniques applied to residential buildings," *Energy and Buildings*, vol. 42, pp. 1309-1313, 2010.
- [22] W. J. Turner, I. S. Walker and J. Roux, "Residential Pre-Cooling: Mechanical Cooling and Air-Side Economizers," Ernest Orlando Lawrence Berkeley National Laboratory, 2012.
- [23] K. Kensek, T. Lanning, T. Kohut and J.-H. Choi, "Economizer performance and verification: The effect of human behavior on economizer efficiency and thermal comfort in southern California," *ASHRAE Transactions CH-15-021*, 2015.
- [24] J. Yiu, S. Wang and F. W. H. Yik, "Assessment of practical applications of outdoor air economiser in Hong Kong," *Proc. CIBSE A: Building Serv. Eng. Technol.*, vol. 21, no. 3, pp. 187-198, 2000.
- [25] Y. Yao and L. Wang, "Energy analysis on VAV system with different air-side economizers in China," *Energy and Buildings*, vol. 42, pp. 1220-1230, 2010.
- [26] K.-P. Lee and H.-L. Chen, "Analysis of energy saving potential of air-side free cooling for data centers in worldwide climate zones," *Energy and Buildings*, vol. 64, pp. 103-112, 2013.
- [27] J. E. Son and K. H. Lee, "Cooling energy performance analysis depending on the economizer cycle control methods in an office building," *Energy and Buildings*, vol. 120, pp. 45-57, 2016.
- [28] H. Bulut and M. A. Aktacir, "Determination of free cooling potential: A case study for Istanbul, Turkey," *Applied Energy*, vol. 88, pp. 680-689, 2011.
- [29] U. Palmiste and H. Voll, "Free cooling potential of an airside economizer in Estonia," *Science and Technology for the Built Environment*, vol. 22, pp. 951-959, 2016.
- [30] M. Olonscheck, A. Holsten and J. P. Kropp, "Heating and cooling energy demand and related emissions of the German residential building stock under climate change," *Energy Policy*, vol. 39, pp. 4795-4806, 2011.

- [31] M. K. Mattinen, J. Heljo, J. Vihola, A. Kurvinen and S. Lehtoranta, "Modeling and visualization of residential sector energy consumption and greenhouse gas emissions," *Journal of Cleaner Production*, vol. 81, pp. 70-80, 2014.
- [32] J. P. Gouveia, P. Fortes and J. Seixas, "Projections of energy services demand for residential buildings: Insights from a bottom-up methodology," *Energy*, vol. 47, pp. 430-442, 2012.
- [33] S. Yu, J. Eom, M. Evans and L. Clarke, "A long-term, integrated impact assessment of alternative building energy code scenarios in China," *Energy Policy*, vol. 67, pp. 626-639, 2014.
- [34] V. Subramanyam, A. Kumar, A. Talaei and M. A. H. Mondal, "Energy Efficiency improvement opportunities and associated greenhouse gas abatement costs for the residential sector," *Energy*, vol. 118, pp. 795-807, 2017.
- [35] *2012 R-2000 Standard*, Natural Resources Canada's Office of Energy Efficiency, 2012.
- [36] "BC Energy Step Code, Design Guide Supplement S3 on Overheating and Air Quality," BC Housing in collaboration with BC Hydro, the City of Vancouver, the City of New Westminster, and the Province of BC., 2019.
- [37] H. E. a. C. S. B. Water and Air Quality Bureau, "Ventilation and the Indoor Environment," Health Canada, Ottawa, ON, 2018.
- [38] A. M. Omer, "Renewable Building Energy Systems and Passive Human Comfort Solutions," *Renewable & Sustainable Reviews*, vol. 12, pp. 1562-1587, 2008.
- [39] Y. Zhang, J. A. Wright and V. I. Hanby, "Energy Aspects of HVAC System Configurations - Problems Definition and Test Cases," *HVAC&R Research Special Issues*, vol. 12, no. 3c, 2006.
- [40] M. H. Sherman and L. S. Walker, "Energy Impact of Residential Ventilation Norms in the United States," Lawrence Berkeley National Laboratory, 2007.
- [41] Y. Zhou, J. Wu and R. Wang, "Performance of Energy Recovery Ventilator with Various Weathers and Temperature Set-points," *Energy and Buildings*, vol. 39, pp. 1202-1210, 2007.

- [42] S.-. M. Kim, J.-. H. Lee, S. Kim, H. J. Moon and J. Cho, "Determining Operation Schedules of Heat Recovery Ventilators for Optimum Energy Savings in High-Rise Residential Buildings," *Energy and Buildings*, vol. 46, pp. 3-13, 2012.
- [43] A. Barker and R. Ramakrishnan, "Parametric Analysis of Energy Recovery Ventilation Performance in the High-Rise Residential Sector," Department of Architectural Science, Ryerson University, Toronto, Ontario.
- [44] J. Laverge and A. Janssens, "Heat Recovery Ventilation Operation Traded off Against Natural and Simple Exhaust Ventilation in Europe by Primary Energy Factor, Carbon Dioxide Emission, Household Consumer Price and Exergy," *Energy and Buildings*, vol. 50, pp. 315-323, 2012.
- [45] S. Jaber and S. Ajib, "Energy Recovery System in Mediterranean Region," *Sustainable Cities and Society*, vol. 3, pp. 24-29, 2012.
- [46] M. Rasouli, C. J. Simonson and R. W. Besant, "Applicability and Optimum Control Strategy of Energy Recovery Ventilators in Different Climate Conditions," *Energy and Buildings*, vol. 42, pp. 1376-1385, 2010.
- [47] C.-A. Roulet, F. Heidt and M.-C. Pibiri, "Heat Recovery with Air Handling Units," *Energy and Buildings*, vol. 33, pp. 495-502, 2001.
- [48] D. Culter, J. Winkler, N. Kruis, C. Christensen and M. Brandemuehl, "Improved Modeling of Residential Air Conditioners and Heat Pumps for Energy Calculations," NREL, Golden, Colorado, 2013.
- [49] J. Hugh I. Henderson and H. M. Sachs, "The Efficacy of SEER as a Seasonal Performance Measure for Different Climates," in *Fifteen Symposium on Improving Building Systems in Hot and Humid Climates*, Orlando, FL., 2006.
- [50] 2008 Standard for Performance Rating of Unitary Air-Conditioning & Air-Source Heat Pump Equipment, Arlington, VA: Air-Conditioning Heating and Refrigeration Institute, 2012.
- [51] J. J. H. a. Associates, "EER & SEER As Predictors of Seasonal Cooling Performance," Southern California Edison Design & Engineering Services, Irwindale, California, 2004.

- [52] *TRNSYS 17 Volume 1 Getting Started*, Madison: Solar Energy Laboratory, University of Wisconsin-Madison, 2014.
- [53] Y. Zhang, "JEPlus- An EnergyPlus simulation manager for parametrics," JEPlus.Org, 2015. [Online]. Available: [http://www.jeplus.org/wiki/doku.php?id=docs:manual\\_1\\_6](http://www.jeplus.org/wiki/doku.php?id=docs:manual_1_6). [Accessed 28 November 2016].
- [54] J. J. H. & Associates, *eQuest- Introductory Tutorial, Version 3.65*, Camarillo, CA: James J. Hirsch & Associates, 2012.
- [55] "Air-Source Heat Pumps," Natural Resources Canada, 29 06 2016. [Online]. Available: <https://www.nrcan.gc.ca/energy/publications/efficiency/heating-heat-pump/6831>. [Accessed 30 11 2016].
- [56] "TESSLibs 17 Volume 6 HVAC Library Mathematical Reference," Thermal Energy System Specialists, LLC of Madison, Wisconsin, USA, Madison, Wisconsin, USA, 2014.
- [57] ANSI/ASHRAE Standard 62.1-2010, Ventilation for Acceptable Indoor Air Quality, Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 2010.
- [58] British Columbia Codes, 2012, National Research Council Canada, 2012.
- [59] I. A. (IEA), "2018 Global Status Report," United Nations Environment Programme and Global Alliance for Buildings and Construction, 2018.
- [60] O. o. E. Efficiency, "Energy Use Data Handbook," Natural Resources Canada, Ottawa ON, 2016.
- [61] O. o. E. Efficiency, "Energy Efficiency Trends in Canada," Minister of Natural Resources, Ottawa, ON, 2016.
- [62] M. A. Aktacir, O. Buyukalaca and T. Yilmaz, "A case study for influence of building thermal insulation on cooling load and air-conditioning system in the hot and humid regions," *Applied Energy*, vol. 87, pp. 599-607, 2010.

- [63] M. Bojic, F. Yik and W. Leung, "Thermal insulation of cooled spaces in high rise residential buildings in Hong Kong," *Energy Conversion and Management*, vol. 43, pp. 165-183, 2002.
- [64] S. Ezzeldin and S. J. Rees, "The potential for office buildings with mixed-mode ventilation and low energy cooling systems in arid climates," *Energy and Buildings*, vol. 65, pp. 368-381, 2013.
- [65] M. Alizadeh and S. M. Sadrameli, "Development of free cooling based ventilation technology for buildings: Thermal energy storage (TES) unit, performance enhancement techniques and design considerations - A review," *Renewable and Sustainable Energy Reviews*, vol. 58, pp. 619-645, 2016.
- [66] H. M. Taleb, "Using passive cooling strategies to improve thermal performance and reduce energy consumption of residential buildings in U.A.E. buildings," *Frontiers of Architectural Research*, vol. 3, pp. 154-165, 2014.
- [67] D. L. Samuel, S. S. Nagendra and M. Maiya, "Passive alternatives to mechanical air conditioning of building: A review," *Building and Environment*, vol. 66, pp. 54-64, 2013.
- [68] K. J. Chua, S. K. Chou, W. M. Yang and J. Yan, "Achieving better energy-efficient air conditioning - A review of technologies and strategies," *Applied Energy*, vol. 104, pp. 87-104, 2013.
- [69] S. Liescheidt, "Economizers in Air Handling Systems," Continuing Education and Development, Inc., Stony Point, NY.
- [70] I. M. Budaiwi, "Energy performance of the economizer cycle under three climatic conditions in Saudi Arabia," *International Journal of Ambient Energy*, vol. 22, no. 2, pp. 83-94, 2001.
- [71] T. B. David, A. Rackes and M. S. Waring, "Alternative ventilation strategies in U.S. offices: Saving energy while enhancing work performance, reducing absenteeism, and considering outdoor pollutant exposure tradeoffs," *Building and Environment*, vol. 116, pp. 140-157, 2017.

- [72] J.-H. Lee, Y.-S. Kim, J.-H. Jo, H. Cho and Y.-H. Cho, "Development of Economizer Control Method with Variable Mixed Air Temperature," *Energies*, vol. 11, p. 2445, 2018.
- [73] J. Siriwardana, S. Jayasekara and S. K. Halgamuge, "Potential of air-side economizers for data center cooling: A case study for key Australian cities," *Applied Energy*, vol. 104, pp. 207-219, 2013.
- [74] G. Wang and L. Song, "An energy performance study of several factors in air economizers with low-limit space humidity," *Energy and Buildings*, vol. 64, pp. 447-455, 2013.
- [75] O. Gozcu and H. S. Erden, "Energy and economic assessment of major free cooling retrofits for data centers in Turkey," *Turkish Journal of Electrical Engineering & Computer Sciences*, vol. 27, pp. 2197-2212, 2019.
- [76] N. R. Canada, "ARCHIVED - Economizers for Packaged Air-Conditioning Units," 15 May 2013. [Online]. Available: <https://www.nrcan.gc.ca/energy/publications/efficiency/buildings/5977#archived>. [Accessed 09 March 2019].
- [77] C. Christensen, R. Anderson, S. Horowitz, A. Courtney and J. Spencer, "BEopt Software for Building Energy Optimization: Features and Capabilities," National Renewable Energy Laboratory, Golden, USA, 2006.
- [78] "BEopt Building Energy Optimization Tool," Zymphonies, 2019. [Online]. Available: <https://beopt.nrel.gov/home>. [Accessed 7th March 2019].
- [79] M. Laslo, "Global Perspective: How Large Are Canadian Homes?," Point2, 17 February 2017. [Online]. Available: <https://www.point2homes.com/news/canada-real-estate/how-large-are-canadian-homes.html>. [Accessed 07 March 2019].
- [80] E. Wilson and S. Horowitz, "2016 Building America Housing Simulation Protocols," National Renewable Energy Laboratory, Golden, USA, 2015.
- [81] ANSI/ASHRAE Standard 62.2-2013, Ventilation for Acceptable Indoor Air Quality, Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 2013.

- [82] T. F. Stocker, D. Qin, G.-K. Plattner, M. M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley, "IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change," Cambridge University Press, Cambridge, 2013.
- [83] *United Nations Framework Convention on Climate Change, Fact sheet: The need for mitigation*, United Nations Framework Convention on Climate Change, 2009.
- [84] "IEA Data and statistics," International Energy Agency, 2020. [Online]. Available: <https://www.iea.org/data-and-statistics/data-tables?country=WORLD&energy=Balances&year=2017>. [Accessed 21 02 2020].
- [85] "International Energy Outlook 2019, with projections to 2050," U.S. Energy Information Administration, Office of Energy Analysis, U.S. Department of Energy, Washington, DC, 2019.
- [86] "2018 Global Status Report: towards a zero-emission, efficient and resilient buildings and construction sector," International Energy Agency and the United Nations Environment Programme (2018), 2018.
- [87] U.-V. Diana and N. Aleksandra, "Potentials and costs of carbon dioxide mitigation in the world's buildings," *Energy Policy*, vol. 36, pp. 642-661, 2008.
- [88] S. Yoshiyuki, Y. Yukio, O. Tomo, T. Ayako and Y. Yohei, "Prediction of greenhouse gas reduction potential in Japanese residential sector by residential energy end-use model," *Applied Energy*, vol. 87, pp. 1944-1952, 2010.
- [89] J. Laustsen, "Energy Efficiency Requirements in Building Codes, Energy Efficiency Policies for New Buildings. IEA Information Paper in Support of the G8 Plan of Action," International Energy Agency, Head of Communication and Information Office, Paris, 2008.
- [90] A. Allouhi, Y. E. Fouih, T. Kousksou, A. Jamil, Y. Zeraouli and Y. Mourad, "Energy consumption and efficiency in buildings: current status and future trends," *Journal of Cleaner Production*, vol. 109, pp. 118-130, 2015.

- [91] L. D. Boeck, S. Verbeke, A. Audenaert and L. D. Mesmeaker, "Improving the energy performance of residential buildings: A literature review," *Renewable and Sustainable Energy Reviews*, vol. 52, pp. 960-975, 2015.
- [92] "Energy Use Data Handbook, 1990-2016," Minister of Natural Resources, Canada, Ottawa ON, 2019.
- [93] "2015 Survey of Household Energy Use," [Online]. Available: <http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/sheu/2015>.
- [94] P. Nejat, F. Jomehzadeh, M. M. Taheri, M. Gohari and M. Z. A. Majid, "A global review of energy consumption, CO2 emissions and policy in the residential sector (with an overview of the top ten CO2 emitting)," *Renewable and Sustainable Energy Reviews*, vol. 43, pp. 843-862, 2015.
- [95] "Energy Step Code," Government of British Columbia, 2019. [Online]. Available: <https://energystepcode.ca/>. [Accessed 08 10 2019].
- [96] J. Glave and R. Wark, "Lessons From the BC Energy Step Code," 2019.
- [97] *GREEN BUILDINGS POLICY FOR REZONING - PROCESS AND REQUIREMENTS*, Vancouver: City of Vancouver, 2019.
- [98] "Criteria for the Passive House, EnerPHit and PHI Low Energy Building Standard," Passive House Institute, 2015.
- [99] "Census in Brief- Dwellings in Canada," Statistics Canada, Ottawa, 2017.
- [100] "Canada Mortgage and Housing Corporation Data Tables," 2019. [Online]. Available: <https://www.cmhc-schl.gc.ca/en/data-and-research/data-tables/number-households-canada-provinces-territories-1976-2036>. [Accessed 15 November 2019].
- [101] G. Doluweera, H. Hosseini and A. Sow, "Greenhouse Gas Emissions Reductions in Canada Through Electrification of Energy Services," Canadian Energy Research Institute, Calgary, Alberta, 2017.
- [102] "Households and the Environment: Energy Use 2011," Statistics Canada, Ottawa, Canada, 2013.

- [103] "Codes and Standards," NAIMA-Canada, 2019. [Online]. Available: <http://www.naimacanada.ca/codes-standards/>. [Accessed 19 November 2019].
- [104] "City Population," City Population, 2019. [Online]. Available: <https://www.citypopulation.de/php/canada-agglo.php>. [Accessed 15 November 2019].
- [105] "Natural Resource Canada," [Online]. Available: [http://oee.rncan.gc.ca/corporate/statistics/neud/dpa/data\\_e/downloads/comprehensive/Excel/2016/res\\_qc\\_16\\_e.xls](http://oee.rncan.gc.ca/corporate/statistics/neud/dpa/data_e/downloads/comprehensive/Excel/2016/res_qc_16_e.xls). [Accessed 9 December 2019].
- [106] J. Higgins, K. Wahlstrom, E. Henderson, G. Finch and T. Ely, "BC Energy Step Code- Builder Guider," BC Housing, 2018.
- [107] "Households and the Environment: Energy Use," Statistics Canada, Ottawa, 2011.
- [108] "EnergyStar Porfolio Technical Manager Technical Reference- Greenhouse Gas Emissions," Energy Star, 2019.

## Appendix- A: Additional Tables and Figures for First Study

Table A-1: Properties of each layer and composition of hypothetical suite envelope in ASHRAE Climate Zone 5

Properties	Exterior Wall	Exposed Roof	Windows	Partition Wall	Boundary Wall
<i>Construction From Inside to outside</i>	0.013 m thick Gypsum Board	0.203m thick Concrete		0.012 m thick Plaster Board	0.012m thick Plaster Board
	2x6 Steel Studs	0.076 m thick Polyurethane		0.012 m thick Plaster Board	0.066 m thick Fiber Glass Insulation
	0.025m thick Polyisocyanurate		N/A		0.203 m thick Concrete
	0.025 m thick Stucco				0.066 m thick Fiber Glass Insulation
					0.012 m thick Plaster Board
Thickness	0.063 m	0.279 m		0.024 m	0.359 m
U Value	0.361 W/m <sup>2</sup> K	0.276 W/m <sup>2</sup> K	2.54 W/m <sup>2</sup> K	3.125 W/m <sup>2</sup> K	0.265 W/m <sup>2</sup> K
SHGC Value	N/A	N/A	0.44	N/A	N/A

Table A-2: Assumed lighting, cooking, computer and other miscellaneous design power

Category	Misc. Loads	Living Room	Bed Room	Bath Room	Kitchen	Suite Entry	Corridor
Interior Lighting	<i>Design Power Density [W/m<sup>2</sup>]</i>	10	10	5	10	5	5
	<i>Convective Part [%]</i>	30	30	30	30	30	30
Cooking Equipment	<i>Design Power [W]</i>				360		
	<i>Convective Part [%]</i>				41		
Computers	<i>Design Power [W]</i>	133					
	<i>Convective Part [%]</i>	82					
Misc. Appliance	<i>Design Power Density [W/m<sup>2</sup>]</i>	3.22	3.22	3.22	3.22		
	<i>Convective Part [%]</i>	0	0	0	0		

Table A-3: Manufacturer performance data of air-to-air heat pump serving the suite in cities within climate zone 5

Key Performance Parameters	Outdoor Unit & Indoor Unit YHJD18 S41S2 & AHE18B
Rated Total Cooling Capacity [kJ/hr]	18,991
Rated Sensible Cooling Capacity [kJ/hr]	15,404
Rated Cooling Power [kJ/hr]	5,399
Rated Heating Capacity [kJ/hr]	11,711
Rated Heating Power [kJ/hr]	5,136
Rated Airflow [l/s]	288
Rated Indoor Fan Power [kJ/hr]	895
Rated Outdoor Fan Power [kJ/hr]	268
Two Stage Electrical Heater [kJ/hr]	3,240 <sup>(1)</sup>

Notes (1): Total electrical heater capacity is  $3,240 \times 2 = 6,480$  kJ/hr

Table A-4: The summary of the key performance data of the selected ventilation devices

	Without HRV		With HRV	
	Supply Air Fan	Exhaust Air Fan	Supply Air Fan	Exhaust Air Fan
Manufacturer	Greenheck		Venmar	
Equipment Mode	SP-80-VG	SP-80-VG	vanEE 40H+	
Airflow Capacity [l/s]	37.8	37.8	38	38
Static Pressure [Pa]	70	70	75	75
Rated Power [W]	6	6	37.5	37.5
Thermal Effectiveness [%]	N/A		71	

Table A-5: The summary of the ventilation airflow of each space of the hypothetical condo unit

Air Conditioned Space	Spaces within Condo Unit	Area [m <sup>2</sup> ]	Space Operating Ventilation Airflow [l/s]	Air-Conditioned Space Operating Ventilation Airflow [l/s]
BED	Bed Room	10.94	7	8
	Bed Room Closet	1.33	1	
ENCL-BALC	Enclosed Balcony	4.73	3	3
	Corridor	2.86	2	
KITCHEN	Entry	4.60	3	17
	Kitchen	12.50	8	
	Bath Room	4.32	3	
	Storage Room	3.06	2	
LIVING	Living Room	11.83	7	7

Table A-6: Properties of each layer and composition of hypothetical suite envelope in ASHRAE Climate Zone 6

Properties	Exterior Wall	Exposed Roof	Windows	Partition Wall	Boundary Wall
<i>Construction From Inside to outside</i>	0.013 m thick Gypsum Board	0.203m thick Concrete		0.012 m thick Plaster Board	0.012m thick Plaster Board
	2x6 Steel Studs	0.076 m thick Polyurethane		0.012 m thick Plaster Board	0.066 m thick Fiber Glass Insulation
	0.025m thick Polyisocyanurate		N/A		0.203 m thick Concrete
	0.025 m thick Stucco				0.066 m thick Fiber Glass Insulation
					0.012 m thick Plaster Board
Thickness	0.063 m	0.279 m		0.024 m	0.359 m
U Value	0.361 W/m <sup>2</sup> K	0.276 W/m <sup>2</sup> K	2.54 W/m <sup>2</sup> K	3.125 W/m <sup>2</sup> K	0.265 W/m <sup>2</sup> K
SHGC Value	N/A	N/A	0.44	N/A	N/A

Table A-7: Properties of each layer and composition of hypothetical suite envelope in ASHRAE Climate Zone 7

Properties	Exterior Wall	Exposed Roof	Windows	Partition Wall	Boundary Wall
Construction From Inside to outside	0.013 m thick Gypsum Board	0.203m thick Concrete		0.012 m thick Plaster Board	0.012m thick Plaster Board
	2x6 Steel Studs	0.076 m thick Polyurethane		0.012 m thick Plaster Board	0.066 m thick Fiber Glass Insulation
	0.056m thick Polyisocyanurate		N/A		0.203 m thick Concrete
	0.025 m thick Stucco				0.066 m thick Fiber Glass Insulation
					0.012 m thick Plaster Board
Thickness	0.094 m	0.279 m		0.024 m	0.359 m
U Value	0.232 W/m <sup>2</sup> K	0.276 W/m <sup>2</sup> K	2.54 W/m <sup>2</sup> K	3.125 W/m <sup>2</sup> K	0.265 W/m <sup>2</sup> K
SHGC Value	N/A	N/A	0.44	N/A	N/A

Table A-8: Key Performance Data of the Selected Air Source Heat Pump with the corresponding Electrical Supplemental Heater Serving the Suite in Different Climate Zones in Parametric Study

Performance Data	Climate Zone 5	Climate Zone 6	Climate Zone 7
Outdoor Unit Model	YHJD18 S41S2		
Indoor Unit Model	AHE18B		
Rated Total Cooling Capacity [kJ/hr]	18,991		
Rated Sensible Cooling Capacity [kJ/hr]	15,404		
Rated Cooling Power [kJ/hr]	5,399		
Rated Heating Capacity [kJ/hr]	11,711		
Rated Heating Power [kJ/hr]	5,136		
Rated Airflow [l/s]	288		
Rated Indoor Fan Power [kJ/hr]	895		
Rated Outdoor Fan Power [kJ/hr]	268		
Two Stage Electrical Heater [kJ/hr] <sup>(1)</sup>	3,240	13,860	13,860

*Notes (1): Total electrical heater capacity equals two times of the value listed in the table*

### Design heating and cooling loads

[Fig.A1](#) shows the suite area normalized design heating load. As can be seen, the colder climate in which the suite is located, the higher suite area normalized design heating load the suite has. The suite design heating load is barely affected by the building azimuth angle since it is dominated by the temperature difference between inside and outdoor design temperatures. However, Prince George and Edmonton are observed to be exceptional. Although both are located in zone 7, their design heating loads are smaller than that of Lethbridge which is located in the relatively warmer climate zone (i.e. ASHRAE Climate Zone-6). This is because the peak winter outdoor temperature obtained during the simulation for Lethbridge is much lower than that of the two aforementioned

cities although Lethbridge and the lower peak winter outdoor temperature leads greater indoor and outdoor temperature difference resulting in higher building design heating load.

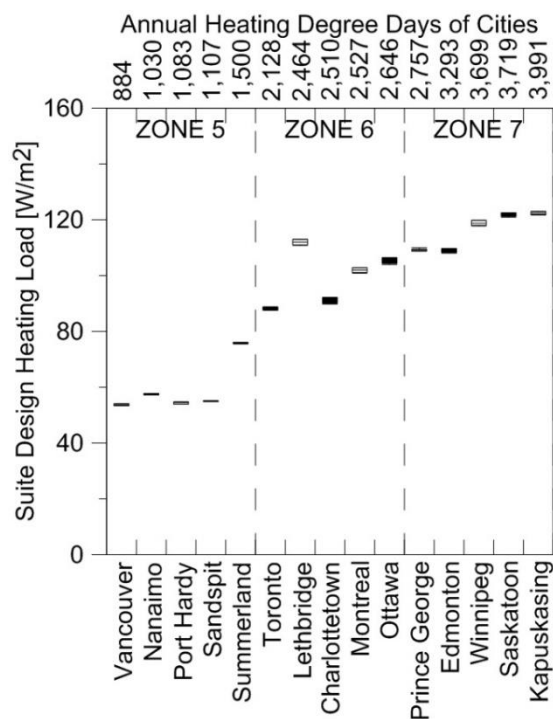


Fig. A1: Suite area normalized design heating loads for fifteen Canadian cities

Fig.A2 shows the suite area normalized design cooling loads. As shown, the suite design cooling load is sensitive to the suite's azimuth angle. The highest design cooling load of the fifteen cities is approximately 18,000 kilojoule per hour ( $321 \text{ kJ/hr/m}^2 \times 56 \text{ m}^2 = 18,000 \text{ kJ/hr}$ ) which can be handled by the smallest market available commercial model of ductable air to air heat pump.

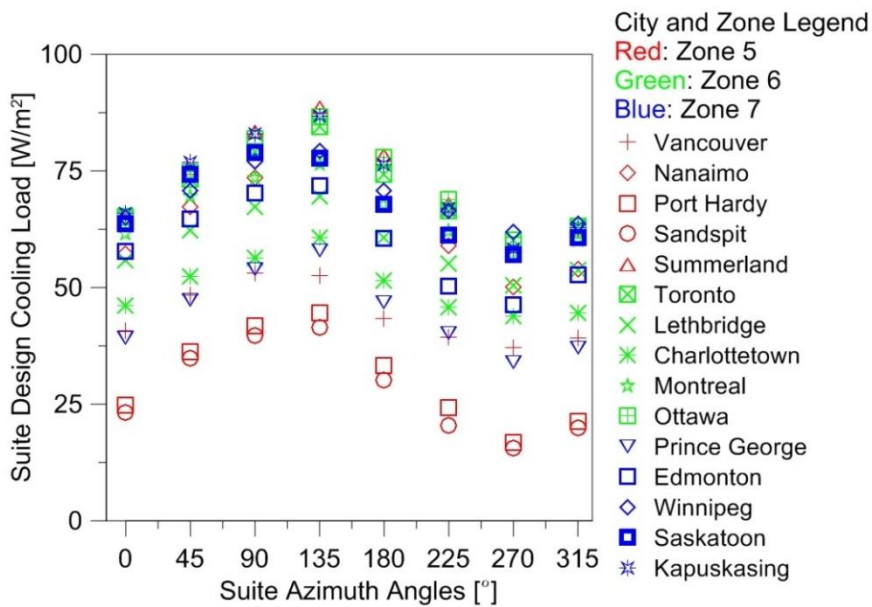


Fig. A2: Suite area normalized design cooling loads for fifteen Canadian cities

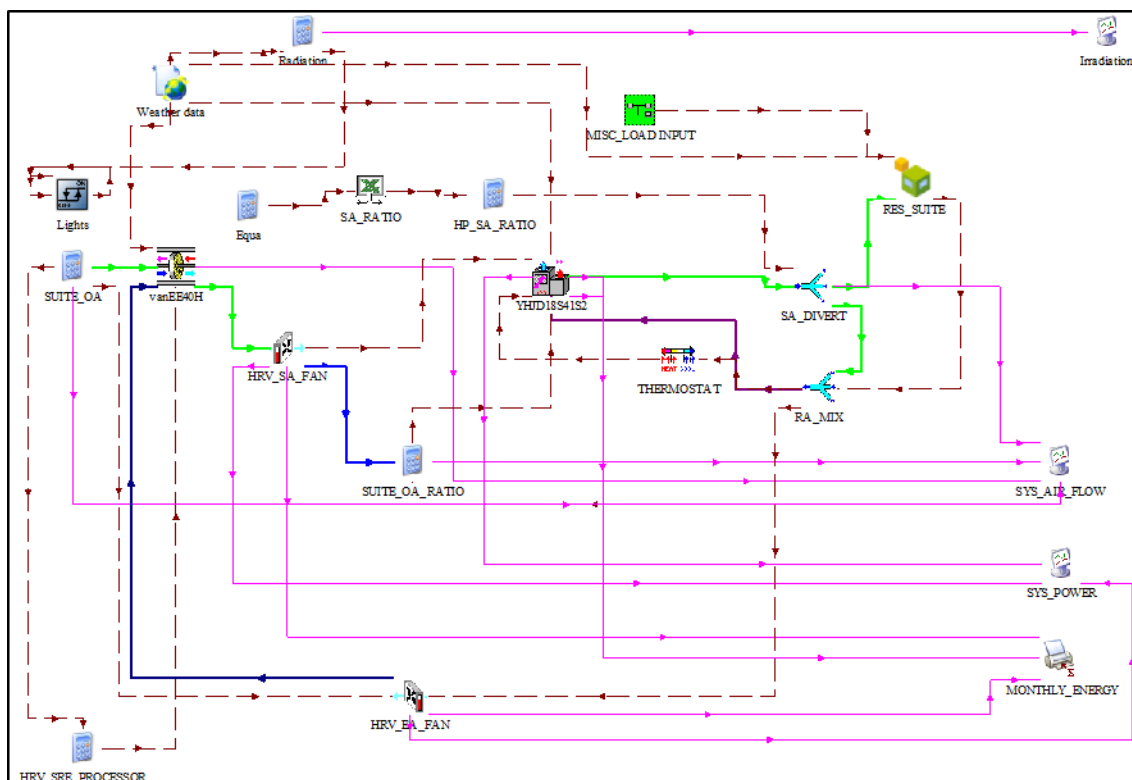


Fig. A3: TRNSYS simulation model for the heat pump coupled with HRV

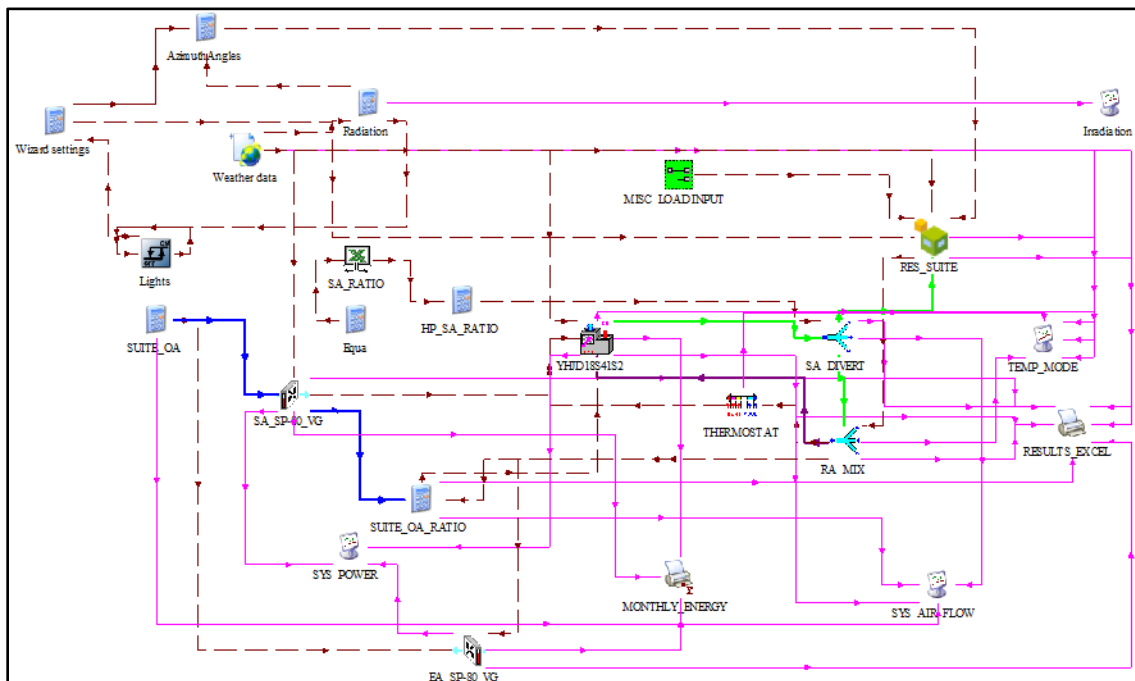


Fig. A4: TRNSYS simulation model for the heat pump coupled with balanced ventilation

Table A-9: Main TRNSYS modeling components and the key parameter settings

TRNSYS Component Type	Component Name	Key Parameters and Settings	Descriptions
Type 15	Weather Data	In *.dck file, each city's TMY-2 weather file is assigned with a unique integer number	Provided weather data in the simulation
Type 56	RES_SUITE	Heating and Cooling equipment modeled external to the Type 56; Ventilation mass flowrate, the air temperature and humidity fed by the outputs of the Type 954 via Type 646; Occupant, lighting and other gains schedules are fed from the outputs of Macro Module MISC_LOADINPUT	Used to model the thermal behavior of the suite; Refer to Table A-1, 6 and 7. for the envelope thermal properties; Refer to Table A-2 for the miscellaneous design power.

Type 954	YHJD18S41 S2	<p>Rated total cooling: 18,991 kJ/hr;  Rated sensible cooling: 15,505 kJ/hr;  Rated cooling power: 5,399 kJ/hr;  Rated heating: 11,711 kJ/hr;  Rated heating power: 5,136 kJ/hr;  Rated airflow: 288 L/s;  Rated indoor fan power: 895 kJ/hr;  Rated outdoor fan power: 268 kJ/hr;  Two stage electrical heater: 3,240 kJ/hr, 13,860 kJ/hr.</p>	<p>Used to model the heat pump performance by utilizing manufacturer's data;  The heat pump has a two-stage electrical heating element.  The built-in heating and cooling performance curves of this components are used due to the lack of sufficient data points available from the real-life heat pump.</p>
Type 108	Five stage room thermostat	<p>First stage heating set-point: 20°C;  Second stage heating set-point: 18°C;  Third stage heating set-point: 16°C;  First stage cooling set-point: 24°C;  Second stage cooling set-point: 26°C;  Temperature deadband: 2°C.</p>	<p>Used to monitor the suite return air temperature and control the heat pump;  Refer to Table 3 for the control of two stage electric heater.</p>
Type 760	VanEE40H	<p>Thermal Effectiveness: 71%;  Fresh and the exhaust air flowrate fed by outputs of HRV_EA_FAN and equation editor SUITE_OA;  The fresh air temperature and humidity fed by outputs of weather data;</p>	<p>Used to model an air-to-air sensible heat recovery core.</p>

		Exhaust air temperature and humidity fed by outputs of type 56 through HRV_EA_FAN.	
Type 744	HRV_EA_FAN HRV_SA_FAN SA_SP-80_VG EA_SP-80_VG	Rated airflow: 38 L/s Rated power 37.5 W Rated airflow: 37.8 L/s Rated power 6.0 W	Used to model the constant flow fresh and exhaust air blowers in the HRV; and the fresh air and exhaust air fans in balanced ventilation system.
Type 62	TRNSYS / Excel Coupling	Input 1: Integer indicating the city; Input 2: Integer indicating the orientation of the building.	Used to assign the ratio of the air supplied from the heat pump to each direct air-conditioned room.
Type 646	SA_DIVERT	Number of outlet ports: 4	Used to split the supply air from the heat pump into four individual streams as inputs for type 56.
Type 648	RA_MIX	Number of inlet ports: 4	Used to mix the air streams returned from each air-conditioned space into one stream.
Type 25	RESULTS_EXCEL	Inputs fed from the outputs of various components	Printed the simulation results to spreadsheet
Type 65	TEMP_MODULE SYS_AIR_FLOW SYS_POWER	Inputs fed from the outputs of various components	Displayed the selected variables during the simulation process
Type 46	MONTHLY_ENERGY	Inputs fed from the outputs of various components	Printed the heating, cooling demand and the energy uses on a monthly basis to a spreadsheet

## Appendix- B: Additional Tables and Figures for Second Study

Table B-1: Lighting, Appliance & Equipment and Miscellaneous Equipment Settings in the Model

<b>Other Equipment</b>	<b>Lighting</b>	<b>Appliance &amp; Fixtures Annual Electrical Use</b>	<b>Miscellaneous Annual Electrical Use</b>
Configurations	<ul style="list-style-type: none"> <li>• Annual lighting 1,470 kWh</li> <li>• Hard-wired light: 60% LED and 40% CFL</li> <li>• Plug-in light: 34% CFL and 66% INC</li> </ul>	<ul style="list-style-type: none"> <li>• Refrigerator: 434 kWh</li> <li>• Cooking range: 500 kWh</li> <li>• Dishwasher: 111 kWh</li> <li>• Cloth Washer: 42.9</li> <li>• Cloth dryer: 3.11b/kWh</li> <li>• DHW: 60 gallons/day</li> </ul>	<ul style="list-style-type: none"> <li>• Plug load: 2,219 kWh</li> </ul>
Schedules	Standard Lighting Profiles [80] Specified by BEopt 2.8	Standard Appliance Schedule Specified by BEopt 2.8	Standard Plug Load Schedule Specified by BEopt 2.8

Table B-2: Internal Heat Gains and HVAC System Settings in the Model

<b>HVAC Systems</b>	<b>Ventilation</b>	<b>Space Cooling</b>	<b>Space Heating</b>
Configurations	<ul style="list-style-type: none"> <li>• Air leakage: 7ACH50</li> <li>• Mechanical ventilation: 91 cfm</li> </ul>	<ul style="list-style-type: none"> <li>• 1 Stage SEER 13 air-cooled split A/C</li> <li>• Central air conditioner</li> </ul>	<ul style="list-style-type: none"> <li>• 90% AFUE gas-fired furnace</li> </ul>
Set-points/Schedule	Continuous operating	Thermostat controlled Set-point of 75°F	Thermostat controlled Set-point of 72°F

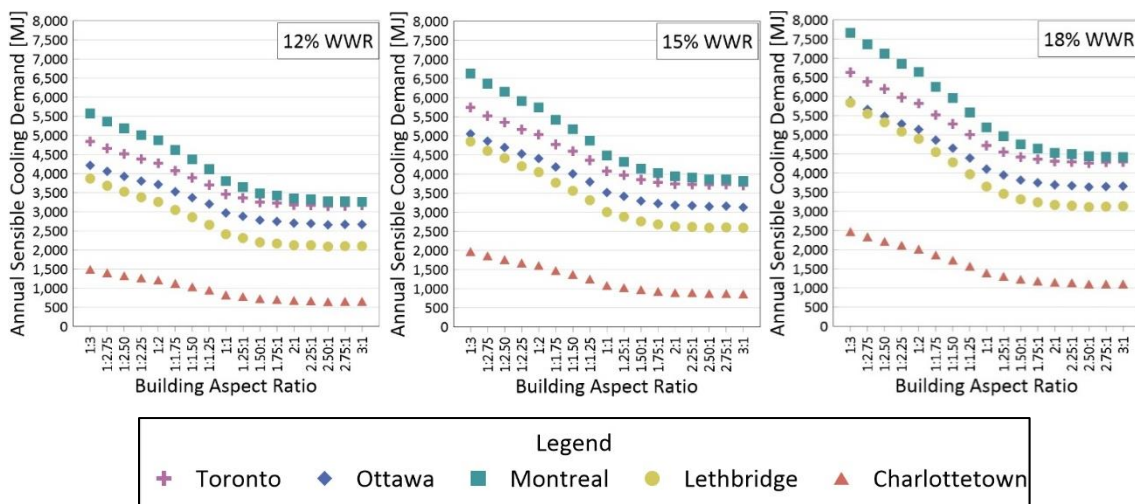


Fig. B1: The building annual cooling demand without the air-side economizer for the sing-family house with varying aspect ratio for the cities in climate zone 6 according to the window to wall ratios

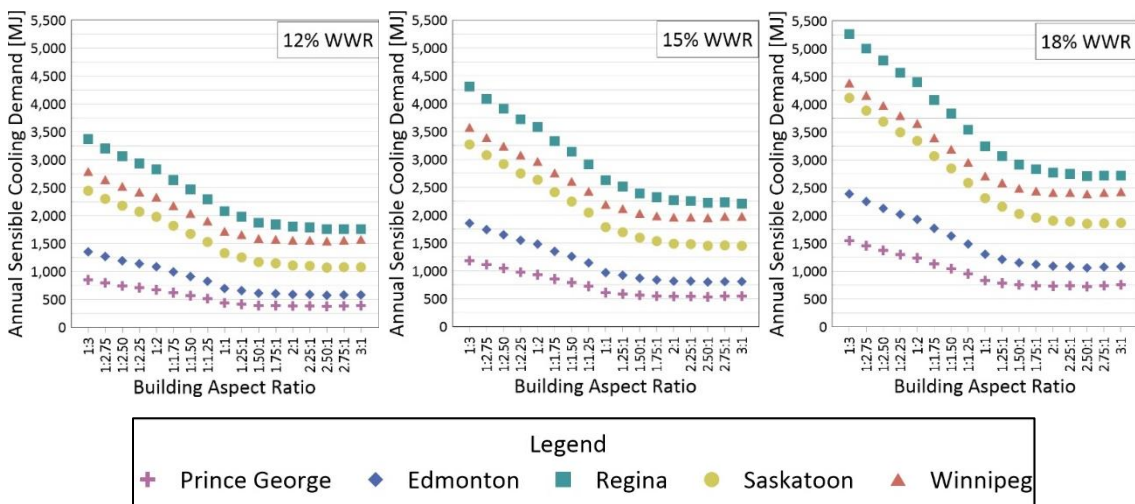


Fig. B2: The building annual cooling demand without the air-side economizer for the sing-family house with varying aspect ratio for the cities in climate zone 7 according to the window to wall ratios

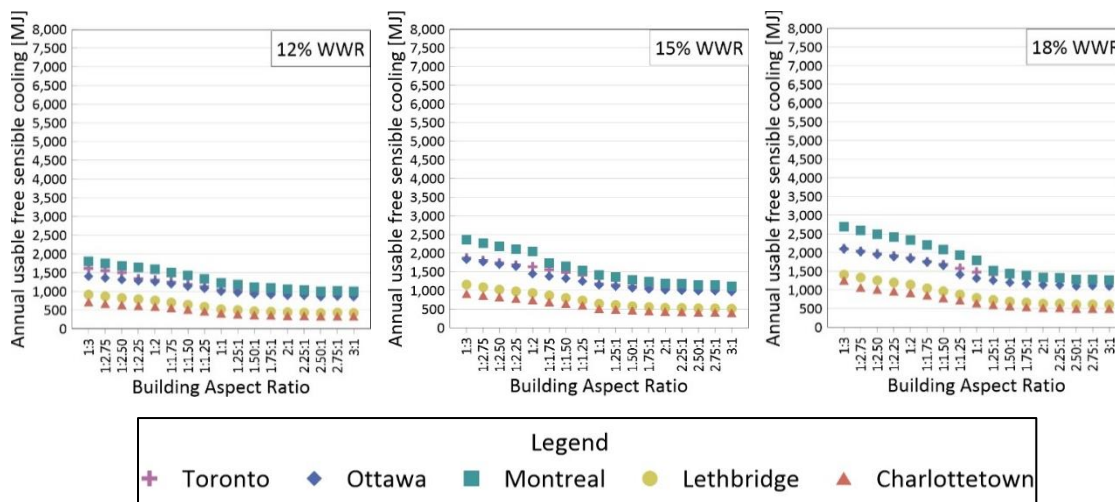


Fig. B3: The annually usable free sensible cooling for the single-family house in the Canadian cities of ASHRAE climate zone 6

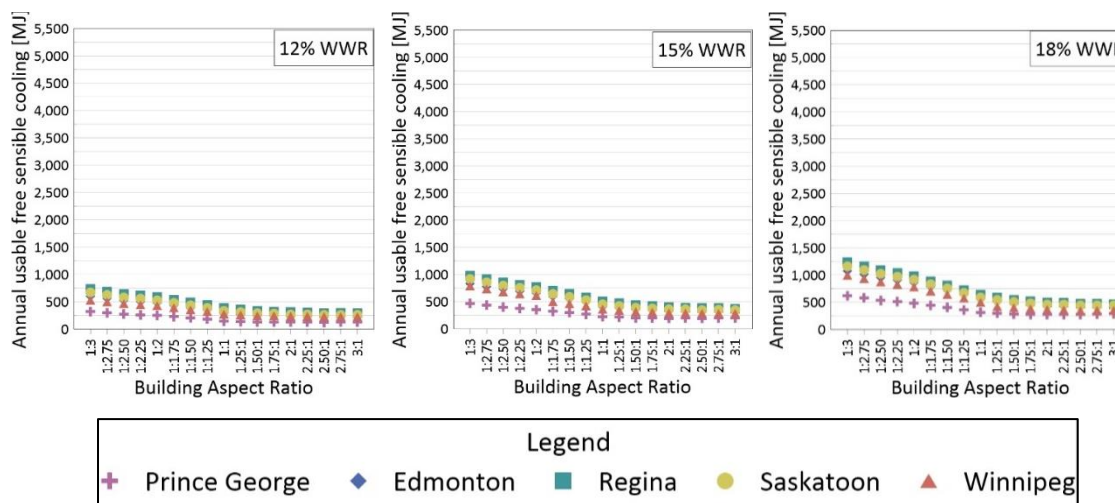


Fig. B4: The annually usable free sensible cooling for the single-family house in the Canadian cities of ASHRAE climate zone 7

Figures A-5 and A-6 show a decreasing trend of the annual usable free sensible cooling for most cities in ASHRAE climate zone 6 and 7 except for Charlottetown (in Fig. A-5) where the free cooling potential is slightly increasing in the 12% WWR scenario and is not sensitive to the building cooling aspect ratio in both 15% and 18% WWR scenarios.

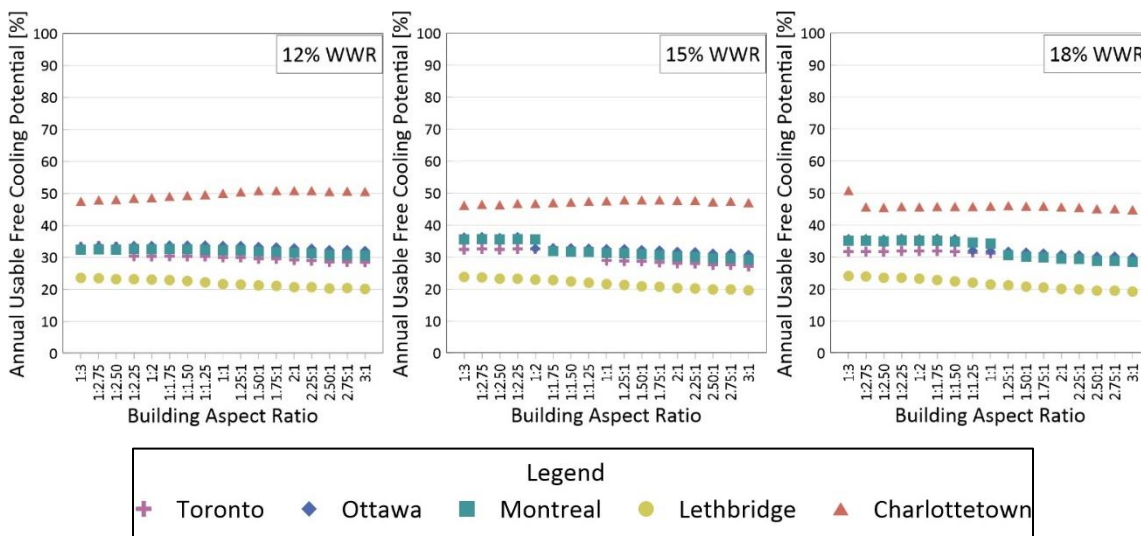


Fig. B5: The annually usable free sensible cooling potential in percentage of the annual building cooling demand for the selected cities in ASHRAE climate zone 6

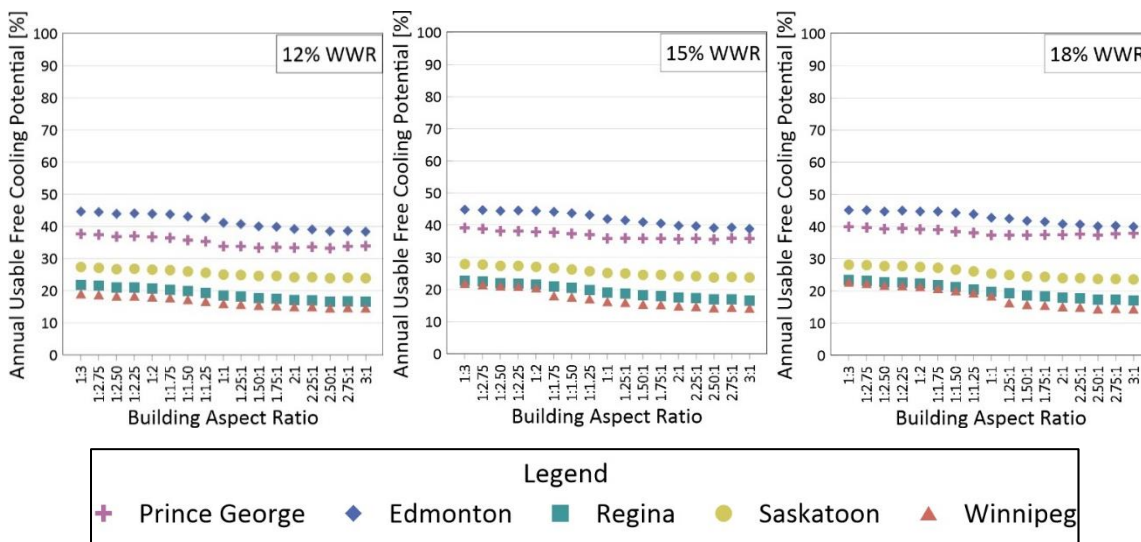


Fig. B6: The annually usable free sensible cooling potential in percentage of the annual building cooling demand for the selected cities in ASHRAE climate zone 7

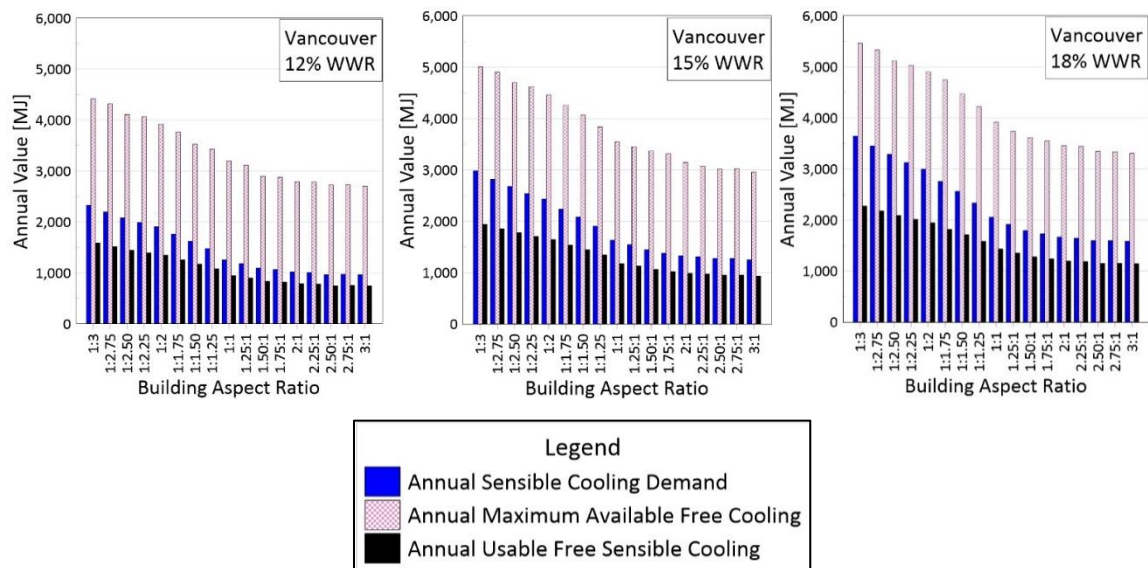


Fig. B7: Comparison of Annual Cooling Demand, Annual Maximum Available Free Cooling and the Annual Usable Free Cooling of the Hypothetical Single-Family House in Vancouver

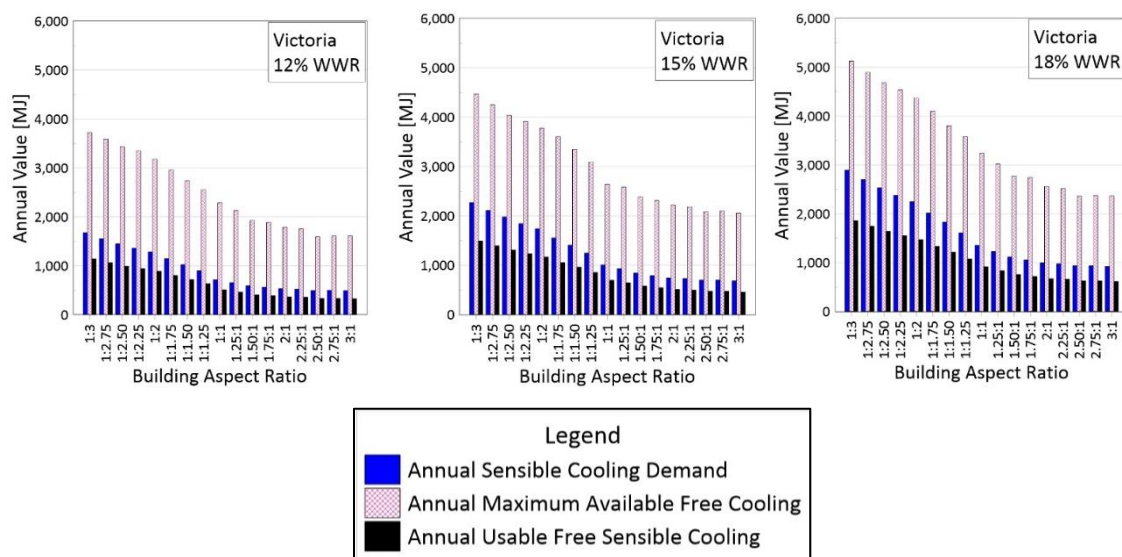


Fig. B8: Comparison of Annual Cooling Demand, Annual Maximum Available Free Cooling and the Annual Usable Free Cooling of the Hypothetical Single-Family House in Victoria

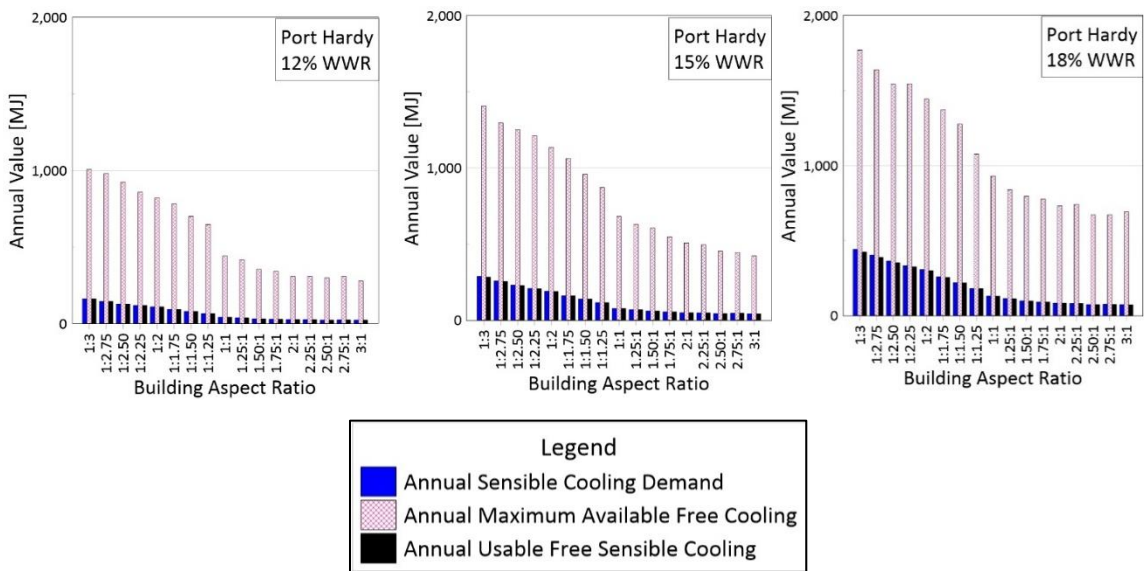


Fig. B9: Comparison of Annual Cooling Demand, Annual Maximum Available Free Cooling and the Annual Usable Free Cooling of the Hypothetical Single-Family House in Port Hardy

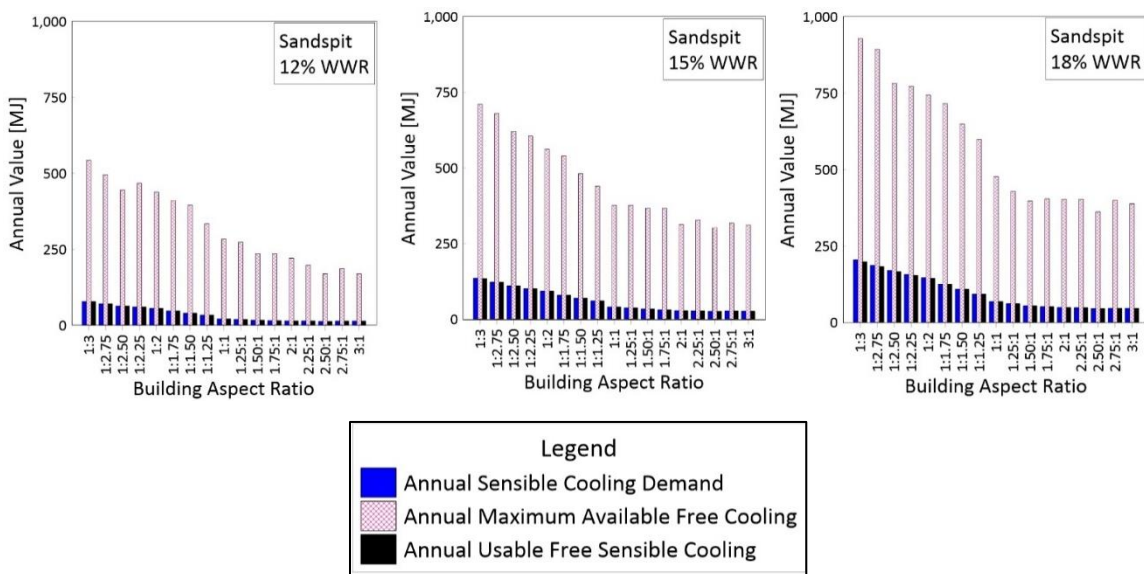


Fig. B10: Comparison of Annual Cooling Demand, Annual Maximum Available Free Cooling and the Annual Usable Free Cooling of the Hypothetical Single-Family House in Sandspit

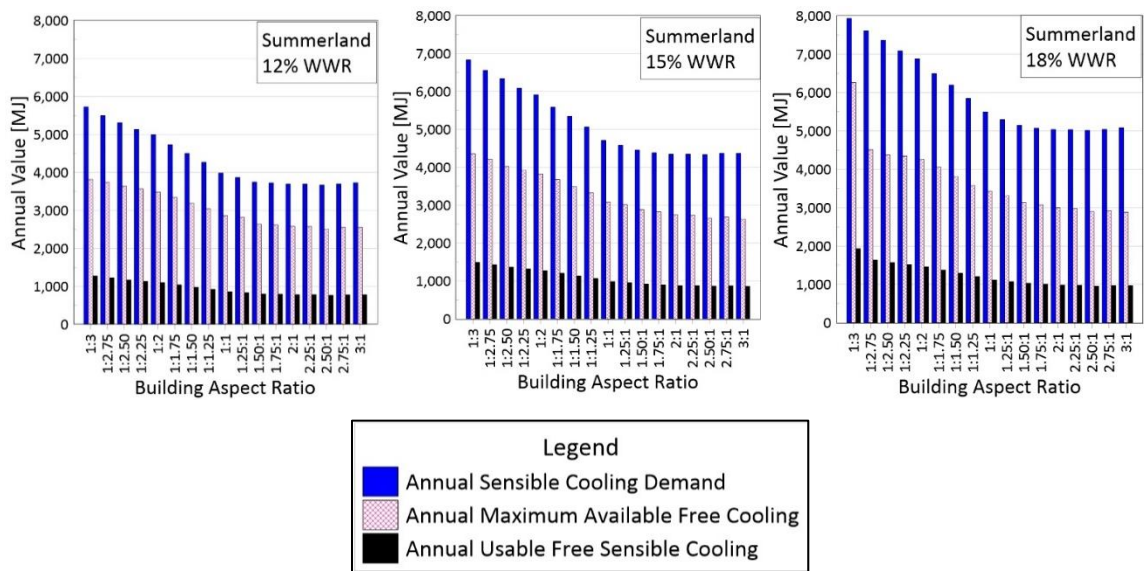


Fig. B11: Comparison of Annual Cooling Demand, Annual Maximum Available Free Cooling and the Annual Usable Free Cooling of the Hypothetical Single-Family House in Summerland

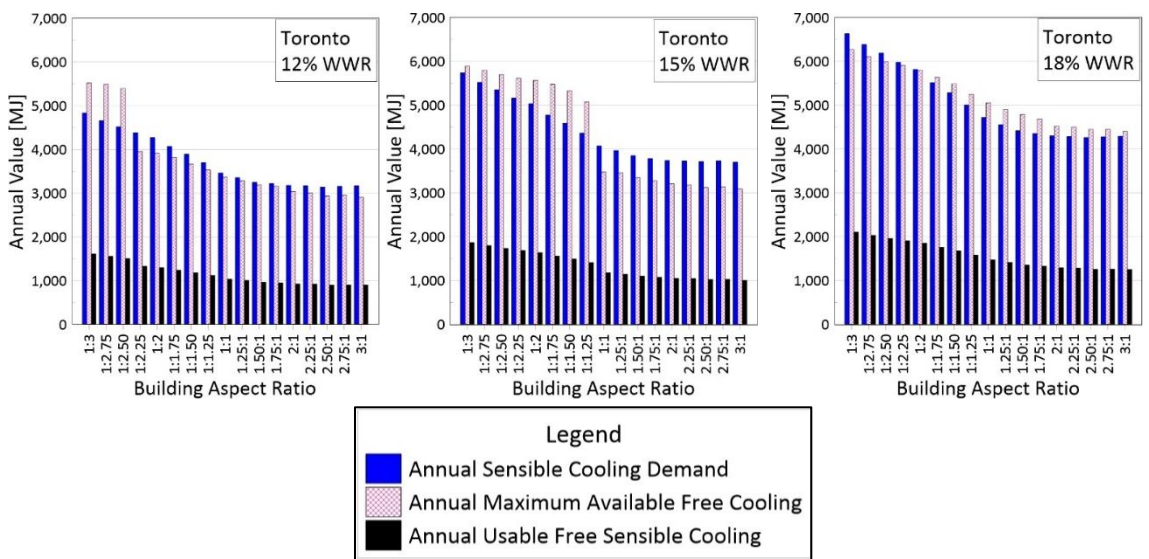


Fig. B12: Comparison of Annual Cooling Demand, Annual Maximum Available Free Cooling and the Annual Usable Free Cooling of the Hypothetical Single-Family House in Toronto

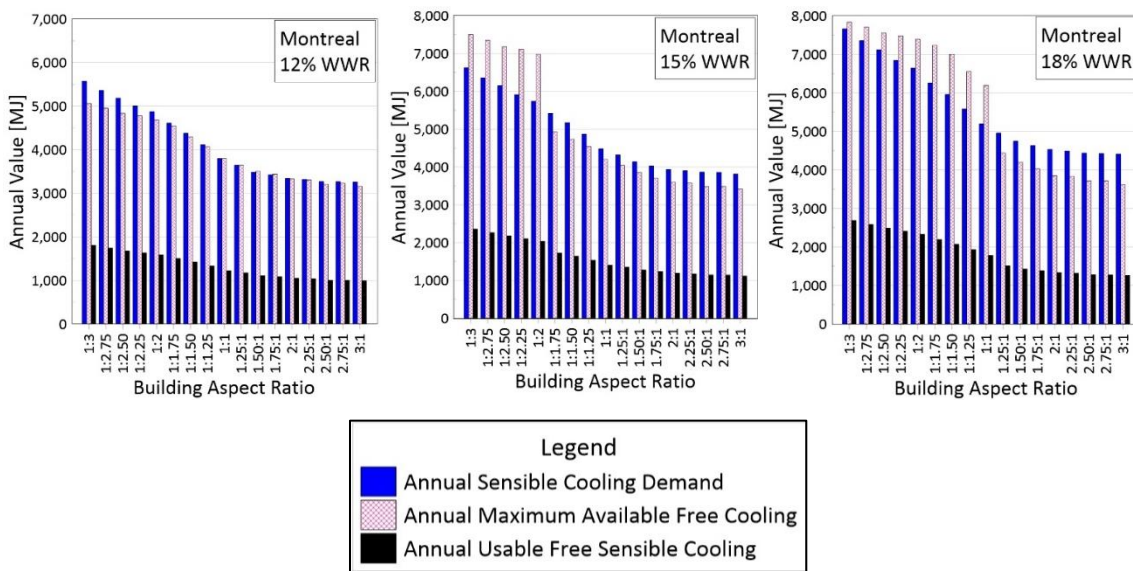


Fig. B13: Comparison of Annual Cooling Demand, Annual Maximum Available Free Cooling and the Annual Usable Free Cooling of the Hypothetical Single-Family House in Montreal

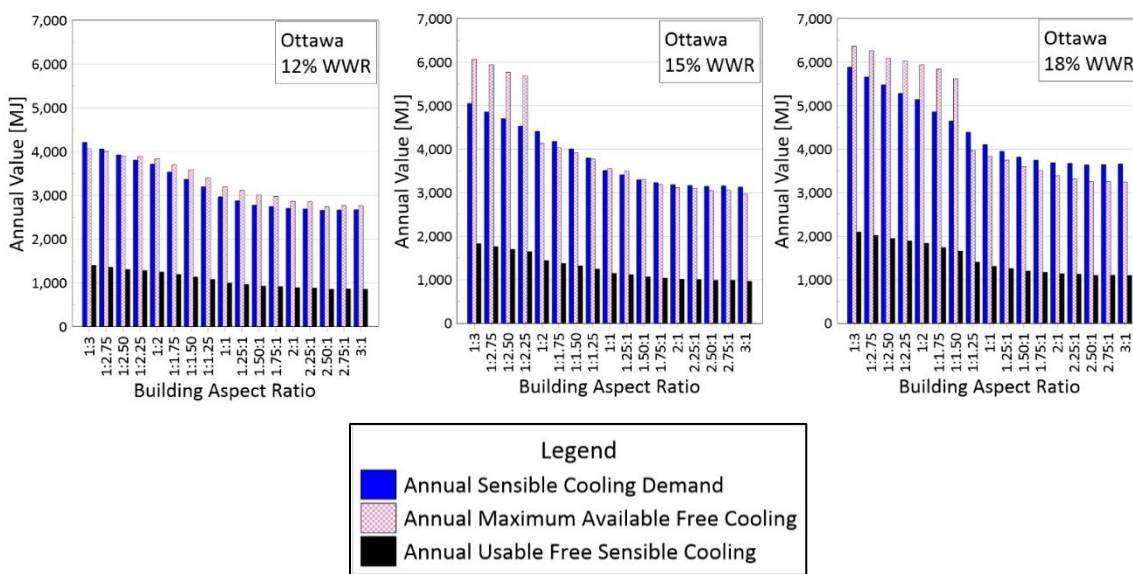


Fig. B14: Comparison of Annual Cooling Demand, Annual Maximum Available Free Cooling and the Annual Usable Free Cooling of the Hypothetical Single-Family House in Ottawa

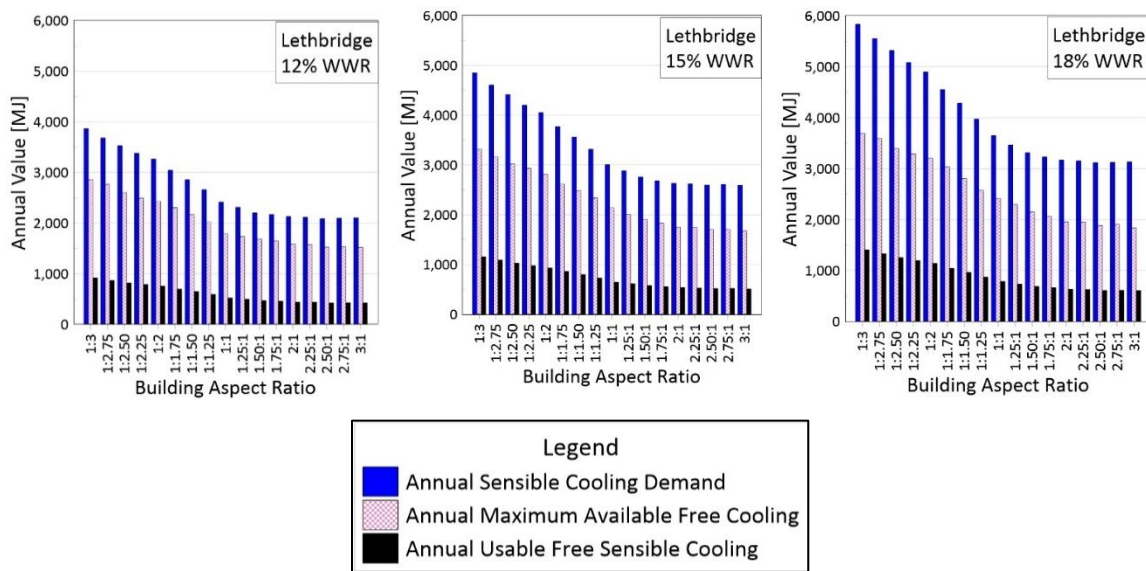


Fig. B15: Comparison of Annual Cooling Demand, Annual Maximum Available Free Cooling and the Annual Usable Free Cooling of the Hypothetical Single-Family House in Lethbridge

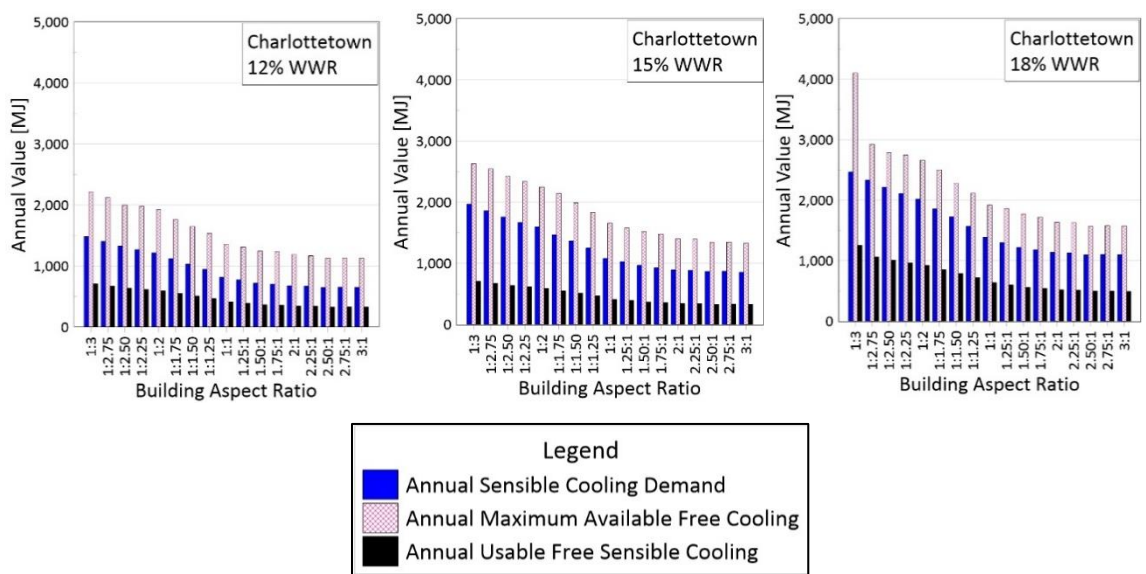


Fig. B16: Comparison of Annual Cooling Demand, Annual Maximum Available Free Cooling and the Annual Usable Free Cooling of the Hypothetical Single-Family House in Charlottetown

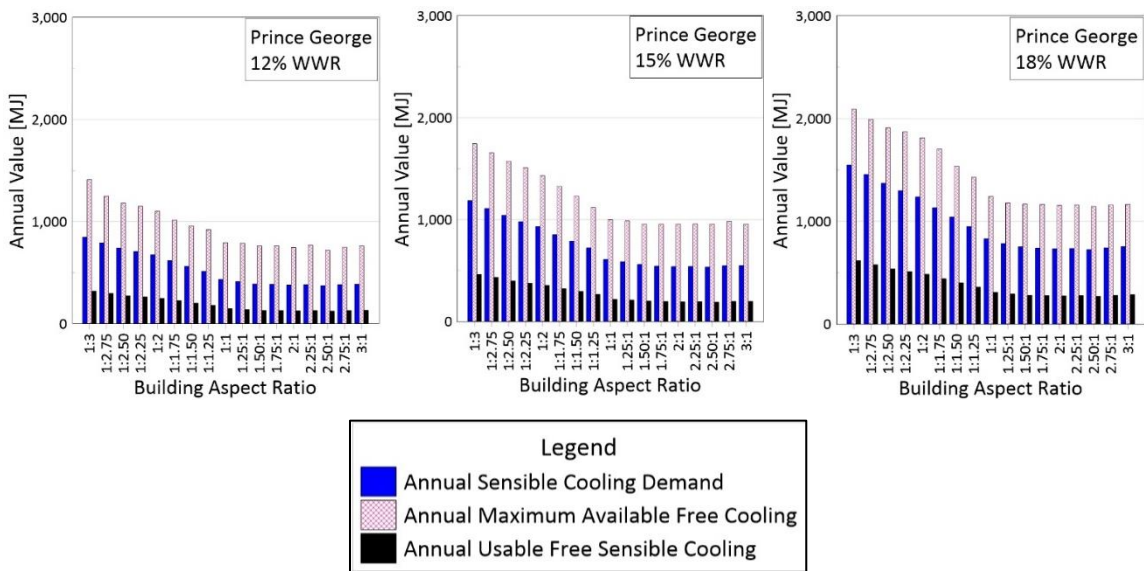


Fig. B17: Comparison of Annual Cooling Demand, Annual Maximum Available Free Cooling and the Annual Usable Free Cooling of the Hypothetical Single-Family House in Prince George

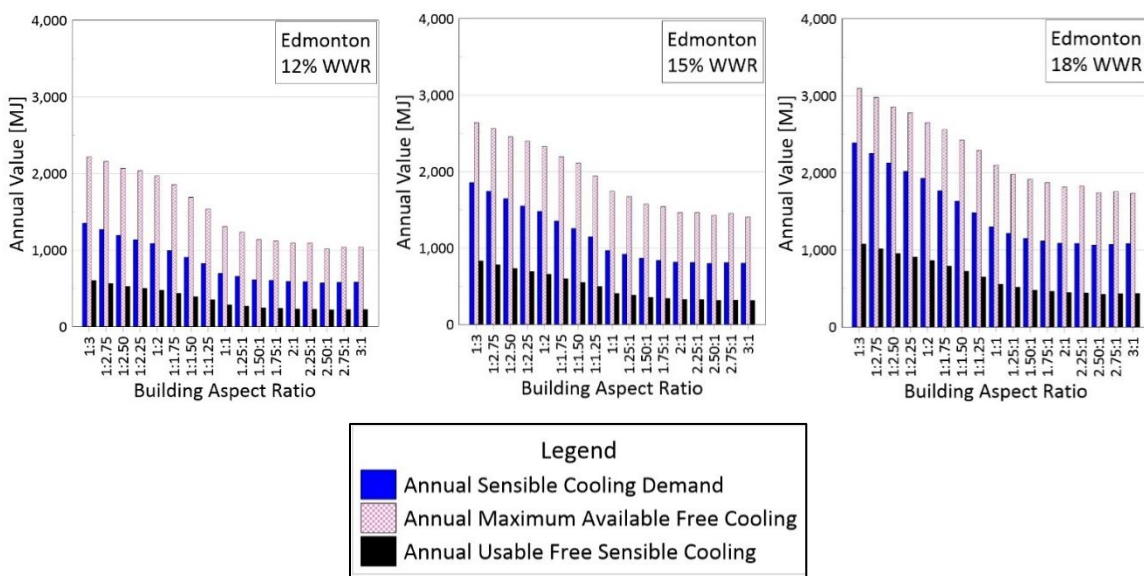


Fig. B18: Comparison of Annual Cooling Demand, Annual Maximum Available Free Cooling and the Annual Usable Free Cooling of the Hypothetical Single-Family House in Edmonton

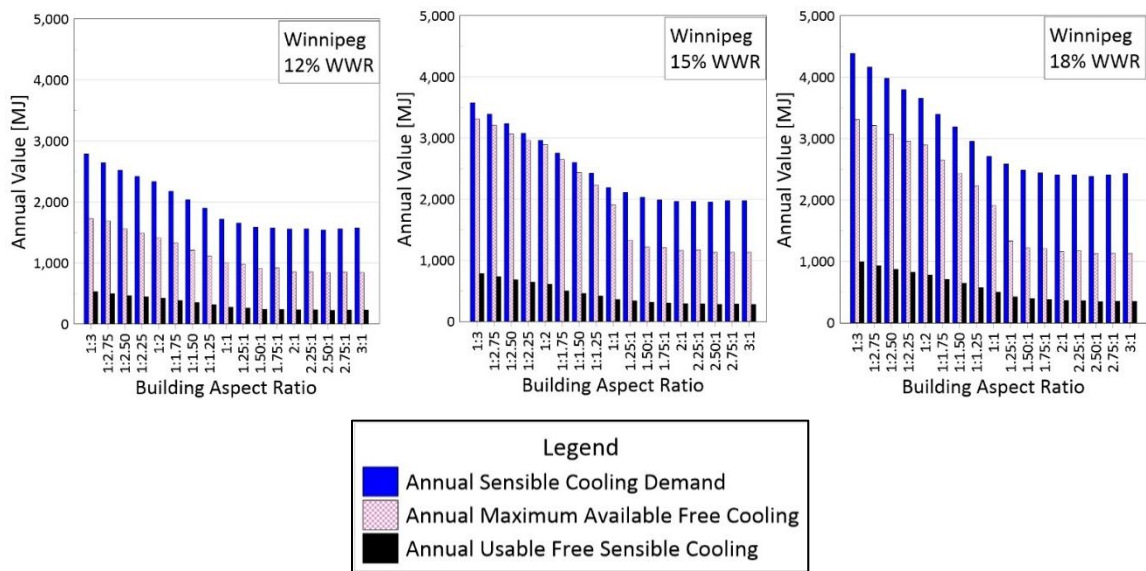


Fig. B19: Comparison of Annual Cooling Demand, Annual Maximum Available Free Cooling and the Annual Usable Free Cooling of the Hypothetical Single-Family House in Winnipeg

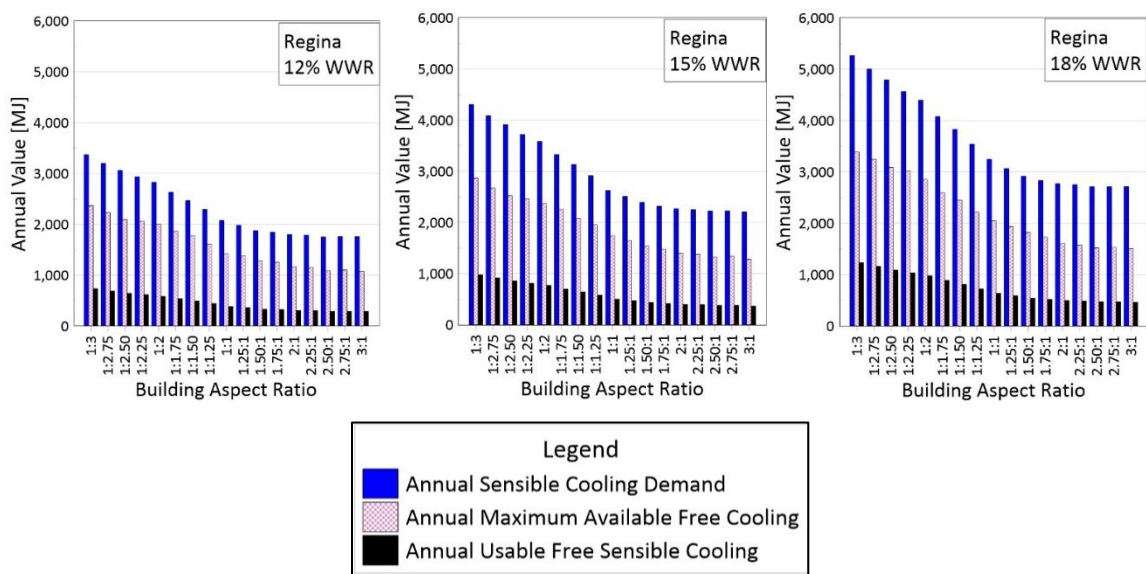


Fig. B20: Comparison of Annual Cooling Demand, Annual Maximum Available Free Cooling and the Annual Usable Free Cooling of the Hypothetical Single-Family House in Regina

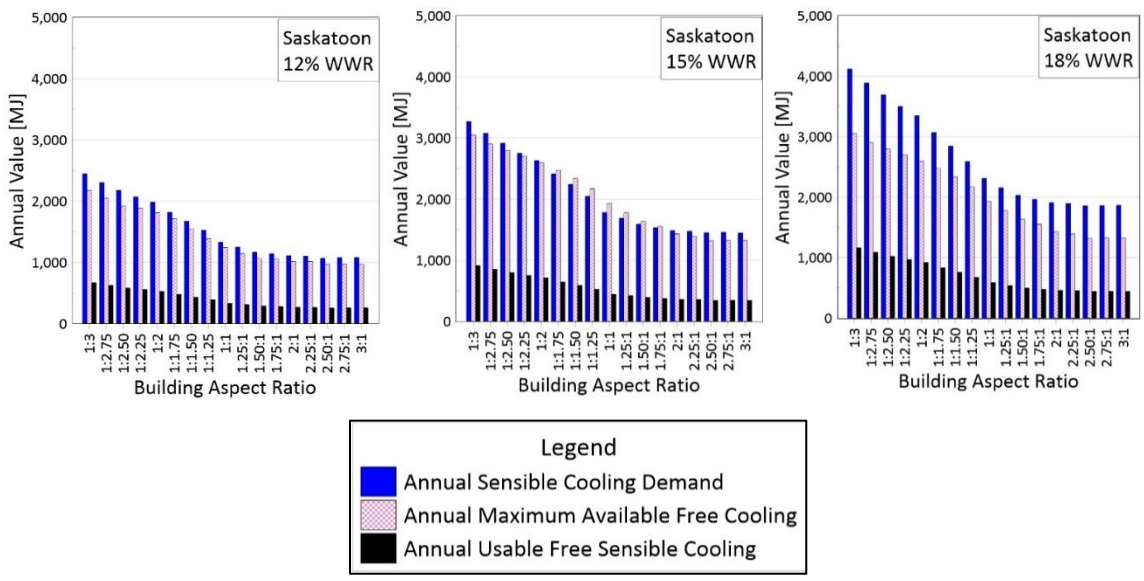


Fig. B21: Comparison of Annual Cooling Demand, Annual Maximum Available Free Cooling and the Annual Usable Free Cooling of the Hypothetical Single-Family House in Saskatoon

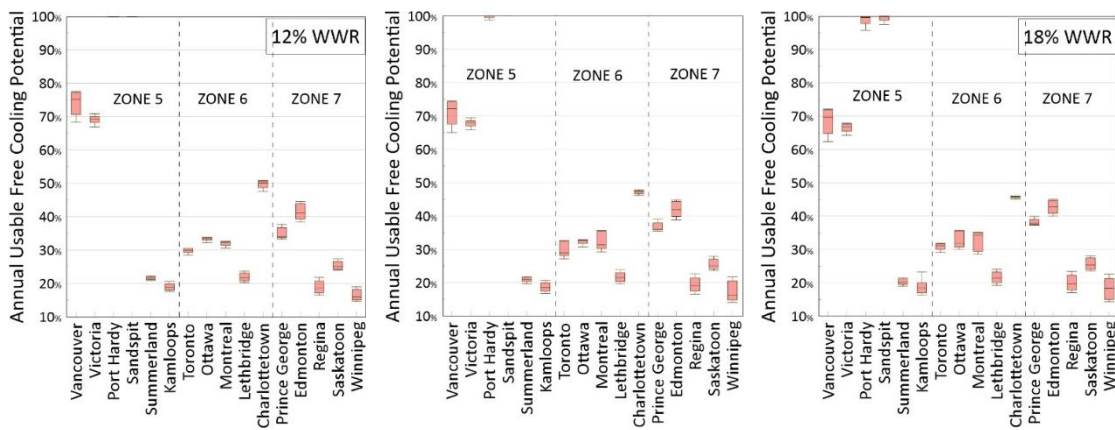


Fig. B22: Comparison of Annual Usable Free Sensible Cooling Potential in the Sixteen Canadian Cities

## Appendix- C: Additional Tables for Third Study

Table C-1: Forecasted overall residential housing stocks in Newfoundland ( $\times 1,000$ ), 2016-2036 [100]

Headship rate scenario	Population growth scenario							
	Year	High growth	Medium growth 1	Medium growth 2	Medium growth 3	Medium growth 4	Medium growth 5	Low growth
High	2016	221	221	220	221	221	225	221
	2021	227	225	222	225	224	235	224
	2026	229	226	220	226	223	242	223
	2031	228	223	216	224	220	246	220
	2036	226	218	208	219	214	248	213
Medium	2016	217	217	216	217	216	220	217
	2021	220	218	215	218	217	226	217
	2026	220	216	211	216	214	231	214
	2031	217	212	205	213	210	234	209
	2036	213	206	197	207	202	234	201
Low	2016	213	213	212	213	212	216	212
	2021	212	211	207	211	209	219	209
	2026	209	207	202	207	205	221	205
	2031	206	202	195	202	199	222	198
	2036	201	194	185	195	191	220	190

Table C-2: Forecasted overall residential housing stocks in Prince Edward Island ( $\times 1,000$ ), 2016-2036 [100]

Headship rate scenario	Population growth scenario							
	Year	High growth	Medium growth 1	Medium growth 2	Medium growth 3	Medium growth 4	Medium growth 5	Low growth
High	2016	62	62	63	62	62	62	62
	2021	68	67	68	68	66	67	66
	2026	73	72	73	72	69	72	70
	2031	79	76	77	77	72	76	72
	2036	84	79	81	81	74	79	74
Medium	2016	61	61	61	61	61	61	61
	2021	66	65	66	65	64	65	64
	2026	70	69	69	69	66	68	67
	2031	75	72	73	73	68	72	68
	2036	79	75	77	76	70	75	70
Low	2016	60	60	60	60	59	60	60
	2021	64	63	63	63	62	63	62
	2026	67	65	66	66	63	65	64
	2031	70	68	69	69	64	68	65
	2036	74	70	72	71	65	70	65

Table C-3: Forecasted overall residential housing stocks in Nova Scotia ( $\times 1,000$ ), 2016-2036 [100]

Headship rate scenario	Population growth scenario							
	Year	High growth	Medium growth 1	Medium growth 2	Medium growth 3	Medium growth 4	Medium growth 5	Low growth
High	2016	418	417	417	417	415	418	416
	2021	436	433	434	434	426	437	430
	2026	451	444	446	446	432	450	437
	2031	462	450	454	454	434	459	440
	2036	470	453	457	457	432	465	438
Medium	2016	409	408	409	409	406	409	407
	2021	421	417	419	419	411	421	414
	2026	430	423	425	425	412	429	417
	2031	436	425	428	428	410	433	415
	2036	441	424	428	429	405	436	411
Low	2016	399	399	399	399	396	400	398
	2021	403	400	401	401	394	403	397
	2026	405	398	400	400	388	404	393
	2031	405	394	397	397	380	402	385
	2036	404	389	392	393	371	399	376

Table C-4: Forecasted overall residential housing stocks in New Brunswick ( $\times 1,000$ ), 2016-2036 [100]

Headship rate scenario	Population growth scenario							
	Year	High growth	Medium growth 1	Medium growth 2	Medium growth 3	Medium growth 4	Medium growth 5	Low growth
High	2016	331	330	330	330	329	331	329
	2021	345	343	343	343	339	346	341
	2026	356	351	352	351	344	356	347
	2031	365	356	358	356	346	364	349
	2036	371	358	361	358	345	368	348
Medium	2016	323	323	323	323	322	324	322
	2021	333	330	331	330	326	333	328
	2026	340	335	336	335	328	340	331
	2031	344	336	338	336	327	343	330
	2036	347	335	337	335	323	344	325
Low	2016	315	315	315	315	314	316	314
	2021	318	316	317	316	312	319	314
	2026	320	315	316	315	309	320	311
	2031	320	312	314	312	304	319	306
	2036	317	307	309	307	295	315	298

Table C-5: Forecasted overall residential housing stocks in Quebec ( $\times 1,000$ ), 2016-2036  
[100]

Headship rate scenario	Population growth scenario							
	Year	High growth	Medium growth 1	Medium growth 2	Medium growth 3	Medium growth 4	Medium growth 5	Low growth
High	2016	3,696	3,689	3,684	3,691	3,689	3,696	3,676
	2021	3,908	3,871	3,856	3,879	3,870	3,892	3,825
	2026	4,096	4,012	3,988	4,026	4,009	4,048	3,918
	2031	4,275	4,137	4,103	4,157	4,131	4,189	3,987
	2036	4,455	4,254	4,209	4,281	4,244	4,323	4,038
Medium	2016	3,643	3,636	3,631	3,639	3,636	3,643	3,623
	2021	3,814	3,778	3,764	3,786	3,777	3,799	3,734
	2026	3,971	3,890	3,867	3,903	3,887	3,925	3,799
	2031	4,125	3,992	3,959	4,011	3,986	4,041	3,847
	2036	4,278	4,085	4,042	4,111	4,075	4,151	3,878
Low	2016	3,590	3,583	3,578	3,586	3,583	3,590	3,571
	2021	3,721	3,686	3,672	3,693	3,684	3,706	3,642
	2026	3,846	3,768	3,745	3,781	3,765	3,801	3,680
	2031	3,974	3,846	3,814	3,865	3,841	3,894	3,707
	2036	4,101	3,916	3,875	3,941	3,907	3,980	3,718

Table C-6: Forecasted overall residential housing stocks in Ontario ( $\times 1,000$ ), 2016-2036  
[100]

Headship rate scenario	Population growth scenario							
	Year	High growth	Medium growth 1	Medium growth 2	Medium growth 3	Medium growth 4	Medium growth 5	Low growth
High	2016	5,453	5,434	5,437	5,450	5,421	5,433	5,403
	2021	5,884	5,799	5,810	5,847	5,760	5,800	5,694
	2026	6,310	6,125	6,144	6,210	6,055	6,127	5,913
	2031	6,725	6,423	6,450	6,551	6,319	6,428	6,086
	2036	7,135	6,698	6,733	6,872	6,554	6,706	6,216
Medium	2016	5,385	5,365	5,369	5,381	5,353	5,365	5,335
	2021	5,760	5,677	5,688	5,725	5,639	5,678	5,575
	2026	6,133	5,954	5,972	6,037	5,886	5,956	5,749
	2031	6,499	6,209	6,235	6,332	6,108	6,214	5,884
	2036	6,860	6,441	6,475	6,609	6,303	6,450	5,980
Low	2016	5,317	5,297	5,301	5,313	5,285	5,297	5,268
	2021	5,636	5,556	5,567	5,602	5,519	5,556	5,456
	2026	5,956	5,783	5,800	5,863	5,717	5,785	5,585
	2031	6,274	5,995	6,019	6,113	5,898	5,999	5,682
	2036	6,586	6,185	6,217	6,346	6,053	6,193	5,743

Table C-7: Forecasted overall residential housing stocks in Manitoba ( $\times 1,000$ ), 2016-2036 [100]

Headship rate scenario	Population growth scenario							
	Year	High growth	Medium growth 1	Medium growth 2	Medium growth 3	Medium growth 4	Medium growth 5	Low growth
High	2016	518	517	516	517	515	519	515
	2021	562	556	555	557	550	563	547
	2026	610	594	592	597	584	607	575
	2031	660	633	630	637	618	652	600
	2036	714	673	668	678	652	700	624
Medium	2016	504	503	503	504	502	505	501
	2021	539	533	532	535	528	539	525
	2026	579	564	562	566	555	576	545
	2031	620	595	592	599	581	613	564
	2036	666	628	623	633	608	653	582
Low	2016	500	498	498	499	497	500	496
	2021	531	525	524	526	520	531	517
	2026	568	553	551	556	544	564	535
	2031	606	582	579	585	568	599	551
	2036	648	612	607	616	593	636	567

Table C-8: Forecasted overall residential housing stocks in Saskatchewan ( $\times 1,000$ ), 2016-2036 [100]

Headship rate scenario	Population growth scenario							
	Year	High growth	Medium growth 1	Medium growth 2	Medium growth 3	Medium growth 4	Medium growth 5	Low growth
High	2016	465	464	463	459	466	471	463
	2021	500	495	490	480	500	516	489
	2026	537	525	516	499	533	563	512
	2031	576	556	542	518	569	613	535
	2036	617	588	568	536	605	667	556
Medium	2016	459	458	456	453	459	464	456
	2021	487	482	477	468	486	502	476
	2026	517	506	497	481	514	542	493
	2031	549	531	517	495	543	585	510
	2036	584	556	538	507	573	631	526
Low	2016	455	454	452	449	456	461	453
	2021	480	475	470	461	479	495	469
	2026	506	495	486	471	503	530	483
	2031	534	516	503	481	528	568	496
	2036	563	537	519	490	553	608	508

Table C-9: Forecasted overall residential housing stocks in Alberta (×1,000), 2016-2036  
[100]

Headship rate scenario	Population growth scenario							
	Year	High growth	Medium growth 1	Medium growth 2	Medium growth 3	Medium growth 4	Medium growth 5	Low growth
High	2016	1,725	1,719	1,715	1,723	1,736	1,702	1,709
	2021	1,981	1,954	1,941	1,967	2,009	1,904	1,921
	2026	2,260	2,198	2,175	2,222	2,296	2,107	2,128
	2031	2,552	2,447	2,413	2,484	2,598	2,310	2,329
	2036	2,867	2,709	2,659	2,760	2,920	2,516	2,529
Medium	2016	1,681	1,676	1,672	1,680	1,693	1,660	1,667
	2021	1,898	1,873	1,861	1,885	1,924	1,825	1,841
	2026	2,136	2,077	2,055	2,099	2,169	1,991	2,011
	2031	2,389	2,291	2,259	2,325	2,430	2,162	2,181
	2036	2,664	2,517	2,471	2,565	2,713	2,339	2,351
Low	2016	1,638	1,633	1,629	1,637	1,649	1,617	1,624
	2021	1,816	1,791	1,780	1,803	1,840	1,745	1,761
	2026	2,011	1,956	1,936	1,977	2,042	1,875	1,894
	2031	2,225	2,134	2,105	2,166	2,263	2,015	2,032
	2036	2,461	2,326	2,284	2,370	2,506	2,162	2,173

Table C-10: Forecasted overall residential housing stocks in Yukon (×1,000), 2016-2036  
[100]

Headship rate scenario	Population growth scenario							
	Year	High growth	Medium growth 1	Medium growth 2	Medium growth 3	Medium growth 4	Medium growth 5	Low growth
High	2016	16.7	16.7	16.2	16.4	17.0	17.4	16.6
	2021	18.3	18.1	16.9	17.3	19.1	20.3	17.8
	2026	19.7	19.2	17.2	17.8	21.0	23.1	18.6
	2031	20.9	20.1	17.3	18.1	22.8	26.1	19.2
	2036	22.1	20.9	17.3	18.3	24.4	29.2	19.5
Medium	2016	16.1	16.1	15.7	15.8	16.5	16.8	16.0
	2021	17.3	17.1	16.0	16.4	18.1	19.2	16.8
	2026	18.4	17.9	16.0	16.7	19.7	21.6	17.4
	2031	19.3	18.6	16.0	16.8	21.1	24.1	17.7
	2036	20.2	19.1	15.8	16.7	22.3	26.7	17.9
Low	2016	15.8	15.7	15.3	15.5	16.1	16.4	15.7
	2021	16.7	16.5	15.4	15.8	17.5	18.5	16.2
	2026	17.5	17.1	15.3	15.9	18.8	20.6	16.6
	2031	18.3	17.6	15.1	15.9	20.0	22.8	16.8
	2036	19.0	17.9	14.8	15.7	21.0	25.1	16.8

Table C-11: Forecasted overall residential housing stocks in Northwest Territories  
(×1,000), 2016-2036 [100]

Headship rate scenario	Population growth scenario							
	Year	High growth	Medium growth 1	Medium growth 2	Medium growth 3	Medium growth 4	Medium growth 5	Low growth
High	2016	16	16	16	16	16	16	16
	2021	17	17	16	17	16	17	17
	2026	17	17	16	18	16	18	17
	2031	18	17	16	18	16	19	17
	2036	18	17	16	19	15	19	17
Medium	2016	16	16	16	16	16	16	16
	2021	16	16	16	17	16	17	16
	2026	17	16	16	17	16	17	16
	2031	17	16	16	18	15	18	16
	2036	17	16	15	18	15	18	16
Low	2016	16	16	16	16	16	16	16
	2021	16	16	15	16	15	16	16
	2026	16	16	15	17	15	17	16
	2031	16	16	15	17	14	17	15
	2036	16	15	15	17	14	17	15

Table C-12: Forecasted overall residential housing stocks in Nunavut (×1,000), 2016-2036 [100]

Headship rate scenario	Population growth scenario							
	Year	High growth	Medium growth 1	Medium growth 2	Medium growth 3	Medium growth 4	Medium growth 5	Low growth
High	2016	11	11	11	11	11	11	11
	2021	12	12	12	12	12	13	12
	2026	13	13	13	13	12	14	13
	2031	14	14	13	14	13	16	13
	2036	15	14	14	15	14	17	14
Medium	2016	11	10	10	11	10	11	10
	2021	11	11	11	11	11	12	11
	2026	12	12	12	12	11	13	12
	2031	13	12	12	13	12	14	12
	2036	13	13	13	14	12	16	13
Low	2016	10	10	10	10	10	11	10
	2021	11	11	11	11	10	12	11
	2026	11	11	11	11	11	13	11
	2031	12	12	11	12	11	14	11
	2036	12	12	12	13	11	15	12

Table C-13: Forecasted housing stocks in Newfoundland (×1,000), 2020-2032

Headship rate scenario	Population growth scenario							
	Year	High growth	Medium growth 1	Medium growth 2	Medium growth 3	Medium growth 4	Medium growth 5	Low growth
High	2020	226	225	222	224	224	233	223
	2021	227	225	222	225	224	235	224
	2022	228	226	222	225	224	237	224
	2023	228	226	222	226	224	238	224
	2024	229	226	221	226	224	240	224
	2025	229	226	221	226	224	241	224
	2026	229	226	220	226	223	242	223
	2027	229	225	220	226	223	243	223
	2028	229	225	219	226	222	244	222
	2029	229	225	218	225	222	245	222
	2030	228	224	217	225	221	245	221
	2031	228	223	216	224	220	246	220
	2032	228	222	214	223	219	247	219
Medium	2020	220	218	215	218	217	225	217
	2021	220	218	215	218	217	226	217
	2022	220	218	214	218	216	227	217
	2023	220	218	214	217	216	228	216
	2024	220	217	213	217	216	229	216
	2025	220	217	212	217	215	230	215
	2026	220	216	211	216	214	231	214
	2027	219	215	210	216	214	232	213
	2028	219	215	209	215	213	232	212
	2029	218	214	208	214	212	233	211
	2030	218	213	206	214	211	234	210
	2031	217	212	205	213	210	234	209
	2032	216	211	203	212	208	234	208
Low	2020	212	211	208	211	210	218	210
	2021	212	211	207	211	209	219	209
	2022	211	210	206	210	208	219	208
	2023	211	210	205	210	208	220	208
	2024	210	209	204	209	207	220	207
	2025	210	208	203	208	206	221	206
	2026	209	207	202	207	205	221	205
	2027	209	206	201	206	204	221	204
	2028	208	205	199	205	203	222	202
	2029	207	204	198	204	202	222	201
	2030	207	203	197	203	200	222	200
	2031	206	202	195	202	199	222	198
	2032	205	200	193	201	198	222	197

Table C-14: Forecasted housing stocks in Prince Edward Island (×1,000), 2020-2032

Headship rate scenario	Population growth scenario							
	Year	High growth	Medium growth 1	Medium growth 2	Medium growth 3	Medium growth 4	Medium growth 5	Low growth
High	2020	66.9	66.3	66.8	66.7	65.0	66.2	65.5
	2021	68.0	67.2	67.8	67.7	65.8	67.1	66.3
	2022	69.1	68.2	68.8	68.7	66.5	68.1	67.0
	2023	70.2	69.1	69.8	69.6	67.2	69.0	67.7
	2024	71.2	69.9	70.8	70.6	67.8	69.8	68.4
	2025	72.3	70.8	71.7	71.5	68.5	70.7	69.0
	2026	73.4	71.6	72.6	72.4	69.1	71.5	69.6
	2027	74.5	72.5	73.6	73.3	69.7	72.4	70.2
	2028	75.5	73.3	74.5	74.2	70.3	73.2	70.7
	2029	76.6	74.1	75.4	75.1	70.8	74.0	71.3
	2030	77.6	74.9	76.3	75.9	71.3	74.8	71.8
	2031	78.7	75.7	77.2	76.8	71.9	75.6	72.3
2032	79.7	76.4	78.0	77.6	72.4	76.4	72.7	
Medium	2020	64.9	64.3	64.8	64.7	63.1	64.2	63.6
	2021	65.8	65.1	65.6	65.5	63.7	65.0	64.2
	2022	66.7	65.8	66.4	66.3	64.2	65.7	64.7
	2023	67.6	66.5	67.2	67.0	64.7	66.4	65.2
	2024	68.4	67.2	68.0	67.8	65.2	67.1	65.7
	2025	69.3	67.9	68.7	68.5	65.6	67.8	66.2
	2026	70.2	68.5	69.5	69.3	66.1	68.4	66.6
	2027	71.1	69.2	70.2	70.0	66.5	69.1	67.0
	2028	72.0	69.8	71.0	70.7	67.0	69.8	67.4
	2029	72.8	70.5	71.7	71.4	67.4	70.4	67.8
	2030	73.7	71.1	72.4	72.1	67.7	71.0	68.1
	2031	74.6	71.7	73.1	72.8	68.1	71.6	68.5
2032	75.4	72.3	73.8	73.4	68.5	72.2	68.8	
Low	2020	62.9	62.3	62.8	62.7	61.1	62.2	61.6
	2021	63.6	62.9	63.4	63.3	61.5	62.8	62.0
	2022	64.3	63.4	64.0	63.9	61.9	63.3	62.3
	2023	65.0	63.9	64.6	64.5	62.2	63.8	62.7
	2024	65.6	64.4	65.2	65.0	62.5	64.4	63.0
	2025	66.3	65.0	65.8	65.6	62.8	64.9	63.3
	2026	67.0	65.4	66.3	66.1	63.1	65.3	63.6
	2027	67.7	65.9	66.9	66.7	63.4	65.8	63.8
	2028	68.4	66.4	67.5	67.2	63.7	66.3	64.1
	2029	69.1	66.9	68.0	67.7	63.9	66.8	64.3
	2030	69.8	67.3	68.5	68.2	64.1	67.2	64.5
	2031	70.4	67.8	69.1	68.8	64.4	67.7	64.7
2032	71.1	68.2	69.6	69.2	64.6	68.1	64.9	

Table C-15: Forecasted housing stocks in Nova Scotia (×1,000), 2020-2032

Headship rate scenario	Population growth scenario							
	Year	High growth	Medium growth 1	Medium growth 2	Medium growth 3	Medium growth 4	Medium growth 5	Low growth
High	2020	433.0	430.2	431.5	431.5	424.3	433.3	427.5
	2021	436.3	432.9	434.5	434.5	426.2	436.5	429.7
	2022	439.6	435.5	437.2	437.2	427.8	439.6	431.7
	2023	442.7	437.8	439.7	439.7	429.3	442.4	433.5
	2024	445.6	440.0	442.1	442.1	430.5	445.1	435.0
	2025	448.4	442.0	444.3	444.2	431.6	447.6	436.4
	2026	451.1	443.7	446.2	446.2	432.4	449.9	437.4
	2027	453.6	445.4	448.0	448.0	433.1	452.1	438.4
	2028	455.9	446.8	449.6	449.6	433.7	454.1	439.1
	2029	458.2	448.1	451.1	451.1	434.0	455.9	439.6
	2030	460.2	449.2	452.4	452.4	434.1	457.6	439.9
	2031	462.2	450.2	453.5	453.6	434.2	459.1	440.1
2032	464.0	450.9	454.5	454.6	434.0	460.5	440.0	
Medium	2020	418.5	415.8	417.1	417.1	410.2	418.8	413.2
	2021	420.6	417.3	418.8	418.8	410.9	420.8	414.3
	2022	422.7	418.7	420.3	420.3	411.4	422.6	415.1
	2023	424.5	419.9	421.7	421.7	411.7	424.3	415.7
	2024	426.3	421.0	423.0	422.9	411.9	425.8	416.2
	2025	428.0	421.9	424.1	424.1	412.0	427.3	416.6
	2026	429.7	422.7	425.0	425.0	411.9	428.5	416.7
	2027	431.1	423.4	425.9	425.9	411.8	429.7	416.7
	2028	432.5	423.9	426.6	426.6	411.5	430.8	416.6
	2029	433.9	424.4	427.2	427.2	411.0	431.7	416.3
	2030	435.1	424.7	427.7	427.7	410.5	432.6	415.9
	2031	436.2	424.9	428.1	428.2	409.8	433.4	415.4
2032	437.3	425.0	428.3	428.4	409.0	434.0	414.7	
Low	2020	402.5	399.9	401.2	401.1	394.5	402.8	397.4
	2021	403.0	399.8	401.2	401.2	393.7	403.1	396.9
	2022	403.5	399.7	401.3	401.3	392.8	403.5	396.3
	2023	403.9	399.5	401.2	401.2	391.8	403.7	395.6
	2024	404.2	399.1	401.0	401.0	390.6	403.8	394.7
	2025	404.5	398.7	400.7	400.7	389.4	403.7	393.7
	2026	404.8	398.2	400.4	400.4	388.1	403.7	392.6
	2027	404.7	397.5	399.9	399.8	386.7	403.4	391.3
	2028	404.8	396.8	399.3	399.3	385.2	403.2	390.0
	2029	404.8	396.0	398.6	398.7	383.6	402.8	388.5
	2030	404.8	395.1	397.9	398.0	381.9	402.5	387.0
	2031	404.6	394.1	397.1	397.1	380.2	401.9	385.3
2032	404.5	393.2	396.3	396.4	378.4	401.5	383.7	

Table C-16: Forecasted housing stocks in New Brunswick ( $\times 1,000$ ), 2020-2032

Headship rate scenario	Population growth scenario							
	Year	High growth	Medium growth 1	Medium growth 2	Medium growth 3	Medium growth 4	Medium growth 5	Low growth
High	2020	342.4	340.5	341.1	340.4	336.9	343.0	338.7
	2021	345.1	342.7	343.4	342.5	338.6	345.6	340.5
	2022	347.6	344.7	345.5	344.5	340.0	348.0	342.1
	2023	349.9	346.5	347.5	346.4	341.3	350.3	343.6
	2024	352.2	348.2	349.3	348.0	342.4	352.5	344.8
	2025	354.3	349.8	350.9	349.6	343.4	354.5	345.9
	2026	356.3	351.2	352.4	351.0	344.2	356.3	346.8
	2027	358.2	352.5	353.8	352.3	344.9	358.0	347.6
	2028	360.0	353.6	355.0	353.4	345.5	359.6	348.2
	2029	361.7	354.7	356.2	354.4	345.9	361.1	348.7
	2030	363.3	355.6	357.1	355.3	346.1	362.5	349.0
	2031	364.8	356.4	358.0	356.1	346.3	363.8	349.2
2032	366.2	357.0	358.7	356.7	346.3	364.9	349.2	
Medium	2020	330.9	329.0	329.6	328.9	325.6	331.5	327.3
	2021	332.5	330.3	331.0	330.1	326.3	333.1	328.2
	2022	334.1	331.4	332.2	331.2	326.9	334.6	328.9
	2023	335.7	332.4	333.3	332.2	327.4	336.0	329.6
	2024	337.1	333.3	334.3	333.1	327.7	337.4	330.1
	2025	338.4	334.1	335.2	333.9	328.0	338.6	330.4
	2026	339.7	334.8	335.9	334.6	328.1	339.7	330.6
	2027	340.8	335.4	336.6	335.1	328.1	340.6	330.7
	2028	341.9	335.8	337.1	335.6	328.0	341.5	330.7
	2029	342.8	336.1	337.6	335.9	327.8	342.3	330.5
	2030	343.7	336.4	337.9	336.1	327.4	342.9	330.2
	2031	344.4	336.5	338.1	336.2	327.0	343.5	329.8
2032	345.1	336.4	338.1	336.2	326.3	343.9	329.2	
Low	2020	317.7	315.9	316.5	315.8	312.6	318.2	314.2
	2021	318.1	316.0	316.6	315.8	312.2	318.7	314.0
	2022	318.6	316.0	316.8	315.9	311.7	319.1	313.7
	2023	319.0	315.9	316.8	315.8	311.2	319.4	313.2
	2024	319.4	315.8	316.8	315.6	310.6	319.6	312.7
	2025	319.6	315.6	316.6	315.4	309.9	319.8	312.1
	2026	319.9	315.3	316.4	315.1	309.1	319.9	311.4
	2027	320.0	314.9	316.1	314.7	308.2	319.9	310.6
	2028	320.1	314.4	315.7	314.2	307.2	319.8	309.7
	2029	320.1	313.9	315.2	313.7	306.1	319.6	308.6
	2030	320.0	313.2	314.6	313.0	304.9	319.3	307.5
	2031	319.7	312.4	313.9	312.2	303.6	318.9	306.2
2032	319.5	311.5	313.1	311.3	302.2	318.4	304.8	

Table C-17: Forecasted housing stocks in Quebec (×1,000), 2020-2032

Headship rate scenario	Population growth scenario							
	Year	High growth	Medium growth 1	Medium growth 2	Medium growth 3	Medium growth 4	Medium growth 5	Low growth
High	2020	342.4	340.5	341.1	340.4	336.9	343.0	338.7
	2021	345.1	342.7	343.4	342.5	338.6	345.6	340.5
	2022	347.6	344.7	345.5	344.5	340.0	348.0	342.1
	2023	349.9	346.5	347.5	346.4	341.3	350.3	343.6
	2024	352.2	348.2	349.3	348.0	342.4	352.5	344.8
	2025	354.3	349.8	350.9	349.6	343.4	354.5	345.9
	2026	356.3	351.2	352.4	351.0	344.2	356.3	346.8
	2027	358.2	352.5	353.8	352.3	344.9	358.0	347.6
	2028	360.0	353.6	355.0	353.4	345.5	359.6	348.2
	2029	361.7	354.7	356.2	354.4	345.9	361.1	348.7
	2030	363.3	355.6	357.1	355.3	346.1	362.5	349.0
	2031	364.8	356.4	358.0	356.1	346.3	363.8	349.2
	2032	366.2	357.0	358.7	356.7	346.3	364.9	349.2
Medium	2020	330.9	329.0	329.6	328.9	325.6	331.5	327.3
	2021	332.5	330.3	331.0	330.1	326.3	333.1	328.2
	2022	334.1	331.4	332.2	331.2	326.9	334.6	328.9
	2023	335.7	332.4	333.3	332.2	327.4	336.0	329.6
	2024	337.1	333.3	334.3	333.1	327.7	337.4	330.1
	2025	338.4	334.1	335.2	333.9	328.0	338.6	330.4
	2026	339.7	334.8	335.9	334.6	328.1	339.7	330.6
	2027	340.8	335.4	336.6	335.1	328.1	340.6	330.7
	2028	341.9	335.8	337.1	335.6	328.0	341.5	330.7
	2029	342.8	336.1	337.6	335.9	327.8	342.3	330.5
	2030	343.7	336.4	337.9	336.1	327.4	342.9	330.2
	2031	344.4	336.5	338.1	336.2	327.0	343.5	329.8
	2032	345.1	336.4	338.1	336.2	326.3	343.9	329.2
Low	2020	317.7	315.9	316.5	315.8	312.6	318.2	314.2
	2021	318.1	316.0	316.6	315.8	312.2	318.7	314.0
	2022	318.6	316.0	316.8	315.9	311.7	319.1	313.7
	2023	319.0	315.9	316.8	315.8	311.2	319.4	313.2
	2024	319.4	315.8	316.8	315.6	310.6	319.6	312.7
	2025	319.6	315.6	316.6	315.4	309.9	319.8	312.1
	2026	319.9	315.3	316.4	315.1	309.1	319.9	311.4
	2027	320.0	314.9	316.1	314.7	308.2	319.9	310.6
	2028	320.1	314.4	315.7	314.2	307.2	319.8	309.7
	2029	320.1	313.9	315.2	313.7	306.1	319.6	308.6
	2030	320.0	313.2	314.6	313.0	304.9	319.3	307.5
	2031	319.7	312.4	313.9	312.2	303.6	318.9	306.2
	2032	319.5	311.5	313.1	311.3	302.2	318.4	304.8

Table C-18: Forecasted housing stocks in Ontario (×1,000), 2020-2032

Headship rate scenario	Population growth scenario							
	Year	High growth	Medium growth 1	Medium growth 2	Medium growth 3	Medium growth 4	Medium growth 5	Low growth
High	2020	5,798.9	5,728.8	5,738.5	5,770.2	5,695.1	5,729.2	5,640.5
	2021	5,883.7	5,799.0	5,810.1	5,847.3	5,759.7	5,799.5	5,693.5
	2022	5,970.0	5,866.6	5,879.3	5,922.0	5,821.6	5,867.5	5,742.0
	2023	6,055.1	5,933.4	5,947.5	5,996.0	5,882.4	5,934.6	5,788.8
	2024	6,140.0	5,998.7	6,014.4	6,068.7	5,941.7	6,000.2	5,833.2
	2025	6,224.5	6,062.7	6,079.9	6,140.4	5,999.4	6,064.6	5,875.3
	2026	6,310.1	6,124.7	6,143.5	6,210.4	6,054.9	6,127.0	5,913.4
	2027	6,392.7	6,187.1	6,207.4	6,280.6	6,110.7	6,189.8	5,953.0
	2028	6,476.4	6,247.5	6,269.4	6,349.3	6,164.4	6,250.8	5,988.8
	2029	6,559.7	6,306.9	6,330.3	6,417.0	6,216.8	6,310.7	6,022.7
	2030	6,642.8	6,365.3	6,390.3	6,484.0	6,268.0	6,369.6	6,054.9
	2031	6,724.6	6,423.2	6,449.8	6,550.8	6,318.7	6,428.1	6,086.3
	2032	6,808.0	6,479.3	6,507.5	6,615.8	6,367.2	6,484.9	6,114.3
Medium	2020	5,685.6	5,617.1	5,626.5	5,657.6	5,584.2	5,617.5	5,530.5
	2021	5,760.1	5,677.4	5,688.4	5,724.5	5,639.2	5,678.0	5,574.6
	2022	5,835.2	5,734.5	5,746.8	5,788.5	5,690.7	5,735.4	5,612.7
	2023	5,909.8	5,791.4	5,805.1	5,852.3	5,741.8	5,792.5	5,650.4
	2024	5,984.2	5,847.1	5,862.2	5,915.1	5,791.7	5,848.5	5,685.9
	2025	6,058.5	5,901.6	5,918.2	5,976.9	5,840.2	5,903.3	5,719.4
	2026	6,133.1	5,953.7	5,971.9	6,036.6	5,886.0	5,955.8	5,749.0
	2027	6,206.4	6,007.5	6,027.0	6,098.0	5,933.6	6,010.0	5,780.5
	2028	6,280.1	6,058.9	6,080.0	6,157.3	5,978.6	6,062.0	5,808.4
	2029	6,353.5	6,109.4	6,132.0	6,215.8	6,022.5	6,113.0	5,834.6
	2030	6,426.7	6,159.1	6,183.2	6,273.7	6,065.3	6,163.2	5,859.3
	2031	6,499.3	6,208.9	6,234.5	6,331.8	6,108.2	6,213.6	5,884.3
	2032	6,572.3	6,256.0	6,283.1	6,387.5	6,148.1	6,261.3	5,904.2
Low	2020	5,572.3	5,505.5	5,514.8	5,545.0	5,473.3	5,505.8	5,421.1
	2021	5,636.5	5,555.9	5,566.6	5,601.8	5,518.6	5,556.4	5,455.7
	2022	5,700.4	5,602.5	5,614.6	5,655.0	5,559.8	5,603.3	5,484.2
	2023	5,764.5	5,649.5	5,663.0	5,708.7	5,601.3	5,650.5	5,512.8
	2024	5,828.5	5,695.5	5,710.3	5,761.5	5,641.7	5,696.8	5,539.4
	2025	5,892.5	5,740.5	5,756.8	5,813.5	5,681.0	5,742.2	5,564.2
	2026	5,956.1	5,782.6	5,800.2	5,862.8	5,717.1	5,784.7	5,584.5
	2027	6,020.1	5,827.9	5,847.0	5,915.4	5,756.5	5,830.4	5,608.8
	2028	6,083.8	5,870.4	5,890.8	5,965.3	5,792.8	5,873.3	5,628.8
	2029	6,147.3	5,912.1	5,933.9	6,014.6	5,828.2	5,915.4	5,647.3
	2030	6,210.6	5,953.0	5,976.3	6,063.4	5,862.7	5,956.9	5,664.4
	2031	6,273.9	5,994.6	6,019.3	6,112.8	5,897.8	5,999.1	5,682.2
	2032	6,336.7	6,032.8	6,059.0	6,159.2	5,929.2	6,037.9	5,694.9

Table C-19: Forecasted housing stocks in Manitoba (×1,000), 2020-2032

Headship rate scenario	Population growth scenario							
	Year	High growth	Medium growth 1	Medium growth 2	Medium growth 3	Medium growth 4	Medium growth 5	Low growth
High	2020	553.3	548.1	547.3	549.4	543.4	553.7	540.9
	2021	562.4	555.9	554.9	557.4	550.4	562.5	547.1
	2022	571.6	563.6	562.4	565.3	557.3	571.2	552.8
	2023	581.0	571.3	569.9	573.2	564.1	580.0	558.5
	2024	590.4	579.0	577.4	581.1	571.0	588.8	564.1
	2025	600.0	586.7	584.9	589.0	577.7	597.7	569.6
	2026	609.8	594.3	592.3	596.9	584.4	606.5	574.7
	2027	619.5	602.1	599.9	604.9	591.3	615.5	580.1
	2028	629.5	609.8	607.3	612.8	598.0	624.6	585.2
	2029	639.5	617.6	614.8	620.8	604.7	633.7	590.2
	2030	649.7	625.3	622.3	628.9	611.4	642.8	595.1
	2031	660.0	633.2	629.8	637.0	618.2	652.1	600.1
2032	670.5	641.0	637.3	645.1	624.9	661.4	604.8	
Medium	2020	532.2	527.2	526.4	528.4	522.7	532.6	520.2
	2021	539.3	533.1	532.2	534.6	527.9	539.4	524.7
	2022	547.0	539.3	538.2	540.9	533.2	546.6	529.0
	2023	554.6	545.4	544.1	547.2	538.5	553.7	533.2
	2024	562.4	551.5	550.0	553.5	543.9	560.8	537.4
	2025	570.3	557.7	556.0	559.9	549.2	568.1	541.4
	2026	578.7	564.0	562.1	566.4	554.6	575.6	545.4
	2027	586.5	570.1	568.0	572.7	559.8	582.8	549.3
	2028	594.8	576.3	574.0	579.2	565.1	590.2	553.1
	2029	603.2	582.6	580.0	585.7	570.5	597.7	556.8
	2030	611.8	588.9	586.1	592.3	575.8	605.3	560.5
	2031	620.3	595.2	592.1	598.8	581.1	612.9	564.2
2032	629.3	601.7	598.3	605.6	586.6	620.8	567.8	
Low	2020	524.6	519.7	518.9	520.9	515.2	524.9	512.8
	2021	531.0	525.0	524.0	526.4	519.8	531.1	516.7
	2022	538.2	530.6	529.5	532.2	524.7	537.7	520.5
	2023	545.2	536.2	534.9	537.9	529.4	544.2	524.2
	2024	552.4	541.7	540.3	543.7	534.2	550.8	527.9
	2025	559.7	547.3	545.7	549.5	539.0	557.5	531.4
	2026	567.5	553.2	551.3	555.5	544.0	564.5	535.0
	2027	574.7	558.6	556.6	561.2	548.6	571.0	538.3
	2028	582.4	564.4	562.1	567.2	553.5	577.9	541.7
	2029	590.3	570.1	567.6	573.2	558.3	584.9	545.0
	2030	598.3	575.9	573.2	579.2	563.2	591.9	548.2
	2031	606.1	581.6	578.6	585.1	567.9	598.9	551.4
2032	614.5	587.6	584.3	591.4	572.9	606.2	554.6	

Table C-20: Forecasted housing stocks in Saskatchewan ( $\times 1,000$ ), 2020-2032

Headship rate scenario	Population growth scenario							
	Year	High growth	Medium growth 1	Medium growth 2	Medium growth 3	Medium growth 4	Medium growth 5	Low growth
High	2020	493.1	488.9	484.4	476.2	492.8	507.2	483.7
	2021	500.3	495.1	489.9	480.4	499.7	516.4	489.0
	2022	507.4	501.0	495.0	484.2	506.3	525.4	493.6
	2023	514.6	507.0	500.2	488.1	513.0	534.7	498.4
	2024	521.9	513.1	505.5	492.0	519.8	544.0	503.1
	2025	529.3	519.2	510.7	495.9	526.7	553.4	507.7
	2026	536.7	524.9	515.6	499.4	533.3	562.7	511.9
	2027	544.4	531.3	521.1	503.4	540.5	572.6	516.8
	2028	552.1	537.4	526.3	507.2	547.4	582.4	521.3
	2029	559.8	543.6	531.5	510.8	554.4	592.4	525.7
	2030	567.7	549.7	536.7	514.5	561.5	602.5	530.1
	2031	575.7	556.1	542.2	518.3	568.8	612.9	534.6
	2032	583.7	562.2	547.2	521.7	575.8	623.2	538.7
Medium	2020	481.0	476.9	472.5	464.5	480.7	494.7	471.9
	2021	486.9	481.8	476.7	467.6	486.3	502.5	475.9
	2022	492.7	486.5	480.7	470.3	491.6	510.1	479.4
	2023	498.6	491.3	484.7	473.1	497.1	517.9	483.0
	2024	504.7	496.1	488.8	475.9	502.7	525.9	486.5
	2025	510.8	501.0	492.8	478.6	508.3	533.9	490.0
	2026	516.9	505.6	496.6	481.1	513.7	541.8	493.1
	2027	523.3	510.7	501.0	484.0	519.6	550.3	496.9
	2028	529.7	515.7	505.0	486.7	525.3	558.6	500.2
	2029	536.2	520.6	509.1	489.4	531.0	567.1	503.6
	2030	542.7	525.6	513.2	492.0	536.8	575.8	506.9
	2031	549.4	530.8	517.5	494.8	542.9	584.7	510.3
	2032	556.1	535.7	521.4	497.2	548.6	593.5	513.4
Low	2020	474.9	470.8	466.5	458.7	474.6	488.3	465.9
	2021	480.0	475.0	470.0	461.0	479.5	495.3	469.2
	2022	485.1	479.0	473.3	463.1	484.1	502.1	472.0
	2023	490.3	483.1	476.7	465.2	488.9	509.1	474.9
	2024	495.5	487.2	480.0	467.3	493.6	516.2	477.8
	2025	500.8	491.2	483.3	469.4	498.4	523.3	480.5
	2026	506.2	495.2	486.4	471.2	503.1	530.4	483.0
	2027	511.6	499.4	489.8	473.4	508.0	537.8	485.9
	2028	517.1	503.5	493.1	475.3	512.9	545.1	488.5
	2029	522.6	507.5	496.4	477.2	517.7	552.6	491.0
	2030	528.2	511.6	499.6	479.1	522.6	560.2	493.5
	2031	533.9	515.8	503.0	481.0	527.6	567.9	496.1
	2032	539.7	519.9	506.1	482.7	532.5	575.6	498.3

Table C-21: Forecasted housing stocks in Alberta (×1,000), 2020-2032

Headship rate scenario	Population growth scenario							
	Year	High growth	Medium growth 1	Medium growth 2	Medium growth 3	Medium growth 4	Medium growth 5	Low growth
High	2020	1,929.3	1,906.9	1,896.1	1,918.3	1,953.6	1,863.8	1,879.2
	2021	1,981.3	1,954.1	1,941.5	1,967.4	2,008.6	1,903.8	1,920.8
	2022	2,036.2	2,002.5	1,987.9	2,017.7	2,065.2	1,944.5	1,962.7
	2023	2,090.7	2,050.7	2,034.2	2,067.9	2,121.9	1,984.9	2,004.1
	2024	2,146.0	2,099.1	2,080.7	2,118.5	2,179.1	2,025.3	2,045.3
	2025	2,202.0	2,147.9	2,127.4	2,169.5	2,237.0	2,065.8	2,086.4
	2026	2,260.4	2,197.7	2,175.0	2,221.6	2,296.3	2,106.8	2,127.6
	2027	2,316.2	2,246.5	2,221.6	2,272.7	2,354.6	2,146.8	2,168.0
	2028	2,374.4	2,296.3	2,269.0	2,324.9	2,414.4	2,187.5	2,208.6
	2029	2,433.3	2,346.4	2,316.8	2,377.6	2,474.9	2,228.2	2,249.0
	2030	2,493.0	2,396.9	2,364.8	2,430.7	2,536.1	2,269.0	2,289.3
	2031	2,552.4	2,447.4	2,412.6	2,483.9	2,597.6	2,309.5	2,329.3
2032	2,614.7	2,499.1	2,461.6	2,538.5	2,660.9	2,350.9	2,369.6	
Medium	2020	1,854.1	1,832.7	1,822.4	1,843.5	1,877.0	1,791.4	1,806.1
	2021	1,898.5	1,872.6	1,860.6	1,885.2	1,924.2	1,824.5	1,840.8
	2022	1,944.7	1,912.7	1,899.0	1,927.2	1,972.0	1,857.5	1,874.9
	2023	1,991.1	1,953.1	1,937.7	1,969.5	2,020.3	1,890.8	1,909.1
	2024	2,038.2	1,994.0	1,976.7	2,012.3	2,069.2	1,924.1	1,943.1
	2025	2,086.1	2,035.1	2,016.0	2,055.5	2,118.7	1,957.6	1,977.1
	2026	2,135.5	2,076.6	2,055.4	2,099.1	2,168.9	1,991.0	2,010.7
	2027	2,184.0	2,118.6	2,095.4	2,143.3	2,219.7	2,024.9	2,044.9
	2028	2,234.2	2,161.0	2,135.7	2,187.9	2,271.2	2,058.9	2,078.8
	2029	2,285.1	2,203.8	2,176.3	2,233.0	2,323.5	2,093.1	2,112.7
	2030	2,336.7	2,247.0	2,217.2	2,278.6	2,376.6	2,127.4	2,146.6
	2031	2,388.6	2,290.8	2,258.6	2,324.9	2,430.4	2,162.1	2,180.7
2032	2,442.5	2,335.0	2,300.3	2,371.7	2,485.1	2,196.9	2,214.5	
Low	2020	1,778.9	1,758.4	1,748.7	1,768.8	1,800.4	1,719.0	1,733.1
	2021	1,815.6	1,791.0	1,779.8	1,803.0	1,839.8	1,745.3	1,760.8
	2022	1,853.2	1,822.9	1,810.1	1,836.7	1,878.7	1,770.6	1,787.1
	2023	1,891.5	1,855.6	1,841.2	1,871.2	1,918.7	1,796.7	1,814.0
	2024	1,930.5	1,888.8	1,872.6	1,906.1	1,959.2	1,822.9	1,840.9
	2025	1,970.2	1,922.3	1,904.4	1,941.5	2,000.4	1,849.4	1,867.8
	2026	2,010.7	1,955.6	1,935.9	1,976.7	2,041.6	1,875.3	1,893.8
	2027	2,051.9	1,990.8	1,969.2	2,013.8	2,084.8	1,903.1	1,921.9
	2028	2,093.9	2,025.7	2,002.2	2,050.8	2,128.0	1,930.4	1,949.0
	2029	2,136.8	2,061.1	2,035.7	2,088.4	2,172.1	1,958.0	1,976.3
	2030	2,180.4	2,097.1	2,069.6	2,126.5	2,217.0	1,985.9	2,003.8
	2031	2,224.9	2,134.2	2,104.5	2,165.8	2,263.1	2,014.7	2,032.1
2032	2,270.3	2,170.9	2,138.9	2,204.8	2,309.3	2,042.9	2,059.3	

Table C-22: Forecasted housing stocks in British Columbia (×1,000), 2020-2032

Headship rate scenario	Population growth scenario							
	Year	High growth	Medium growth 1	Medium growth 2	Medium growth 3	Medium growth 4	Medium growth 5	Low growth
High	2020	2,114.7	2,077.0	2,094.2	2,025.6	2,083.8	2,061.0	2,032.0
	2021	2,151.9	2,106.8	2,126.8	2,047.0	2,114.6	2,088.3	2,053.5
	2022	2,189.7	2,135.3	2,158.2	2,066.8	2,144.2	2,114.2	2,072.8
	2023	2,227.4	2,163.9	2,189.9	2,086.6	2,173.9	2,140.2	2,092.0
	2024	2,265.5	2,192.3	2,221.4	2,105.8	2,203.5	2,165.9	2,110.4
	2025	2,303.7	2,220.5	2,252.7	2,124.6	2,232.8	2,191.4	2,128.2
	2026	2,342.5	2,247.8	2,283.3	2,142.2	2,261.3	2,215.8	2,144.3
	2027	2,381.0	2,276.3	2,315.1	2,160.8	2,291.0	2,241.5	2,161.9
	2028	2,420.0	2,304.0	2,346.3	2,178.3	2,319.9	2,266.3	2,177.9
	2029	2,459.4	2,331.7	2,377.5	2,195.4	2,348.8	2,290.9	2,193.5
	2030	2,499.0	2,359.2	2,408.8	2,212.2	2,377.7	2,315.4	2,208.6
	2031	2,538.8	2,387.3	2,440.7	2,229.2	2,407.0	2,340.4	2,224.1
	2032	2,579.3	2,414.4	2,471.8	2,244.9	2,435.5	2,364.3	2,237.7
Medium	2020	2,049.4	2,013.2	2,029.7	1,963.6	2,019.8	1,997.8	1,969.8
	2021	2,081.7	2,038.3	2,057.5	1,980.8	2,046.0	2,020.5	1,987.1
	2022	2,114.3	2,062.1	2,084.1	1,996.3	2,070.9	2,041.9	2,002.1
	2023	2,147.2	2,086.4	2,111.2	2,012.2	2,096.2	2,063.6	2,017.3
	2024	2,180.5	2,110.6	2,138.3	2,027.7	2,121.5	2,085.2	2,032.0
	2025	2,214.1	2,134.6	2,165.3	2,042.8	2,146.7	2,106.7	2,046.2
	2026	2,248.0	2,157.6	2,191.4	2,056.7	2,170.8	2,127.0	2,058.7
	2027	2,282.2	2,182.4	2,219.4	2,072.1	2,196.8	2,149.2	2,073.1
	2028	2,316.6	2,206.2	2,246.4	2,086.3	2,221.7	2,170.2	2,085.9
	2029	2,351.4	2,229.9	2,273.5	2,100.1	2,246.7	2,191.1	2,098.2
	2030	2,386.3	2,253.6	2,300.6	2,113.7	2,271.5	2,211.9	2,110.2
	2031	2,421.6	2,277.8	2,328.3	2,127.5	2,297.0	2,233.2	2,122.6
	2032	2,457.0	2,300.8	2,355.0	2,139.8	2,321.2	2,253.1	2,132.9
Low	2020	2,048.9	2,012.7	2,029.1	1,963.3	2,019.3	1,997.3	1,969.4
	2021	2,081.2	2,037.8	2,056.9	1,980.5	2,045.5	2,020.1	1,986.7
	2022	2,113.2	2,061.1	2,083.0	1,995.6	2,069.8	2,041.0	2,001.2
	2023	2,146.0	2,085.2	2,109.9	2,011.3	2,095.0	2,062.6	2,016.3
	2024	2,179.0	2,109.2	2,136.8	2,026.6	2,120.1	2,084.0	2,030.9
	2025	2,212.5	2,133.1	2,163.6	2,041.7	2,145.1	2,105.3	2,044.9
	2026	2,245.7	2,155.5	2,189.1	2,055.0	2,168.7	2,125.1	2,056.9
	2027	2,280.2	2,180.6	2,217.3	2,070.7	2,194.9	2,147.5	2,071.6
	2028	2,314.4	2,204.2	2,244.1	2,084.7	2,219.7	2,168.3	2,084.2
	2029	2,348.9	2,227.7	2,271.0	2,098.4	2,244.4	2,189.1	2,096.3
	2030	2,383.6	2,251.1	2,297.8	2,111.8	2,269.1	2,209.6	2,108.1
	2031	2,418.8	2,275.3	2,325.6	2,125.6	2,294.5	2,230.9	2,120.5
	2032	2,453.5	2,297.7	2,351.6	2,137.4	2,318.1	2,250.3	2,130.3

Table C-23: Forecasted housing stocks in Yukon ( $\times 1,000$ ), 2020-2032

Headship rate scenario	Population growth scenario							
	Year	High growth	Medium growth 1	Medium growth 2	Medium growth 3	Medium growth 4	Medium growth 5	Low growth
High	2020	18.0	17.8	16.8	17.1	18.7	19.7	17.6
	2021	18.3	18.1	16.9	17.3	19.1	20.3	17.8
	2022	18.6	18.3	17.0	17.4	19.5	20.9	18.0
	2023	18.9	18.5	17.0	17.5	19.9	21.4	18.2
	2024	19.1	18.8	17.1	17.7	20.3	22.0	18.3
	2025	19.4	19.0	17.2	17.8	20.7	22.6	18.5
	2026	19.7	19.2	17.2	17.8	21.0	23.1	18.6
	2027	19.9	19.4	17.2	17.9	21.4	23.7	18.7
	2028	20.2	19.6	17.3	18.0	21.7	24.3	18.9
	2029	20.5	19.7	17.3	18.0	22.1	24.9	19.0
	2030	20.7	19.9	17.3	18.1	22.4	25.5	19.1
	2031	20.9	20.1	17.3	18.1	22.8	26.1	19.2
	2032	21.2	20.3	17.3	18.2	23.1	26.7	19.3
Medium	2020	17.1	16.9	15.9	16.3	17.8	18.7	16.7
	2021	17.3	17.1	16.0	16.4	18.1	19.2	16.8
	2022	17.5	17.3	16.0	16.5	18.4	19.7	17.0
	2023	17.7	17.4	16.0	16.5	18.8	20.2	17.1
	2024	18.0	17.6	16.0	16.6	19.1	20.6	17.2
	2025	18.2	17.8	16.0	16.6	19.4	21.1	17.3
	2026	18.4	17.9	16.0	16.7	19.7	21.6	17.4
	2027	18.6	18.0	16.0	16.7	19.9	22.1	17.5
	2028	18.8	18.2	16.0	16.7	20.2	22.6	17.5
	2029	19.0	18.3	16.0	16.7	20.5	23.1	17.6
	2030	19.1	18.4	16.0	16.8	20.8	23.6	17.7
	2031	19.3	18.6	16.0	16.8	21.1	24.1	17.7
	2032	19.5	18.7	15.9	16.8	21.3	24.6	17.7
Low	2020	16.5	16.3	15.4	15.7	17.2	18.1	16.1
	2021	16.7	16.5	15.4	15.8	17.5	18.5	16.2
	2022	16.9	16.6	15.4	15.8	17.7	18.9	16.3
	2023	17.0	16.7	15.4	15.9	18.0	19.4	16.4
	2024	17.2	16.8	15.4	15.9	18.3	19.8	16.5
	2025	17.4	17.0	15.3	15.9	18.5	20.2	16.5
	2026	17.5	17.1	15.3	15.9	18.8	20.6	16.6
	2027	17.7	17.2	15.3	15.9	19.0	21.1	16.6
	2028	17.8	17.3	15.2	15.9	19.3	21.5	16.7
	2029	18.0	17.4	15.2	15.9	19.5	21.9	16.7
	2030	18.2	17.5	15.2	15.9	19.7	22.4	16.7
	2031	18.3	17.6	15.1	15.9	20.0	22.8	16.8
	2032	18.4	17.7	15.1	15.9	20.2	23.3	16.8

Table C-24: Forecasted housing stocks in Northwest Territories (×1,000), 2020-2032

Headship rate scenario	Population growth scenario							
	Year	High growth	Medium growth 1	Medium growth 2	Medium growth 3	Medium growth 4	Medium growth 5	Low growth
High	2020	16.8	16.7	16.3	17.2	16.3	17.3	16.6
	2021	16.9	16.8	16.4	17.3	16.3	17.4	16.6
	2022	17.0	16.8	16.4	17.5	16.3	17.6	16.7
	2023	17.1	16.9	16.4	17.6	16.3	17.7	16.7
	2024	17.2	17.0	16.5	17.7	16.2	17.8	16.8
	2025	17.2	17.0	16.5	17.9	16.2	18.0	16.8
	2026	17.3	17.1	16.5	18.0	16.2	18.1	16.8
	2027	17.4	17.1	16.5	18.1	16.1	18.2	16.8
	2028	17.5	17.1	16.5	18.2	16.0	18.3	16.8
	2029	17.5	17.2	16.5	18.3	16.0	18.4	16.8
	2030	17.6	17.2	16.5	18.4	15.9	18.5	16.8
	2031	17.6	17.2	16.5	18.5	15.8	18.6	16.8
	2032	17.7	17.2	16.4	18.5	15.8	18.7	16.8
Medium	2020	16.4	16.3	15.9	16.7	15.8	16.8	16.2
	2021	16.4	16.3	15.9	16.9	15.8	16.9	16.2
	2022	16.5	16.3	15.9	17.0	15.8	17.1	16.2
	2023	16.5	16.4	15.9	17.1	15.7	17.2	16.2
	2024	16.6	16.4	15.9	17.1	15.7	17.2	16.2
	2025	16.6	16.4	15.9	17.2	15.6	17.3	16.2
	2026	16.7	16.4	15.9	17.3	15.6	17.4	16.2
	2027	16.7	16.4	15.8	17.4	15.5	17.5	16.2
	2028	16.8	16.4	15.8	17.4	15.4	17.6	16.1
	2029	16.8	16.4	15.8	17.5	15.3	17.6	16.1
	2030	16.8	16.4	15.7	17.6	15.2	17.7	16.1
	2031	16.8	16.4	15.7	17.6	15.1	17.7	16.0
	2032	16.9	16.4	15.7	17.7	15.0	17.8	16.0
Low	2020	15.9	15.8	15.5	16.3	15.4	16.4	15.7
	2021	16.0	15.9	15.5	16.4	15.4	16.5	15.7
	2022	16.0	15.8	15.4	16.4	15.3	16.5	15.7
	2023	16.0	15.8	15.4	16.5	15.2	16.6	15.7
	2024	16.0	15.8	15.4	16.6	15.1	16.7	15.6
	2025	16.0	15.8	15.3	16.6	15.0	16.7	15.6
	2026	16.0	15.8	15.3	16.6	15.0	16.7	15.6
	2027	16.0	15.8	15.2	16.7	14.8	16.8	15.5
	2028	16.0	15.7	15.1	16.7	14.7	16.8	15.5
	2029	16.0	15.7	15.1	16.7	14.6	16.8	15.4
	2030	16.0	15.7	15.0	16.8	14.5	16.9	15.3
	2031	16.0	15.7	15.0	16.8	14.4	16.9	15.3
	2032	16.0	15.6	14.9	16.8	14.3	16.9	15.2

Table C-25: Forecasted housing stocks in Nunavut (×1,000), 2020-2032

Headship rate scenario	Population growth scenario							
	Year	High growth	Medium growth 1	Medium growth 2	Medium growth 3	Medium growth 4	Medium growth 5	Low growth
High	2020	11.8	11.7	12.0	11.8	11.7	12.4	12.0
	2021	12.0	12.0	12.0	12.0	12.0	13.0	12.0
	2022	12.2	12.2	12.3	12.2	11.9	13.1	12.3
	2023	12.4	12.4	12.4	12.4	12.0	13.4	12.4
	2024	12.6	12.6	12.6	12.6	12.1	13.7	12.6
	2025	12.8	12.9	12.7	12.8	12.2	14.0	12.7
	2026	13.0	13.0	13.0	13.0	12.0	14.0	13.0
	2027	13.2	13.3	12.8	13.2	12.3	14.6	12.8
	2028	13.4	13.5	12.9	13.4	12.4	14.9	12.9
	2029	13.6	13.7	13.0	13.6	12.6	15.2	13.0
	2030	13.8	13.8	13.1	13.8	12.7	15.5	13.1
	2031	14.0	14.0	13.0	14.0	13.0	16.0	13.0
	2032	14.2	14.0	13.3	14.2	13.0	16.0	13.3
Medium	2020	10.9	11.0	11.0	11.0	10.6	11.9	11.0
	2021	11.0	11.0	11.0	11.0	11.0	12.0	11.0
	2022	11.2	11.3	11.3	11.2	10.9	12.2	11.3
	2023	11.3	11.4	11.4	11.3	11.0	12.4	11.4
	2024	11.5	11.6	11.6	11.5	11.1	12.6	11.6
	2025	11.8	11.7	11.7	11.7	11.2	12.7	11.7
	2026	12.0	12.0	12.0	12.0	11.0	13.0	12.0
	2027	12.2	11.8	11.8	12.1	11.4	13.1	11.8
	2028	12.5	11.9	11.9	12.4	11.5	13.3	11.9
	2029	12.7	12.0	12.0	12.6	11.6	13.5	12.0
	2030	12.8	12.1	12.1	12.8	11.7	13.8	12.1
	2031	13.0	12.0	12.0	13.0	12.0	14.0	12.0
	2032	13.1	12.3	12.3	13.3	11.8	14.4	12.3
Low	2020	10.6	10.6	10.9	10.7	10.1	11.8	10.9
	2021	11.0	11.0	11.0	11.0	10.0	12.0	11.0
	2022	10.9	10.9	11.0	10.9	10.3	12.2	11.0
	2023	11.0	11.0	11.1	11.0	10.4	12.4	11.1
	2024	11.1	11.1	11.1	11.1	10.5	12.6	11.1
	2025	11.2	11.2	11.0	11.2	10.6	12.8	11.0
	2026	11.0	11.0	11.0	11.0	11.0	13.0	11.0
	2027	11.4	11.4	11.0	11.3	10.9	13.2	11.0
	2028	11.5	11.5	10.9	11.4	11.0	13.4	10.9
	2029	11.6	11.6	10.9	11.6	11.0	13.6	10.9
	2030	11.7	11.7	11.0	11.7	11.1	13.8	11.0
	2031	12.0	12.0	11.0	12.0	11.0	14.0	11.0
	2032	11.8	11.8	11.1	12.0	11.2	14.2	11.1

Table C-26: The selected cities for the climate zone specific population ratio calculation

City	HDD 18	Climate Zone	Population	Province
Bonavista	5000	7A	3,140	Newfoundland
Channel-Port aux Basques	5000	7A	3,665	Newfoundland
Corner Brook	4760	6	19,547	Newfoundland
Gander	5110	7A	10,220	Newfoundland
Grand Bank	4550	6	2,230	Newfoundland
Grand Falls	5020	7A	12,046	Newfoundland
Happy Valley-Goose Bay	6670	7B	6,408	Newfoundland
Labrador City	7710	8	8,622	Newfoundland
St. Anthony	6440	7B	2,049	Newfoundland
St. John's	4800	6	178,427	Newfoundland
Stephenville	4850	6	7,114	Newfoundland
Wabana	4750	6	1,325	Newfoundland
Charlottetown	4460	6	51,148	Prince Edward Island
Souris	4550	6	3,014	Prince Edward Island
Summerside	4600	6	16,448	Prince Edward Island
Amherst	4500	6	9,550	Nova Scotia
Antigonish	4510	6	5,002	Nova Scotia
Bridgewater	4140	6	8,532	Nova Scotia
Digby	4020	6	2,060	Nova Scotia
Kingston - Greenwood	4140	6	6,879	Nova Scotia
Halifax	4000	6	316,701	Nova Scotia
Kentville	4130	6	12,088	Nova Scotia
Liverpool	3990	5	2,549	Nova Scotia
Lunenburg	4140	6	2,085	Nova Scotia
New Glasgow	4320	6	18,665	Nova Scotia
North Sydney	4500	6	12,823	Nova Scotia
Pictou	4310	6	2,711	Nova Scotia
Port Hawkesbury	4500	6	3,004	Nova Scotia
Springhill	4540	6	2,743	Nova Scotia
Cape Breton - Sydney	4530	6	37,248	Nova Scotia
Truro	4500	6	22,954	Nova Scotia
Wolfville	4140	6	16,283	Nova Scotia
Yarmouth	3990	5	7,217	Nova Scotia
Bathurst	5020	7A	15,557	New Brunswick
Campbellton	5500	7A	10,716	New Brunswick
Edmundston	5320	7A	12,086	New Brunswick
Fredericton	4670	6	59,405	New Brunswick
Grand Falls	5300	7A	4,221	New Brunswick

<b>City</b>	<b>HDD 18</b>	<b>Climate Zone</b>	<b>Population</b>	<b>Province</b>
Miramichi	4950	6	11,329	New Brunswick
Moncton	4680	6	108,620	New Brunswick
Oromocto	4650	6	8,805	New Brunswick
Sackville	4590	6	2,963	New Brunswick
Saint Andrews	4680	6	1,501	New Brunswick
Saint John	4570	6	82,786	New Brunswick
Shippagan	4930	6	2,130	New Brunswick
St. Stephen	4700	6	3,233	New Brunswick
Woodstock	4910	6	4,277	New Brunswick
Acton Vale	4620	6	5,399	Quebec
Alma	5800	7A	21,406	Quebec
Amos	6160	7B	10,005	Quebec
Asbestos	4800	6	5,205	Quebec
Baie-Comeau	6020	7B	9,610	Quebec
Baie-Saint-Paul	5280	7A	4,868	Quebec
Bedford	4420	6	2,550	Quebec
Beloeil	4500	6	50,845	Quebec
Buckingham	4880	6	16,685	Quebec
Coaticook	4750	6	6,524	Quebec
Contrecoeur	4500	6	6,236	Quebec
Cowansville	4540	6	11,809	Quebec
Dolbeau	6250	7B	11,388	Quebec
Drummondville	4700	6	68,601	Quebec
Farnham	4500	6	6,731	Quebec
Fort-Coulonge	4950	6	2,359	Quebec
Gaspé	5500	7A	2,609	Quebec
Granby	4500	6	59,691	Quebec
Havre-Saint-Pierre	6100	7B	2,925	Quebec
Inukjuak	9150	8	1,312	Quebec
Joliette	4720	6	45,508	Quebec
Kuujuuaq	8550	8	1,353	Quebec
La Pocatière	5160	7A	3,928	Quebec
Lachute	4640	6	10,082	Quebec
Lac-Mégantic	5180	7A	5,647	Quebec
La Malbaie	5400	7A	3,520	Quebec
La Tuque	5500	7A	7,751	Quebec
Lavaltrie	4500	6	10,767	Quebec
Louiseville	4900	6	5,396	Quebec
Magog	4730	6	20,830	Quebec
Malartic	6200	7B	2,972	Quebec

City	HDD 18	Climate Zone	Population	Province
Maniwaki	5280	7A	3,778	Quebec
Matane	5510	7A	10,787	Quebec
Mont-Joli	5370	7A	5,604	Quebec
Mont-Laurier	5320	7A	7,644	Quebec
Montmagny	5090	7A	9,041	Quebec
Montréal	4200	6	3,519,595	Quebec
Nicolet	4900	6	5,669	Quebec
Plessisville	5100	7A	7,195	Quebec
Port-Cartier	6060	7B	5,609	Quebec
Puvirnituq	9200	8	1,038	Quebec
Québec	5080	7A	705,103	Quebec
Richmond	4700	6	3,046	Quebec
Rimouski	5300	7A	36,942	Quebec
Roberval	5750	7A	8,204	Quebec
Rouyn-Noranda	6050	7B	23,504	Quebec
Rivière-du-Loup	5520	7A	17,973	Quebec
Saint-Jean-sur-Richelieu	4450	6	84,685	Quebec
Salaberry-de-Valleyfield	4400	6	39,048	Quebec
Senneterre	6180	7B	2,239	Quebec
Sept-Îles	6200	7B	22,218	Quebec
Shawinigan	5050	7A	38,211	Quebec
Shawville	4880	6	1,203	Quebec
Sherbrooke	4700	6	139,565	Quebec
Sorel	4550	6	36,088	Quebec
Sainte-Agathe-des-Monts - Val-David	5390	7A	11,108	Quebec
Saint-Félicien	5850	7A	7,096	Quebec
Saint-Hyacinthe	4500	6	50,032	Quebec
Saint-Jérôme	4820	6	77,146	Quebec
Saint-Jovite	5250	7A	5,515	Quebec
Hudson	4520	6	21,419	Quebec
Témiscaming	5020	7A	1,361	Quebec
Thetford Mines	5120	7A	16,174	Quebec
Thurso	4820	6	2,533	Quebec
Trois-Rivières	4900	6	114,203	Quebec
Val-d'Or	6180	7B	25,541	Quebec
Varennnes	4500	6	20,575	Quebec
Verchères	4450	6	4,429	Quebec

<b>City</b>	<b>HDD 18</b>	<b>Climate Zone</b>	<b>Population</b>	<b>Province</b>
Victoriaville	4900	6	44,735	Quebec
Ville-Marie	5550	7A	2,113	Quebec
Waterloo	4650	6	3,401	Quebec
Windsor	4700	6	5,064	Quebec
Alexandria	4600	6	2,845	Ontario
Alliston	4200	6	18,809	Ontario
Almonte	4620	6	5,039	Ontario
Arnprior	4680	6	10,426	Ontario
Atikokan	5750	7A	1,944	Ontario
Attawapiskat	7100	8	1,501	Ontario
Barrie	4380	6	145,614	Ontario
Beaverton	4300	6	2,822	Ontario
Belleville	3910	5	67,666	Ontario
Belmont	3840	5	1,140	Ontario
Bracebridge	4800	6	9,232	Ontario
Bradford	4280	6	29,862	Ontario
Brantford	3900	5	98,179	Ontario
Brighton	4000	6	5,861	Ontario
Brockville	4060	6	21,854	Ontario
Campbellford	4280	6	3,473	Ontario
Cannington	4310	6	1,845	Ontario
Carleton Place	4600	6	11,936	Ontario
Chapleau	5900	7A	1,170	Ontario
Chatham	3470	5	43,550	Ontario
Chesley	4320	6	1,843	Ontario
Clinton	4150	6	3,049	Ontario
Cobourg	3980	5	19,031	Ontario
Cochrane	6200	7B	3,648	Ontario
Colborne	3980	5	1,577	Ontario
Collingwood	4180	6	20,102	Ontario
Cornwall	4250	6	45,723	Ontario
Corunna	3600	5	5,686	Ontario
Deep River	4900	6	3,658	Ontario
Deseronto	4070	6	1,645	Ontario
Dorchester	3900	5	3,911	Ontario
Dresden	3750	5	2,451	Ontario
Dryden	5850	7A	5,586	Ontario
Dundalk	4700	6	2,046	Ontario
Dunnville	3660	5	5,759	Ontario

<b>City</b>	<b>HDD 18</b>	<b>Climate Zone</b>	<b>Population</b>	<b>Province</b>
Durham	4340	6	2,609	Ontario
Dutton	3700	5	1,368	Ontario
Elliot Lake	4950	6	10,498	Ontario
Elmvale	4200	6	2,314	Ontario
Englehart	5800	7A	1,418	Ontario
Espanola	4920	6	3,693	Ontario
Exeter	3900	5	4,649	Ontario
Fenelon Falls	4440	6	2,464	Ontario
Fergus	4300	6	20,767	Ontario
Forest	3740	5	2,277	Ontario
Fort Erie	3650	5	14,621	Ontario
Fort Erie	3600	5	14,621	Ontario
Fort Frances	5440	7A	7,420	Ontario
Gananoque	4010	6	5,159	Ontario
Geraldton	6450	7B	1,828	Ontario
Glencoe	3680	5	2,126	Ontario
Goderich	4000	6	7,536	Ontario
Gravenhurst	4760	6	5,349	Ontario
Guelph	4270	6	132,397	Ontario
Haileybury	5600	7A	3,266	Ontario
Caledonia	3750	5	9,674	Ontario
Hagersville	3760	5	2,939	Ontario
Haliburton Village	4840	6	1,149	Ontario
Georgetown	4200	6	42,123	Ontario
Hamilton	3460	5	693,645	Ontario
Hanover	4300	6	7,413	Ontario
Hastings	4280	6	1,115	Ontario
Hawkesbury	4610	6	11,715	Ontario
Hearst	6450	7B	3,835	Ontario
Huntsville	4850	6	6,482	Ontario
Ingersoll	3920	5	12,587	Ontario
Iroquois Falls	6100	7B	2,955	Ontario
Kapuskasing	6250	7B	7,378	Ontario
Kemptville	4540	6	3,911	Ontario
Kenora	5630	7A	10,687	Ontario
Kincardine	3890	5	8,315	Ontario
Kingston	4000	6	117,660	Ontario
Kirkland Lake	6000	7B	6,305	Ontario

<b>City</b>	<b>HDD 18</b>	<b>Climate Zone</b>	<b>Population</b>	<b>Province</b>
Kitchener	4200	6	470,015	Ontario
Lakefield	4330	6	2,753	Ontario
Leamington	3400	5	32,991	Ontario
Lindsay	4320	6	20,713	Ontario
Listowel	4300	6	7,530	Ontario
London	3900	5	383,437	Ontario
Lucan	3900	5	2,541	Ontario
Markdale	4500	6	1,216	Ontario
Mattawa	5050	7A	1,786	Ontario
Midland	4200	6	24,353	Ontario
Milton	3920	5	101,715	Ontario
Milverton	4200	6	1,576	Ontario
Mississauga Beach	3780	5	4,662	Ontario
Mitchell	4100	6	4,573	Ontario
Moosonee	6800	7B	1,405	Ontario
Morrisburg	4370	6	2,385	Ontario
Mount Forest	4700	6	4,643	Ontario
Jarvis	3700	5	1,037	Ontario
Port Dover	3600	5	6,161	Ontario
Napanee	4140	6	7,439	Ontario
New Liskeard	5570	7A	4,402	Ontario
Newcastle	3990	5	9,167	Ontario
Bowmanville	4000	6	39,371	Ontario
North Bay	5150	7A	50,396	Ontario
Norwood	4320	6	1,380	Ontario
Orangeville	4450	6	30,734	Ontario
Orillia	4260	6	31,128	Ontario
Oshawa	3860	5	308,875	Ontario
Ottawa - Gatineau	4500	6	989,567	Ontario
Owen Sound	4030	6	22,032	Ontario
Paris	4000	6	12,310	Ontario
Parkhill	3800	5	1,737	Ontario
Parry Sound	4640	6	6,321	Ontario
Pembroke	4980	6	15,940	Ontario
Perth	4540	6	5,573	Ontario
Petawawa	4980	6	13,701	Ontario
Peterborough	4400	6	82,094	Ontario
Petrolia	3640	5	5,375	Ontario

<b>City</b>	<b>HDD 18</b>	<b>Climate Zone</b>	<b>Population</b>	<b>Province</b>
Picton	3980	5	4,702	Ontario
Plattsville	4150	6	1,366	Ontario
Port Colborne	3600	5	15,037	Ontario
Port Elgin	4100	6	7,862	Ontario
Port Hope	3970	5	12,587	Ontario
Port Perry	4260	6	9,453	Ontario
Port Stanley	3850	5	2,148	Ontario
Prescott	4120	6	3,965	Ontario
Chelmsford	5200	7A	6,215	Ontario
Red Lake	6220	7B	1,177	Ontario
Renfrew	4900	6	8,152	Ontario
Rockland	4600	6	12,302	Ontario
Sarnia	3750	5	72,125	Ontario
Sault Ste. Marie	4960	6	66,313	Ontario
Seaforth	4100	6	2,680	Ontario
Shelburne	4700	6	8,126	Ontario
Simcoe	3700	5	13,922	Ontario
Sioux Lookout	5950	7A	2,941	Ontario
Smiths Falls	4540	6	8,885	Ontario
Smithville	3650	5	5,489	Ontario
Southampton	4100	6	3,678	Ontario
St. Catharines - Niagara Falls	3540	5	229,246	Ontario
St. Marys	4000	6	6,951	Ontario
St. Thomas	3780	5	41,813	Ontario
Stirling	4220	6	2,030	Ontario
Stratford	4050	6	31,053	Ontario
Strathroy	3780	5	14,401	Ontario
Sturgeon Falls	5200	7A	6,798	Ontario
Sudbury	5180	7A	88,054	Ontario
Tavistock	4100	6	2,955	Ontario
Thamesford	3950	5	2,116	Ontario
Thunder Bay	5650	7A	93,952	Ontario
Tillsonburg	3840	5	15,594	Ontario
Timmins	5940	7A	29,331	Ontario
Timmins	6000	7B	29,331	Ontario
Toronto	3520	5	5,429,524	Ontario
Uxbridge	4240	6	11,832	Ontario
Walkerton	4300	6	4,517	Ontario
Wallaceburg	3600	5	10,098	Ontario

<b>City</b>	<b>HDD 18</b>	<b>Climate Zone</b>	<b>Population</b>	<b>Province</b>
Watford	3740	5	1,536	Ontario
Wawa	5840	7A	2,610	Ontario
Welland	3670	5	62,388	Ontario
West Lorne	3700	5	1,337	Ontario
Warton	4300	6	1,989	Ontario
Windsor	3400	5	287,069	Ontario
Wingham	4220	6	2,934	Ontario
Woodstock	3910	5	40,404	Ontario
Wyoming	3700	5	2,361	Ontario
Beausejour	5680	7A	2,895	Manitoba
Boissevain	5500	7A	1,656	Manitoba
Brandon	5760	7A	48,324	Manitoba
Dauphin	5900	7A	8,095	Manitoba
Flin Flon	6440	7B	4,791	Manitoba
Gimli	5800	7A	2,246	Manitoba
Lac du Bonnet	5730	7A	1,089	Manitoba
Morden	5400	7A	7,907	Manitoba
Neepawa	5760	7A	3,939	Manitoba
Portage la Prairie	5600	7A	12,949	Manitoba
Rivers	5840	7A	1,257	Manitoba
Selkirk	5700	7A	9,839	Manitoba
Steinbach	5700	7A	14,753	Manitoba
Swan River	6100	7B	3,964	Manitoba
The Pas	6480	7B	5,368	Manitoba
Thompson	7600	8	12,878	Manitoba
Virden	5620	7A	3,082	Manitoba
Winnipeg	5670	7A	711,925	Manitoba
Assiniboia	5180	7A	2,389	Saskatchewan
Biggar	5720	7A	2,165	Saskatchewan
Estevan	5340	7A	11,258	Saskatchewan
Hudson Bay	6280	7B	1,306	Saskatchewan
Humboldt	6000	7B	4,872	Saskatchewan
Kamsack	6040	7B	1,775	Saskatchewan
Kindersley	5550	7A	3,052	Saskatchewan
Maple Creek	4780	6	2,074	Saskatchewan
Meadow Lake	6280	7B	5,266	Saskatchewan
Melfort	6050	7B	5,778	Saskatchewan
Melville	5880	7A	4,127	Saskatchewan

<b>City</b>	<b>HDD 18</b>	<b>Climate Zone</b>	<b>Population</b>	<b>Province</b>
Moose Jaw	5270	7A	32,724	Saskatchewan
Nipawin	6300	7B	3,989	Saskatchewan
North Battleford	5900	7A	13,567	Saskatchewan
Prince Albert	6100	7B	35,102	Saskatchewan
Fort Qu'Appelle	5620	7A	1,920	Saskatchewan
Regina	5600	7A	214,631	Saskatchewan
Rosetown	5620	7A	2,331	Saskatchewan
Saskatoon	5700	7A	245,181	Saskatchewan
Swift Current	5150	7A	16,022	Saskatchewan
Weyburn	5400	7A	10,679	Saskatchewan
Yorkton	6000	7B	16,041	Saskatchewan
Athabasca	6000	7B	1,250	Alberta
Banff	5500	7A	7,851	Alberta
Barrhead	5740	7A	4,387	Alberta
Beaverlodge	5700	7A	2,327	Alberta
Brooks	4880	6	14,436	Alberta
Calgary	5000	7A	1,237,656	Alberta
Camrose	5500	7A	18,520	Alberta
Canmore	5400	7A	11,764	Alberta
Cardston	4700	6	3,258	Alberta
Claresholm	4680	6	3,424	Alberta
Cold Lake	5860	7A	6,678	Alberta
Coleman	5210	7A	1,475	Alberta
Drumheller	5050	7A	6,439	Alberta
Edmonton	5120	7A	1,062,643	Alberta
Edson	5750	7A	8,148	Alberta
Fairview	5840	7A	2,598	Alberta
Fort MacLeod	4600	6	2,708	Alberta
Fort McMurray	6250	7B	66,573	Alberta
Fort Saskatchewan	5420	7A	23,895	Alberta
Grande Prairie	5790	7A	62,320	Alberta
High River	4900	6	13,420	Alberta
Hinton	5500	7A	9,205	Alberta
Jasper	5300	7A	3,948	Alberta
Lac la Biche	6100	7B	2,294	Alberta
Lacombe	5500	7A	12,442	Alberta
Lethbridge	4500	6	87,572	Alberta
Manning	6300	7B	1,072	Alberta
Medicine Hat	4540	6	62,935	Alberta

<b>City</b>	<b>HDD 18</b>	<b>Climate Zone</b>	<b>Population</b>	<b>Province</b>
Peace River	6050	7B	3,924	Alberta
Pincher Creek	4740	6	3,523	Alberta
Red Deer	5550	7A	99,718	Alberta
Rocky Mountain House	5640	7A	6,429	Alberta
Slave Lake	5850	7A	6,155	Alberta
Stettler	5300	7A	5,862	Alberta
Stony Plain	5300	7A	16,271	Alberta
Taber	4580	6	8,548	Alberta
Turner Valley	5220	7A	2,249	Alberta
Valleyview	5600	7A	1,421	Alberta
Vegreville	5780	7A	5,436	Alberta
Vermilion	5740	7A	3,617	Alberta
Wainwright	5700	7A	6,153	Alberta
Wetaskiwin	5500	7A	12,486	Alberta
Whitecourt	5650	7A	9,515	Alberta
One Hundred Mile House	5030	7A	1,811	British Columbia
Abbotsford	2860	4	121,279	British Columbia
Ashcroft	3700	5	1,084	British Columbia
Burns Lake	5450	7A	1,932	British Columbia
Campbell River	3000	5	35,138	British Columbia
Castlegar	3580	5	9,023	British Columbia
Chilliwack	2780	4	73,161	British Columbia
Courtenay	3100	5	45,018	British Columbia
Cranbrook	4400	6	19,259	British Columbia
Crofton	2880	4	1,373	British Columbia
Dawson Creek	5900	7A	11,574	British Columbia
Duncan	2980	4	23,278	British Columbia
Elkford	4600	6	1,752	British Columbia
Fernie	4750	6	4,850	British Columbia
Fort Nelson	6710	7B	3,366	British Columbia
Fort St. John	5750	7A	19,897	British Columbia
Golden	4750	6	3,240	British Columbia
Grand Forks	3820	5	3,953	British Columbia
Hope	3000	5	4,067	British Columbia
Kamloops	3450	5	78,026	British Columbia
Kelowna	3400	5	151,957	British Columbia
Kimberley	4650	6	4,513	British Columbia
Kitimat	3750	5	6,394	British Columbia
Ladner	2600	4	22,193	British Columbia

<b>City</b>	<b>HDD 18</b>	<b>Climate Zone</b>	<b>Population</b>	<b>Province</b>
Ladysmith	3000	5	10,637	British Columbia
Lillooet	3400	5	1,560	British Columbia
Mackenzie	5550	7A	3,262	British Columbia
Merritt	3900	5	5,321	British Columbia
Mission	2850	4	33,261	British Columbia
Nakusp	3560	5	1,130	British Columbia
Nanaimo	3000	5	92,004	British Columbia
Nelson	3500	5	10,664	British Columbia
Osoyoos	3100	5	4,520	British Columbia
Parksville	3200	5	23,574	British Columbia
Penticton	3350	5	33,617	British Columbia
Port Alberni	3100	5	20,712	British Columbia
Port Hardy	3440	5	3,643	British Columbia
Port McNeill	3410	5	2,064	British Columbia
Powell River	3100	5	12,384	British Columbia
Prince George	4720	6	65,510	British Columbia
Prince Rupert	3900	5	11,733	British Columbia
Princeton	4250	6	2,745	British Columbia
Quesnel	4650	6	12,064	British Columbia
Revelstoke	4000	6	6,719	British Columbia
Salmon Arm	3650	5	12,875	British Columbia
Sechelt	2680	4	8,832	British Columbia
Smithers	5040	7A	5,351	British Columbia
Sooke	2900	4	9,269	British Columbia
Squamish	2950	4	17,587	British Columbia
Terrace	4150	6	13,663	British Columbia
Trail - Fruitvale	3600	5	12,643	British Columbia
Ucluelet	3120	5	1,576	British Columbia
Vancouver	2825	4	2,264,823	British Columbia
Vernon	3600	5	48,073	British Columbia
Victoria	2650	4	335,696	British Columbia
Whistler	4180	6	8,713	British Columbia
White Rock	2620	4	93,729	British Columbia
Williams Lake	4400	6	10,508	British Columbia
Whitehorse	6580	7B	25,085	Yukon
Haines Junction	7100	8	613	Yukon
Faro	7300	8	348	Yukon
Watson Lake	7470	8	790	Yukon
Dawson city	8120	8	1,375	Yukon

<b>City</b>	<b>HDD 18</b>	<b>Climate Zone</b>	<b>Population</b>	<b>Province</b>
Aklavik	9600	8	623	Northwest Territories
Fort Good Hope	8700	8	570	Northwest Territories
Fort McPherson	9150	8	684	Northwest Territories
Fort Providence	7620	8	719	Northwest Territories
Fort Simpson	7660	8	1,296	Northwest Territories
Fort Smith	7300	8	2,709	Northwest Territories
Hay River	7550	8	3,824	Northwest Territories
Inuvik	9600	8	3,536	Northwest Territories
Norman Wells	8510	8	818	Northwest Territories
Behchokò (Rae-Edzo)	8300	8	2,010	Northwest Territories
Yellowknife	8170	8	20,607	Northwest Territories
Arviat (Eskimo Point)	9850	8	2,657	Nunavut
Baker Lake (Qamani'tuaq)	10700	8	2,069	Nunavut
Cambridge Bay (Iqaluktuuttiaq)	11670	8	1,766	Nunavut
Kugluktuk (Coppermine)	10300	8	1,491	Nunavut
Rankin Inlet (Kangiqliniq)	10500	8	2,842	Nunavut

Table C-27: Main types of space heating fuels in each province and territories of Canada

Regions	Share of main heating fuel types by province, $r_{fuel\ typ}^p$			
	Electricity	Natural Gas	Oil	Wood
Canada	39%	50%	7%	6%
NL	57%	0%	21%	22%
PE	0%	0%	76%	32%
NS	29%	0%	54%	26%
NB	66%	0%	13%	23%
QC	85%	3%	8%	7%
ON	14%	76%	5%	3%
MB	37%	61%	0%	0%
SK	11%	87%	0%	0%
AB	9%	91%	0%	0%
BC	39%	55%	3%	5%
YT	39%	50%	7%	6%
NT	39%	50%	7%	6%
NU	39%	50%	7%	6%

Table C-28: Provincial GHG emissions factors by heating fuel types

Regions	GHG Emissions Factors by Heating Fuel [g/kWh]			
	Electricity	Natural Gas	Oil	Wood
NL	38.0	176.4	256.4	344.5
PE	330.0	176.4	256.4	344.5
NS	750.0	176.4	256.4	344.5
NB	330.0	176.4	256.4	344.5
QC	1.8	175.1	256.4	344.5
ON	40.0	175.2	256.4	344.5
MB	2.1	175.0	256.4	344.5
SK	710.0	169.8	256.4	344.5
AB	860.0	178.9	256.4	344.5
BC	12.0	178.7	256.4	344.5
YT	50.0	176.4	256.4	344.5
NT	210.0	176.4	256.4	344.5
NU	770.0	176.4	256.4	344.5