Impact on building energy performance by deployment of dynamic insulation in residential buildings in Canada

by

Anoopkumar Shukla

Bachelor of Engineering, Gujarat Technological University, 2017

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Dr. Caterina Valeo, Department of Mechanical Engineering
Supervisor

Dr. Phalguni Mukhopadhyaya, Department of Civil Engineering
Supervisor

Abstract

This report summarizes the results of an analysis evaluating the energy performance of small residential buildings in Canada. Using the HOT2000, an energy simulation modelling program created and maintained by Natural Resources Canada, the goal of this work is to investigate dynamic insulations, run simulations, and assess the possible energy savings brought on by using dynamic insulation materials (DIMs) in exterior walls in place of conventional static insulation. DIMs can alter their thermal properties based on control procedures, unlike conventional static insulations, to accomplish desired goals. In this analysis, exterior walls with DIMs are controlled to minimize heating and cooling thermal loads in residential buildings, located in different climate zones in Canada. In particular, 2-step manual controls are used to switch the R-value of variable insulation between low and high levels based on the thermal interactions between the outside and inside a prototypical one-story home, thereby reducing heating and cooling requirements while maintaining thermal comfort. According to the analysis's findings, dynamic insulations can drastically lower the amount of energy needed to run heating and cooling systems. The use of 2-step control techniques operating DIMs, in particular, can lower yearly energy consumption by up to 44% for space cooling and by up to 33% for space heating, resulting in up to 36% annual energy savings.

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Finally, I want to thank all the professors who guided and helped me during my studies, all the staff at the administrative office and the library as well as fellow students at UVIC, with whom I had a lot of fun over the past two years to learn and grow together.

Abbreviation

DI/DIMS – Dynamic insulation/ Dynamic insulation materials
SIS – Switchable insulations
CO_2 – Carbon dioxide
MJ - Megajoule
PJ – Petajoule
HVAC – Heating, ventilation, and air conditioning system
T_i – Temperature at indoor wall surface
T_m – Temperature at middle of wall surface
T_o – Temperature at outdoor wall surface
RSI – R-value System International
SHGC – Solar heat gain coefficient
ER – Energy rating
ACH – Air changes per hour
HVI – Home ventilating institute
HVR – Heat recovery ventilators
UVIC – University of Victoria
ECM – Electronically commutated motor
VCHP- Variable conductance heat pipe
CSA – Canadian standards association
HDD – Heating degree days
IECC – International Energy Conservation Code
NBC – National Building code
NEC/NECB – National Energy Code of Canada for Buildings
AZ – Arizona (A U.S. state)
NV – Nevada (A U.S. state)
MD – Maryland (A U.S. state)
CO – Colorado (A U.S. state)
CA – California (A U.S. state)
WA – Washington (A U.S. state)
MN – Minnesota (A U.S. state)
BC – British Columbia (A Canadian province)
ON – Ontario (A Canadian province)
QC – Quebec (Canadian province)
AB – Alberta (Canadian province)

1. Introduction

1.1 Dynamic insulation and its importance

The building sector is a significant contributor to global energy consumption. Nearly 36% of the world's energy demand and roughly 40% of all direct and indirect CO2 emissions come from buildings. [1]. In Canada alone, the residential and commercial sectors annually consume about 2434.6 petajoule (PJ), which is around 30% of total Canada energy consumption [2]. Additionally, HVAC and water heating accounted for 83% of all energy utilized in residential structures in 2013. [2].

To counter unfavorable environmental effects such as climate change and global warming from the energy sources, a wide range of energy efficiency standards and programs are enforced and being followed by countries around the world. A special emphasis of building energy efficiency standards is the enhancement of the energy performance of building envelope elements including exterior walls. As a result, the application of high-performance thermal insulation systems has become widely expected and required for opaque building envelopes.

However, having highly insulated envelope elements is not always desirable. It is advantageous to have low R-value insulation in summer to eject indoor heat to the outside, thus reducing cooling load of the building[3]–[5]. Static insulation choices for outside walls can be effectively replaced by dynamic insulation systems with changeable thermal characteristics to lower heating and cooling loads in both residential and commercial buildings. [6]. Additionally, due to climate change, colder places around the world are now experiencing warmer and longer summers. As houses in these places are constructed considering cold weather, they are less efficient in summers. A dynamic insulation system can play an important role here.

Dynamic insulation, also known as switchable insulation, is a type of adaptive building envelope that can be defined as an insulation structure within the envelope that is capable of switching back and forth between an insulated and uninsulated conditions to control how much heat is transferred through building walls [7]. Inspired by the response of animal skins to the variation in thermal environment, the core idea is to selectively transfer heat across the envelope, making it possible to insulate heat flux and dissipate/absorb heat on-demand, thereby supplementing conventional heating and cooling technologies for the indoor environment as the need arises.

Although very limited research is published on use of variable insulation in building space, similar technology exist in other applications such as thermal regulation in batteries [8], vehicles [9], and aerospace applications [10]–[12]. A systematic review of the mechanisms of heat transfer and applications in a wide range of engineering fields has revealed five main switchable insulation technologies that can be applied to the build environment including [7], [13]:

- Active vacuum thermal insulation: As shown in diagram the system typically consists of: (1) an envelope which seals the volume, and (2) a pump which controls the pressure inside the volume[14]. The core idea of vacuum-based switchable thermal insulation is to alternate the heat transfer by reversibly pressurizing or evacuating the enclosure with a thermally conductive gas[14].

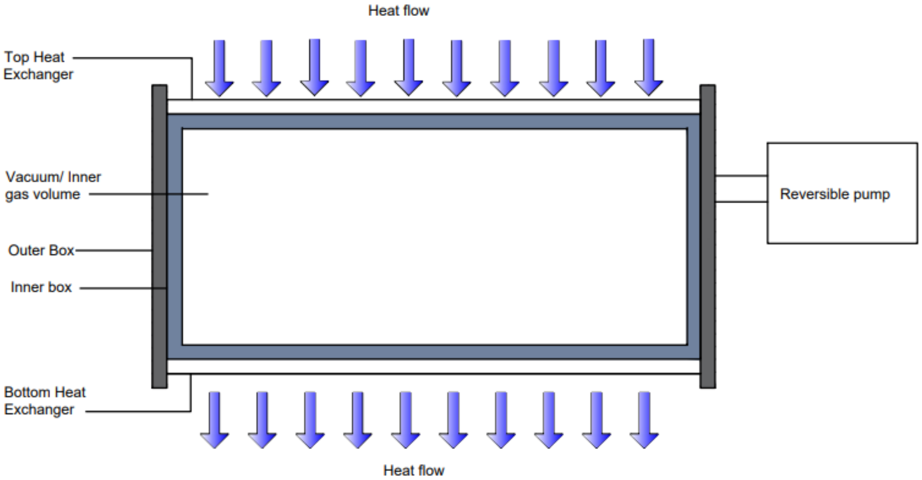

Figure 1. Active vacuum thermal insulation[14]

- Mechanical contact switch insulation: It is one of the most intuitive schemes for controlling the heat flux across solid surfaces. It involves bringing two solid surfaces into/off mechanical contact[14]. The presence/absence of mechanical contact causes a change in the thermal transfer mechanism from gaseous convection or to solid thermal conduction, resulting in a rapid alternation in overall heat transfer rate[14]. Typically, a mechanical thermal switch consists of: (1) two polished solid surfaces, (2) an actuator which separates two surfaces or brings two surfaces into contact, and (3) an enclosed cavity[14].

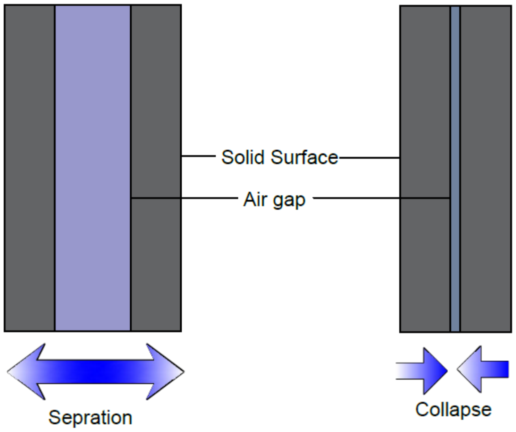

Figure 2. Mechanical contact switch insulation[14], [15]

- Suspended particle based switchable insulation: It consists of thermally conductive insoluble particles and here external electric and/or magnetic fields is used to beak or form microstructures[14]. As magnetic fields are applied, magnetite nanoparticles suspended align into chain-like structures, and they revert to the disordered state, when the external magnetic field is removed[14], [16].

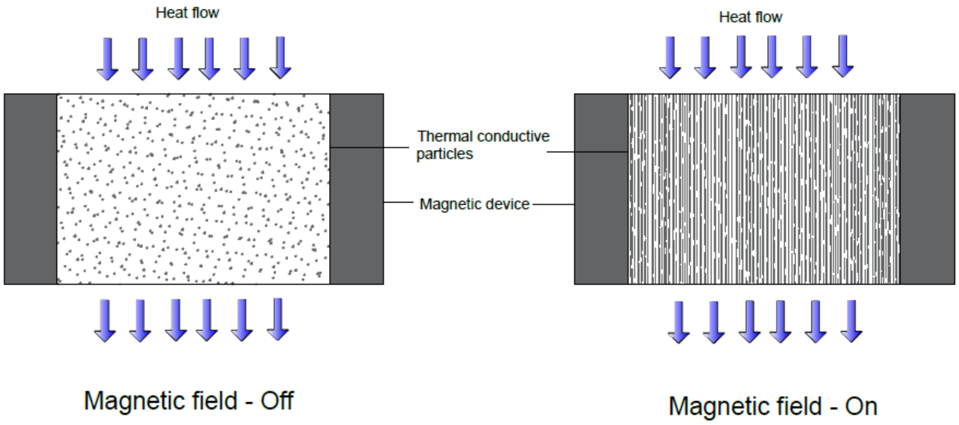

Figure 3. Suspended particle based switchable insulation[14], [17]

- Pipe-embedded switchable insulation: Pipe-embedded switchable insulation controls the heat transfer across the pipes, by accelerating/impeding the motion of fluid particles[14]. In the insulated state, the fluid in the pipe is stationary[14]. Due to the large length-to-diameter ratio of the pipe, the heat transfer rate through it is almost same as the fluid conduction[18]. Once switched to the conductive state, the fluid is mobilized by the actuators, leading to a more effective convection-dominated heat transfer mode[14].

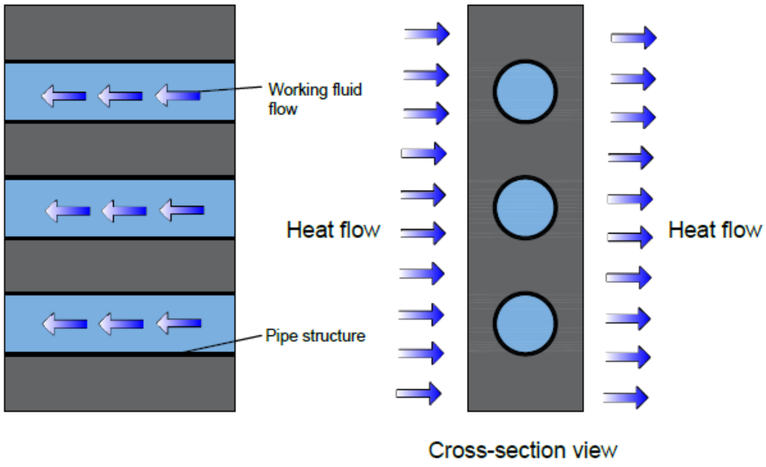

Figure 4. Pipe-embedded switchable insulation[14], [19]

- Phase-change switchable insulation: The phase of substances undergoes transitions, most commonly between solid, liquid and gaseous states, as a result of the change in boundary conditions, such as temperature and pressure[14]. During phase transitions, part of potential energy in electrostatic bonds will be converted into kinetic energy, or vice versa[14], [20]. The basic idea of a phase-change switchable insulation is to intermittently interrupt the evaporation-condensation cycle, leading to an alternation in heat transfer between (1) a conductive state, where heat is mostly transported by evaporation and condensation processes, and (2) an insulated state, where the gaseous conduction is dominant[14]. The variable conductance heat pipe (VCHP) is one of the most effective phase-change switchable insulation (Figure 14). A typical VCHP consists of four basic elements: (1) a working fluid which undergoes phase transition during heat transfer, (2) a sealed container, consisting of evaporator, condenser and transport (adiabatic) section, (3) a wick structure, pumping condensates back to the evaporator by capillary pressure and (4) a control unit which purposefully and reversibly interrupts the evaporation- condensation cycle[14].

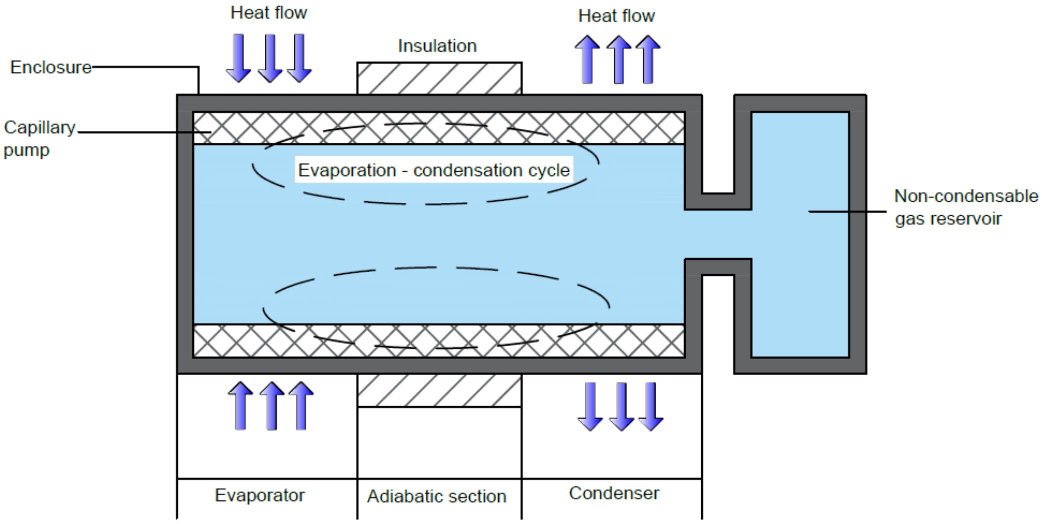

Figure 5. Phase-change switchable insulation[14]

1.2 Energy savings by dynamic insulations

Several switchable insulation technologies were investigated to evaluate potential energy savings from them when applied to building envelopes. For instance, Menyhart and Krarti [21] applied a 2-step variable insulation to exterior walls in US residential buildings. They investigated two control schemes to determine effectiveness of DIMs, 1) Automatic control which triggered the switching mechanism using temperature sensors based on temperature profile, 2) by switching control mechanism manually based on patterns in weather and climate. Climate had a considerable impact on how well DIMs worked, with overall energy savings ranging from 7% to 42%. Then, Dehwah and Krarti [6] analyzed the energy benefits of DIMs by utilizing it on the roof of US residential buildings. By using 2-step control strategies operating SISs in the dwellings, annual energy consumption for space cooling was reduced by up to 44% and up to 17% energy saving was reported for space heating. Rupp and Krarti [3] considered a multi-step control strategy to operate switchable wall assemblies for US residential buildings. It is concluded that while the multi-step controls can provide additional energy use reduction, the simple 2-step ruleset capture most of the expected energy savings from SIS technologies.

These papers confirm the energy savings by deployment of DIMs in residential buildings in US, however no such analysis is done for Canadian cities. Despite having cities with similar climate zones, results would be different for Canadian cities as they have different source energy factor compared to the US [24], [25]. Also, there is difference in building standards code used in US and Canada (NBC and NEC/NECB in Canada, while most US states follows the IECC code) which might not produce the similar results. In addition, this thesis aims to provide more realistic results by assigning roof and floor insulation as per building code rather than assigning the adiabatic properties.

Table 1. Input data comparison of available literature depicting energy savings by dynamic insulation

Reference, Year	Location studied	Climate zones	Software	Building type	Floor area (m^2)	Height (m)	WWR (%)	U-Factor ($W/m^2.K$) [Climate zone - U-factor]	SHGC [Climate zone - SHGC]	Occupancy	Roof (RSI) [Climate zone - RSI]	Floor (RSI) [Climate zone - RSI]	Wall (RSI) [Climate zone - RSI]	Source energy factor	Building code
[15], 2020	Phoenix, AZ; Las Vegas, NV; Baltimore, MD; Denver, CO	2b,3b,4a,5b (IECC Climate zones)[16]	COMSOL Multiphysics [17]	NA	NA	0.286	NA	NA	NA	NA	NA	NA	3.78	NA	IECC [16]
[14], 2016	44 Cities across US	All climate zones (IECC Climate zones) [16]	3R2C [4], [18], [19]	Single storey - detached house	64	3	15	1-0.5; 2-0.4; 3,4-0.35; 5,6,7-0.32	1,2,3 - 0.25; 4,5,6,7 - 0.39	2	Adiabatic	Adiabatic	1,2 - 1.9; 3,4,5 - 3; 6,7,8 - 3.9	1.092 Natural gas, 3.365 Electricity [31]	IECC [16]
[6], 2020	Phoenix, AZ; San Francisco, CA; Seattle, WA; Golden, CO and Minneapolis, MN	2,3,4,5,6 (ASHRAE Climate zones) [20]	3R2C [4], [18], [19]	Single storey - detached house	225	3	15	1.9	0.3	3	5.2	0.38	2.21	1.092 Natural gas, 3.365 Electricity [31]	IECC [16]
Current paper	Vancouver, BC; Toronto, ON; Montreal, QC; Calgary, AB	4,5,6,7A (ASHRAE Climate zones) [20]	HOT2000 [21], [22]	Single storey - detached house	100	3	7.2	0.98	0.37	2- Adults, 1- Children	4-5.18; 5-6.41; 6-6.41; 7-7.25	4-4.41; 5-5.46; 6-5.46; 7-6.17	4 - 3.17; 5 - 3.60; 6 - 4.05; 7 - 4.76	1.01 Natural gas, 1.96 electricity [30], [31]	NBC [29]

1.3 Objectives

The thesis aims at investigating the potential energy savings by deploying DIMs in residential buildings in Canada. First, a brief description of the residential building model used for the analysis is provided. Then, the modelling approach is described including the simulation environment and the two-step control rule sets considered in this study. The energy performance of the 2-step insulation in exterior wall for the prototypical residential building is evaluated under different climatic conditions. Finally, these results are summarized and studied for a wide range of operating conditions.

2. Modelling approach

2.1 Simulation tool

HOT2000, an energy simulation modelling program, served as the simulation tool for this investigation. It was created and being maintained by Natural Resources Canada to support the EnerGGuide Rating System, ENERGY STAR for New Homes, and R-2000 home energy efficiency efforts. The application has undergone rigorous validation testing against hourly simulation programs and real-world house monitoring. [22].

Program requires input data such as construction features (above and below grade), building geometry, mechanical component specifications (HVAC & domestic hot water), geographical location of the home and have provision to input additional information such as fuel costs and economic data. This input data is entered via a graphical user interface. Simulation provides reports on the house analysis, weather file, economic and financial conditions, and fuel costs. The house analysis contains comprehensive monthly tables, annual heat loss data, HVAC load figures, etc.

A major advantage of this software is that it performs the building energy simulation very quick, in seconds. This can be used to assess the cost-effectiveness of energy efficiency improvements and annual energy use. The simulation includes a thorough air infiltration model, a foundation heat loss model, and it compensates for thermal bridging in wall assemblies through studs. Heat balances are carried out in the basement, main floor and the attic. Additionally, it can simulate five different fuel types and a wide range of HVAC systems, including heat pumps and heat recovery ventilators.

2.2 Control strategy

Major advantage of Dynamic insulation is that its R-values can be varied between its upper and lower limit for energy savings and human comfort. Greater control over thermal conductivity would be possible with a control system that has more than two steps. However, simulation done in this project involves only two step control mechanism (low-R and high-R) applied to the exterior walls. At all times, the dynamic insulation is in one of these two states. The resistance of the wall could be set to low-R or high-R either by manually switching it or by using an automated system.

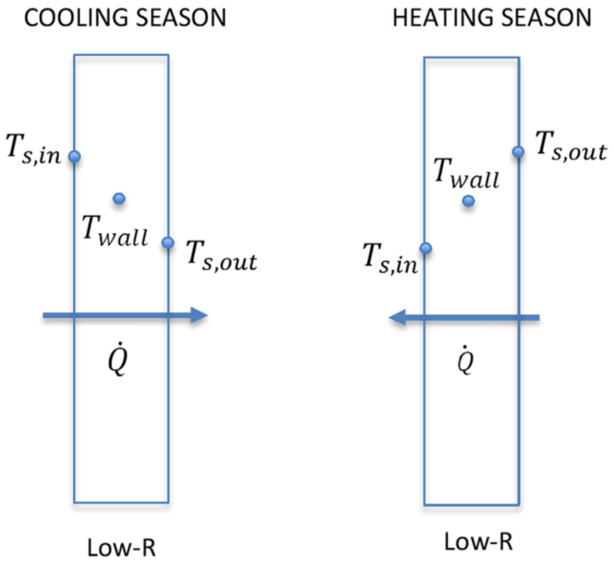

Figure 6. Dynamic insulation: Control scheme scenarios with Low-R [21]

2.2.1 Automated control

For the automated control system, it would be required to place temperature sensors in three locations: indoor wall surface (T_i), middle of the wall (T_m), and outdoor wall surface temperature (T_o), as well as the operation mode (heating or cooling season) and the thermostat setpoint. The wall would switch to a low-R value in two different scenarios: 1) If it is heating season and $T_i < T_m < T_o$, or 2) if it is cooling season and $T_i > T_m > T_o$. In both cases, the wall would be programmed to remain at the lower R-value until the setpoint temperature is reached. Otherwise, the wall would remain at the high-R value.

2.2.2 Manual control

Manual control would be similar to opening or closing a window with a crank. One could imagine turning a crank to change the R-value of a wall. This could be done daily or seasonally.

2.3 Building model description

The baseline model used in this analysis resembles to a small residential building in Canada. Modelled building is single detached one storey house. Building's front is in east direction, with rectangular footprint (10m X 10m) and height of 3 m. It is a simple building, and it has only one zone for heating and cooling. It does not have basement and comprises of an attic/hip constructed roof and slab on grade flooring. Each wall has a window of similar shape and size, and door is located in east wall. Soil is assumed to be mixture of dry sand, loam, and clay, with normal thermal conductivity. The water table level is assumed to be normal (7-10m/23-33ft). Light thermal mass is used in the construction of the house. These parameters are selected as per the Natural Resource Canada guidelines [23].

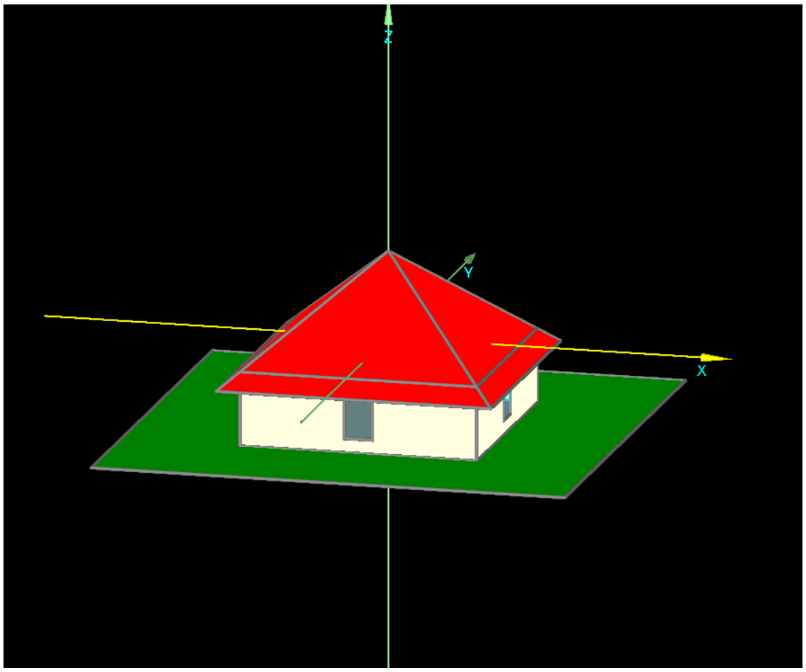

Figure 7. Baseline Building as viewed from the east direction

Surface area of different building components in heated space are depicted in table 2. As per heat transfer fundamentals, heat gain or heat loss through a building is proportion to the surface area of the building components in the heating space [24]. The table makes it clear that outside walls, ceilings, and floors should receive top priority if heat movement through a building is to be minimized.

Table 2. Building components area

Building Components	**Net area (m^2)**
Ceiling	100.00
Exterior Walls	109.47
Doors	1.89
North Window	2.16
South Window	2.16
East Window	2.16
West Window	2.16
Slab on Grade	100

2.3.1 Roof/Ceiling

Modelled building has attic/gable type of roof. The sloped roof constitutes of asphalt shingles at exterior and has Plywood/Part. bd 12.7 mm (1/2 in) as sheathing material. Their R-value is 0.08 RSI and 0.11 RSI respectively. Gable end has Hollow metal/vinyl cladding layer at exterior, and it uses Plywood/Part. bd 9.5 mm (3/8 in) as sheathing. R-value of cladding and sheathing is 0.08 RSI and 0.11 RSI respectively. Total cavity volume is 85.1 m^3 with ventilation rate of 0.50 ACH/hr. Other parameters are specified in the table 3.

Table 3. Roof parameters

	Construction type	Roof slope	Heel height (m)	Section Area (m2)
Ceiling	Attic/gable	5.004/12	0.13	100.00

2.3.2 Exterior walls

Components of exterior walls are specified in table 4. They are divided in four categories corresponding to the direction they face. HOT2000 uses number of corners and intersections to classify interior features such as bedrooms, kitchen etc. in the house. Walls are assumed to not have lintels for any of the openings.

Table 4. Exterior wall parameters

Wall label	Direction facing	Number of corners	Number of intersections	Height (m)	Length (m)	Area (m^2)
Wall_East	East	2	2	3.0	10.0	30.0
Wall_West	West	2	2	3.0	10.0	30.0
Wall_North	North	2	2	3.0	10.0	30.0
Wall_South	South	2	2	3.0	10.0	30.0

2.3.3 Door

Modelled building has a single door, in east wall. It is labelled according to the wall location in which it is fitted and are assumed to be energy star rated. They are assumed to be wooden with solid core and have RSI of 0.53 W/m.K.

Table 5. Door parameters

Label	Location	Height (m)	Width (m)	Gross area (m^2)	RSI (W/m.K)
Door_East	Wall_East	2.1	0.9	1.89	0.53

2.3.4 Windows

Windows consist of clear double-pane glass along with the wooden frame and they are assumed to be energy star rated. Each wall has a window, and they are labeled as per wall location. Window modeled without overhangs as per HOT2000 energy modelling guidelines [23].

Table 6. Windows parameters

Label	Location	Overhang width (m)	Header height (m)	Window width (m)	Window height (m)	Toral area (m2)
South	Wall_South	0	0	1.2	1.8	2.16
East	Wall_East	0	0	1.2	1.8	2.16
West	Wall_West	0	0	1.2	1.8	2.16
North	Wall_North	0	0	1.2	1.8	2.16

Windows are designed considering parameters shown in table 6 and their final performance parameters are as described in table 7. Window Energy Rating (ER 2009) estimated for actual dimensions is shown in table 8. Air tightness type and air leakage rate is assumed to be CSA A1 and 1.86 L/s.m^2 respectively. Above grade wall area occupied by windows is 7.2%.

Table 7. Windows design parameters

RSI - Centre of glass	RSI - Edge of glass	RSI – Frame	Frame height (m)	Centre of glass SHGC
1.205	0.833	0.586	39.3	0.42

Table 8. Windows actual performance parameters

Label	Curtain factor	Shutter (RSI)	Window (RSI)	SHGC	ER
South	1	0	1.012	0.3779	38.5
East	1	0	1.012	0.3779	38.5
West	1	0	1.012	0.3779	38.5
North	1	0	1.012	0.3779	38.5

2.3.5 Foundation

Building has slab-on-grade type of foundation and insulation is provided below slab. Floor is rectangular in shape and has width and length of 10.0 m and it does not have skirt or any thermal break. Floor is made up of concrete and do not have crawl space and basement. Except for the footing and foundation wall, the slab's bottom is completely insulated (i.e., the insulation begins 0.25 m (10 in) from the edge). Non-brick veneer or bricks thermally separated from the concrete floor makes up the first floor. It is assumed that floor is constructed above the frostline.

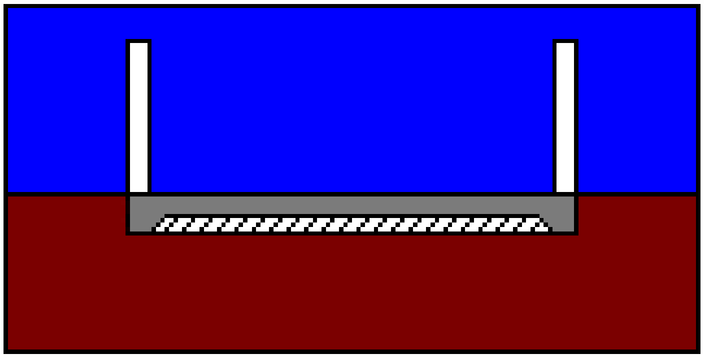

Figure 8. Foundation configuration

2.4 Internal loads

Since internal gains have been shown to affect the performance of DIMs [4], they were included in the model. Park et al. [4] showed that accounting for solar heat gain and internal gains in the model reduced the potential heating savings and increased the potential cooling savings. Also, internal gains increase the cooling demand in the summer and reduce the heating load in the winter. Occupants, lighting, and equipment are primary source of the internal load. The internal loads used in the model are listed in Table 9.

Table 9. Internal loads

Source	kWh/day
Occupants, 2 adults and 2 children for 50% of the time	2.4
Interior lighting	2.0
Electrical Appliances	9.0
Other	9.0

2.5 Air leakage and mechanical ventilation

HOT2000 uses CAN/CSA-F326 standard to establish the ventilation requirement of the building based on its enclosed spaces and same for the modelled house is stated below in table 10 [25]. Building envelope has surface area of 100.00 m^2 *(refer Table 2.)*. Maximum supply and exhaust air rate is calculated to be 30 L/s by the software and ACH is set to 0.29 [26]. Air tightness of the building is assumed to be 3.57 ACH @50 Pa.

Table 10. F326 Ventilation requirements

Room	Capacity, L/s
Kitchen, Living Room, Dining Room	3 rooms @ 5.0 L/s: 15.0 L/s
Bedroom	1 rooms @ 10.0 L/s: 10.0

	L/s
Bathroom	1 rooms @ 5.0 L/s: 5.0 L/s
Basement Rooms	0.0 L/s

Building leakage fractions are depicted in table 11. Estimated equivalent leakage area @10 Pa is 778.79 cm^2 and normalized leakage area @10 Pa is 2.4636 cm^2/m^2. Estimated airflow required to produce pressure difference of 5 Pa and 10 Pa is 50 L/s and 78 L/s, respectively and estimated airflow is calculated using considering equivalent leakage area to be 311.52 cm$^{2.}$

Table 11. Building components leakage fraction

Building component	Leakage fraction
Ceiling	0.3
Walls	0.5
Floors	0.2

2.6 Building component sizing

2.6.1 Central ventilation system

Modelled building utilizes LIFEBREATH 95 Max, HVI certified heat recovery ventilator (HRV) system to meet indoor air requirements for whole building. HRV system is capable of providing supply airflow and exhaust airflow at 35.0 L/S, which is appropriate against design requirement of 30 L/S. Fan and preheater power at 0.0°C and -25.0°C is adjusted at 112 Watts and 133 Watts respectively. Sensible heat recovery efficiency of the system at 0.0°C and -25.0°C is 88% and 68% and total heat recovery efficiency in cooling mode is 25% [27]. Depressurization limit of vented combustion appliance is set to 5.00 Pa.

Table 12. Supply and exhaust ventilation duct specifications

	Ventilation supply duct	Ventilation exhaust duct
Location	Main floor	Main floor
Length	1.5 m	1.5 m
Insulation	0.7 RSI	0.7 RSI
Type	Flexible	Flexible
Diameter	152.4	152.4
Sealing characteristic	Sealed	Sealed

Supply and exhaust ventilation ducts are assumed to have similar specification as specified in table 12. Modelled building being single storey with no basement, location of supply and exhaust duct is on the main floor. Duct is assumed to be flexible and sealed following industry standards.

2.6.2 Heating and cooling components

HOT2000 software has capability to estimate capacity of heating and cooling components based on various parameters of the modelled house such as location of the house, localized weather, insulation level in building components (walls, roof, floor, windows, and doors), construction practice etc. However, in this project capacity of heating and cooling components is kept unchanged for all the simulations. These components are sized to meet heating and cooling requirements in each test location, with varying insulation from 0.4 RSI to 5.46 RSI. This is done to ensure the simulated building has same operating conditions while simulating. Building temperature requirements are specified in table 13.

Table 13. House setpoint temperatures

Heating temperature	
Daytime setpoint	21°C
Nighttime setpoint	18°C
Nighttime setback duration	8 Hours
24 hours average	20°C

Cooling temperature	25°C

2.6.2.1 Space heating system

January is selected as design month and required indoor temperature for heating is considered as 21°C to size space heating system. Induced draft fan/boiler-based furnace is used for space heating purpose which uses natural gas as primary fuel. Output capacity of the designed heating system is 17.50 kW with steady state efficiency of 80%. Power rating of high-speed motor is calculated to be 340 watts.

Table 14. Heating system specification

Primary heating fuel	Natural gas
Specified output capacity	17.5 Kw
Steady state efficiency	80.00%
Fan mode	Auto
ECM motor	No
Low speed fan power	0 Watts
High speed fan power	340 Watts

2.6.2.2 Air conditioning system

Central split type air conditioning system is used to fulfil the cooling demand in the modelled house, and it is assumed to be integrated with the heating system. Air conditioning system is sized by considering July as design month and required indoor temperature for cooling to be 25°C. Specifications of the air conditioning is depicted in table 15.

Table 15. Air conditioning system specification

Capacity	2000 Watts
Sensible heat ratio	0.76
Indoor fan flow rate	121.10 L/s
Ventilator flow rate	0.0 L/s
Cooling system capacity sizing factor	1

Economizer control	N/A
Rated COP	3.5
Fan power	57.90 Watts
Crankcase heated power	60.00 Watts
ECM motor	Yes
Indoor fan operation	Auto

2.6.2.3 Domestic water heating system

Conventional tank is used for domestic water heating and the main fuel for water heating is natural gas. Tank has capacity of 151.4 Litres and tank blanket is uninsulated. Other specifications are mentioned in the table 16.

Table 16. Domestic water heating system specification

Primary water heating fuel	Natural gas
Water heating equipment	Conventional tank
Energy factor	0.554
Tank capacity	151.4 Liters
Tank location	Main floor
Pilot energy	0.0 MJ/ day
Tank blanket insulation	0.0 RSI
Flue diameter	76.2 mm

2.7 Climate zone and weather data

The climate zones used for this study are those that have been defined by the ASHRAE 90.1-2010 [28]. Among different climate zone found in Canada, the following cities, listed in Table 17 were considered for this analysis. For each location, the most up-to-date weather data for a typical meteorological year was used in the simulation [29].

Table 17. Climate Zones and associated Canada cities considered in the Analysis

Climate zone	Cities	HDD of building location (below 18°C)
Zone 4	Vancouver, BC	2825
Zone 5	Toronto, ON	3520
Zone 6	Montreal, QC	4200
Zone 7A	Calgary, AB	5000

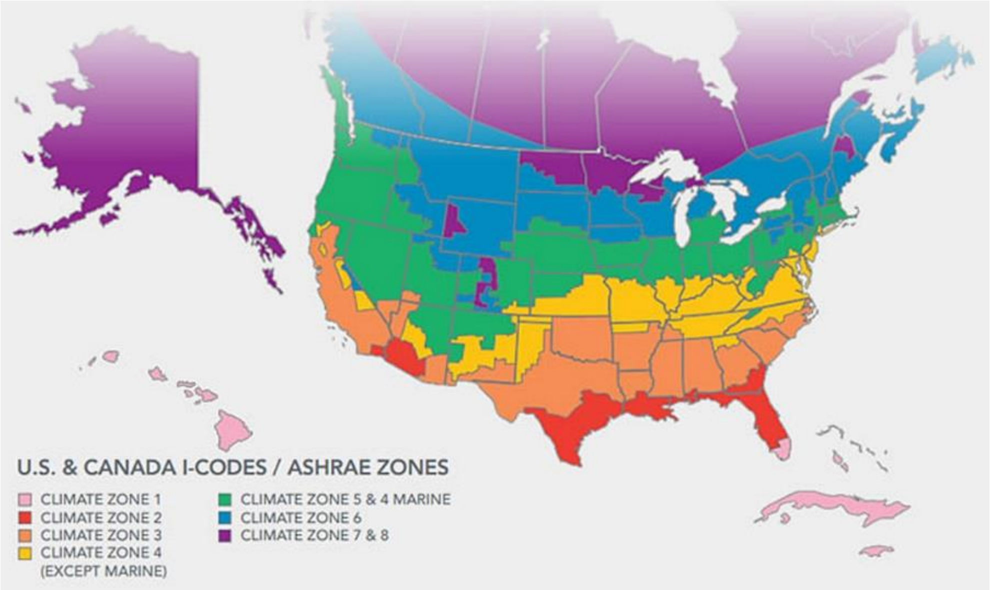

Figure 9. U.S. and Canada climate zone defined by ASHRAE [30]

The potential energy savings was quantified by comparing the heating and cooling loads of a house with DIMs to one with static insulation level. Since the selection of insulation in a new building is typically based on code requirements, the point of comparison for potential energy savings in each climate zone is based on what is required by the National Building Code of Canada 2015.

Table 18. Building envelope requirements as per National Building Code of Canada 2015[31]

Components	Heating Degree-Days of Building Location, in Celsius Degree-Days					
	Zone 4 <3000	Zone 5 3000 to 3999	Zone 6 4000 to 4999	Zone 7A 5000 to 5900	Zone 7B 6000 to 6900	Zone 8 ≥ 7000
	Maximum Overall Thermal Transmittance, W/(m2·K)					
Walls	0.315	0.278	0.247	0.21	0.21	0.183
Roofs	0.193	0.156	0.156	0.138	0.138	0.121
Floors	0.227	0.183	0.183	0.162	0.162	0.142
Doors	2.1	1.9	1.9	1.9	1.9	1.4
Fenestration	2.1	1.9	1.9	1.9	1.9	1.4

3. Result and analysis

3.1 Impact of variable insulation level

First a preliminary analysis is carried out using various level of static insulation as well as different combination of two-step variable insulations (Table 19) to determine how a 2-step dynamic insulation would perform with different insulation steps. This analysis was conducted in Vancouver, British Columbia (Climate zone 4), which has both cool winters and warm summers, with more mild temperatures in the spring and fall.

Table 19. Insulation level and steps evaluated

Static insulation	RSI-0.4
	RSI-1.4
	RSI-3.17
	RSI-4.76
	RSI-5.46
Variable/2-Step insulation	RSI-1.4/3.17
	RSI-0.4/3.17
	RSI-1.4/4.76
	RSI-0.4/4.76
	RSI-1.4/5.46
	RSI-0.4/5.46

The energy consumptions and savings are reported in terms of source energy. Source energy accounts for losses during extraction, production and transmission of energy and to better quantify the environmental impact, the total site energy was then multiplied by the factors listed in Table 20 [32], [33].

Table 20. Source energy factors for energy delivered to the buildings [31], [32]

Energy source	Source energy factor
Electricity	1.96
Natural Gas	1.01

Performance of different constant and 2-step variable insulations, tested in Vancouver, BC is shown in Figure 10. Despite the fact that Vancouver has a climate that is mostly conducive to heating, the efficiency and source energy factors taken into account make the energy used for cooling more significant than the energy used for heating.

From the figure, it is clear that energy savings can be improved either by increasing static R-value of the insulation or using 2-step insulation. However, the lowest energy consumption corelates with the 2-step insulation, which has highest R-value swing (RSI-0.4/5.46). In this case, this building would use 39.01% less energy than code-required insulation and 30.5% less energy than static insulation with an R-value of RSI-5.46. These savings are achieved through reducing both heating and cooling load. However cooling energy savings contributed more, with 44.41% improvement than code-required insulation compared to the 33.02% of heating energy savings. Similar results were observed for other R-value swings, too. It is also clear that simply adding insulation (i.e., improving the static R-value above what is required by NBC 2015), had little effect on the heating and cooling energy use.

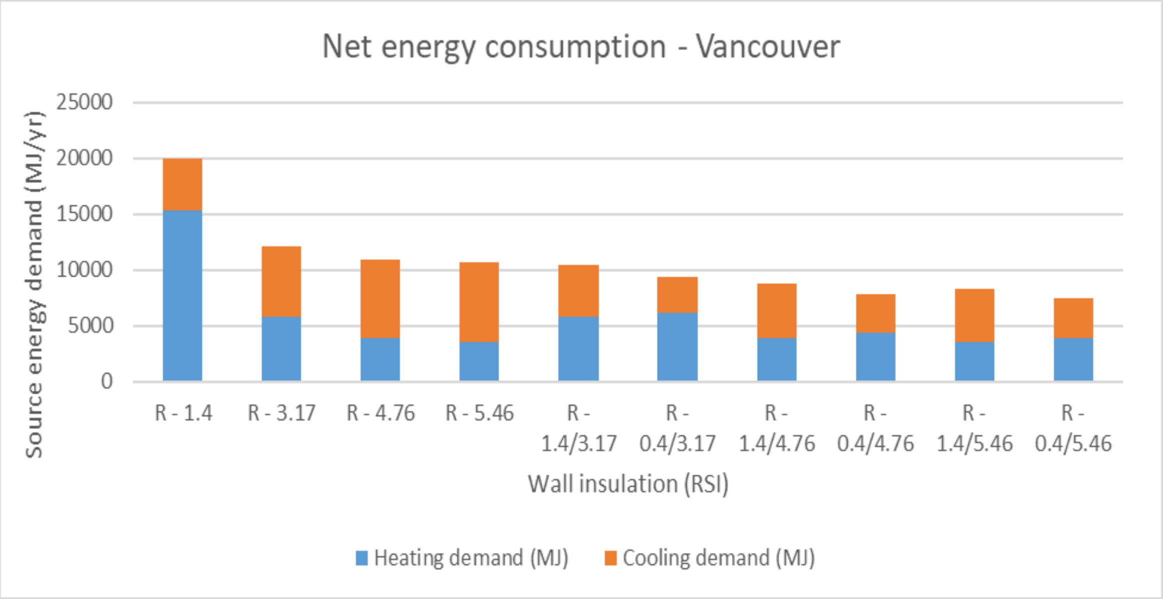

Figure 10. Net Energy Consumption – Vancouver, BC

Figure 11 shows the source energy savings in terms of step size (ΔR) in Vancouver, BC. Each line represents different 2-step combinations with different low R-values (RSI-0.4 and RSI-1.4). It can be concluded that in this location, changing the low-R of the 2-Step combination had a more significant effect on energy use than changing the upper value (i.e., high-R).

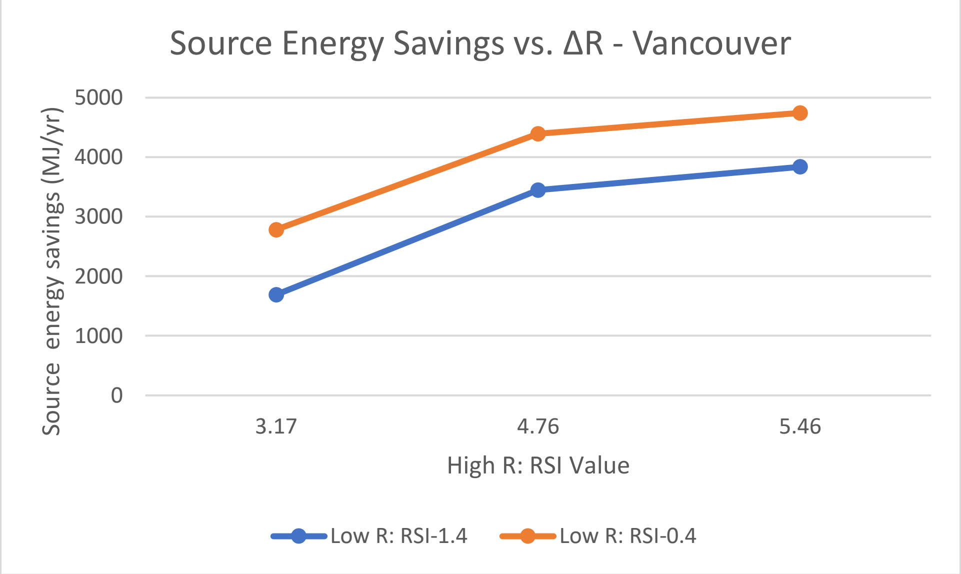

Figure 11. Source energy savings vs ΔR – Vancouver, BC

Overall, Dynamic Insulation Materials (DIMs) have a greater impact on the cooling load than the heating load and are most effective when the step size between the low R-value and high R-value is largest.

3.2 Impact of climate

To determine the effectiveness of the dynamic insulations in other locations, a broader analysis is carried by testing them in three more cities, located in three different climate zones (Figure 12,13 and 14). This analysis covers cities having heating degree days between 2500 to 5999 HDD (Climate zone 4 to 7A). Locations having more than 6000 HDD are not included in the analysis, assuming they do not have significant cooling requirement.

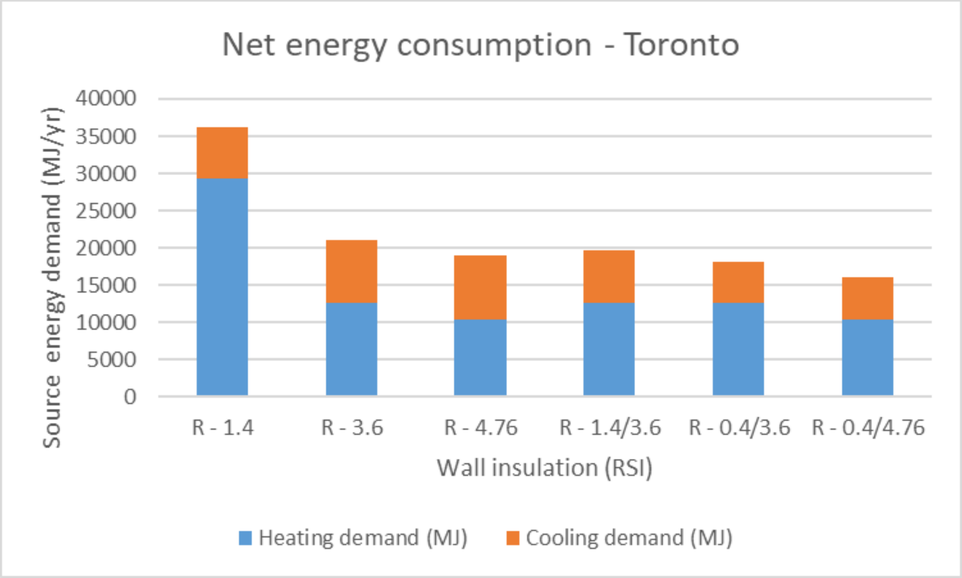

Figure 12. Net Energy Consumption – Toronto, ON

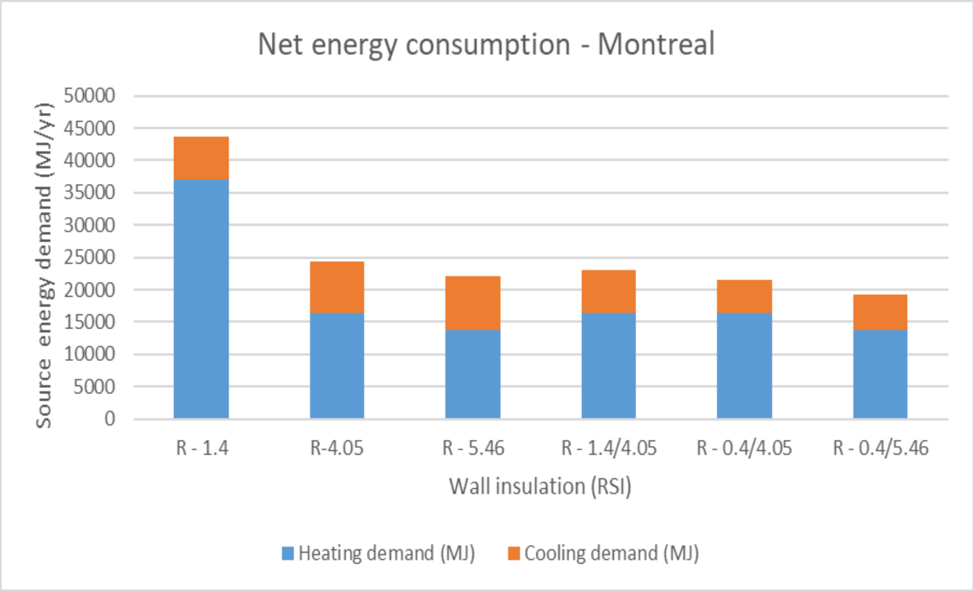

Figure 13. Net Energy Consumption – Montreal, QC

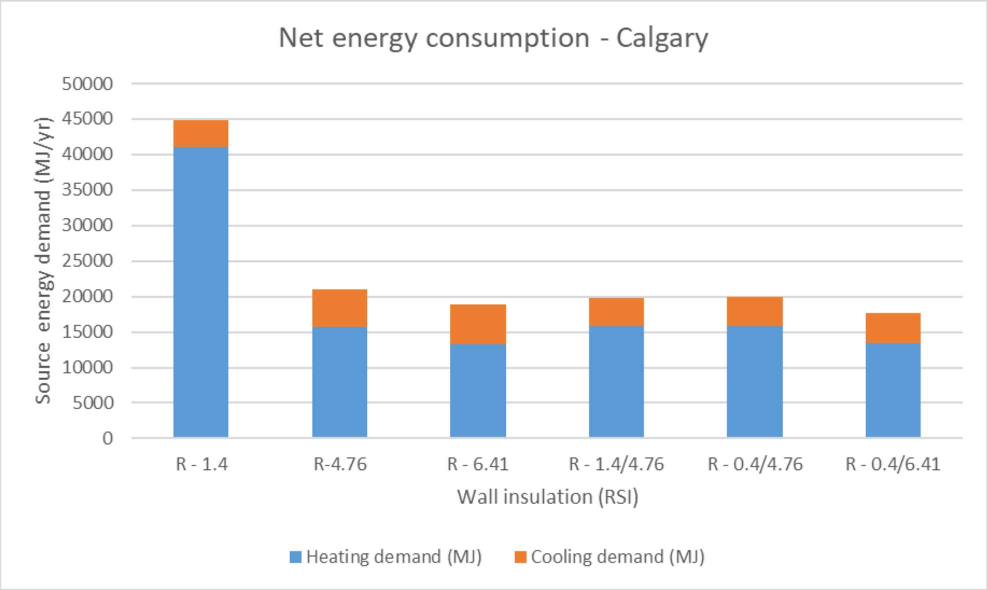

Figure 14. Net Energy Consumption – Calgary, AB

R-values of for both static and variable insulation for each city discussed in table 17 are listed in table 21. Largest step size that was compared in this analysis is listed in None/High column of the table. An even larger step size was tested for given locations, and it resulted in a larger energy savings. However, the largest step size was not included in this analysis. Selecting this more conservative step size represents the trade-off between potential energy savings and cost. It is assumed that a 2-Step insulation with a swing of RSI-0.4/RSI-4.76 would cost less than RSI-0.4/RSI-5.46 and would be more appropriate for a climate with code-required insulation of RSI-3.17.

Table 21. Summary of insulation levels tested by climate zone

	Static insulation			2-Step variable insulation		
Climate zone	None	Code	High	Med/Code	None/Code	None/High
4	0.4	3.17	4.76	1.4/3.17	0.4/3.17	0.4/4.76
5	0.4	3.6	4.76	1.4/3.6	0.4/3.6	0.4/4.76
6	0.4	4.05	5.46	1.4/4.05	0.4/4.05	0.4/5.46
7A	0.4	4.76	6.41	1.4/4.76	0.4/4.76	0.4/6.41

In all cases tested, variable insulation was more effective than static insulation.

3.2.1 Seasonal control

In this project, control scheme is assumed to be seasonal control scheme, which could be switched manually as per need. Based on the energy performance of the building model with various insulation level (R-None and R-High) at different location, manual control scheme with most promising energy savings is identified and it is listed in table 22.

Table 22. Tested seasonal control scheme

Month	Control scheme
January	High-R

February	High-R
March	High-R
April	High-R
May	High-R
June	Low-R
July	Low-R
August	Low-R
September	Low-R
October	High-R
November	High-R
December	High-R

In warmer climates, dynamic insulation would be useful in winter months by letting walls switch to the higher thermal conductivity. During winter days, when the outdoor temperature is warmer than the indoor temperatures, the wall becomes more thermally conductive, allowing heat transfer from outside to inside, which offsets the heating load. On the other hand, dynamic insulation is used almost exclusively during summer months in colder climates to offset the cooling load, which is generally a case with almost every Canadian city. This pattern can be seen in monthly energy consumption graph of Vancouver, BC (figure 15) and same trend is observed for the other tested cities.

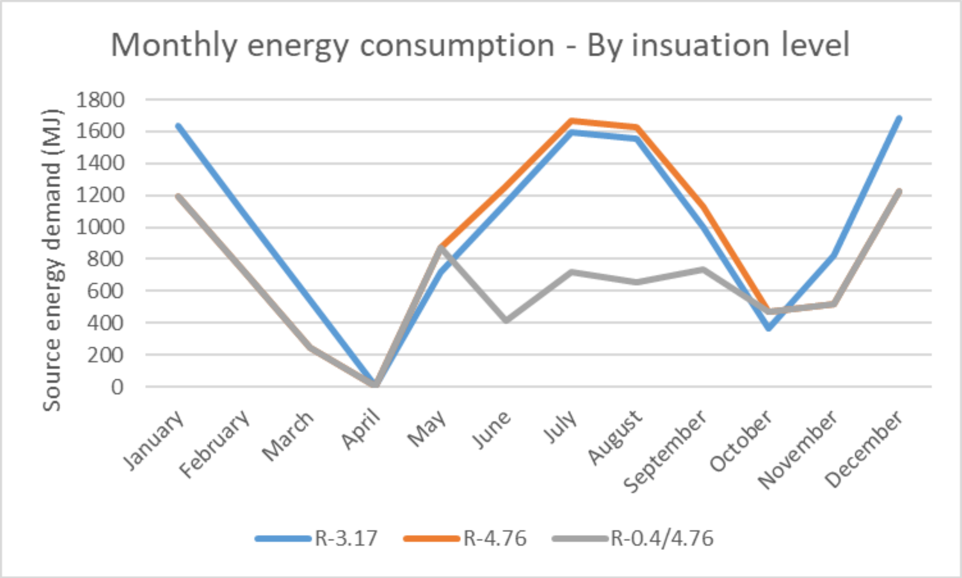

Figure 15. Monthly energy consumption – Vancouver, BC

3.2.2 Degree days

For the building energy analysis, climate conditions are often characterized by heating and cooling degree days. Heating degree days (HDD) can be defined as the rate of fuel or energy consumption necessary to maintain the interior of a small building at 21°C when the outside air temperature is below 18°C and it is roughly proportional to the difference between 18°C and the outside temperature [31]. Since degree-days vary by the weather data that is used, all heating and cooling degree days used in this project were calculated from weather data that was used in the simulation with a base temperature of 65°F (18°C).

3.2.2.1 Heating energy savings

Heating energy savings to heating degree days are compared for each location and plotted in chart (Figure 16). It is clear that deployment of DIMs in colder climate (with high HDD values) has the greater potential for heating energy savings and this trend can be seen in the figure 16.

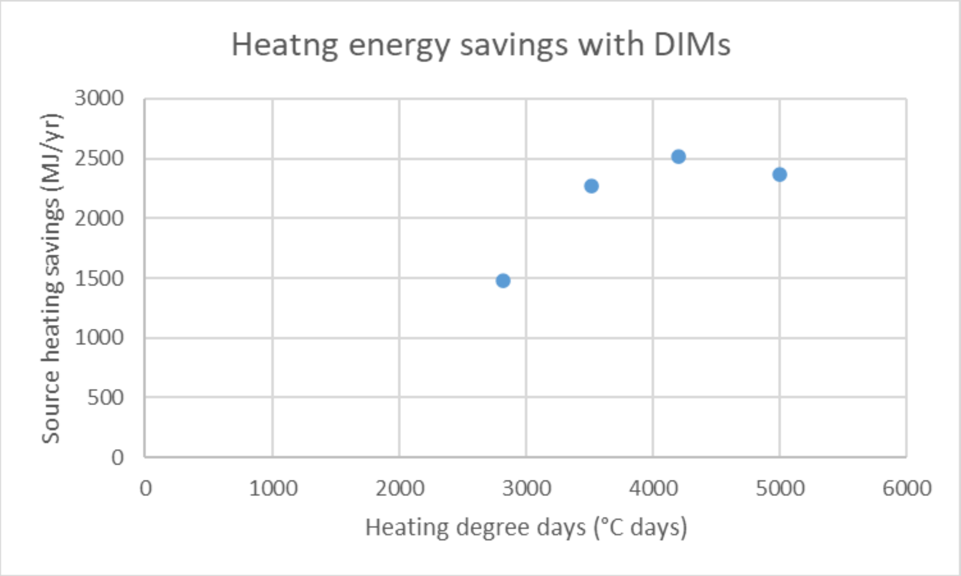

Figure 16. Net heating energy savings with DIMs by HDD

Although there is variation among cities within each climate zone, heating degree-days seems to be a fairly good indicator of the savings that could be realized with the deployment of DIMs for a given location.

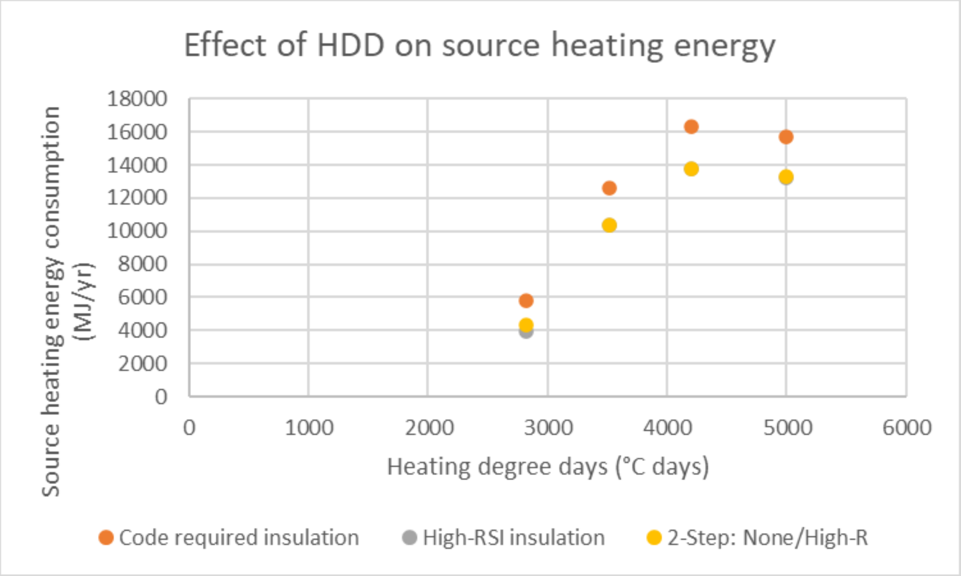

Figure 17. Effect of HDD on source heating energy

The best correlation for the source heating energy savings due to the deployment of DIMs as a function of HDD is obtained and is shown in Figure 17. In this correlation, different types of insulation with their source heating energy consumption are plotted in the graph. The difference between static high R value insulation and variable 2-Step: None/High is observed to be negligible, especially as HDD increases.

Only in the warmest climates, where the heating load can be offset in the winter by allowing heat transfer into the building, is there an advantage to deploy dynamic insulation.

3.2.2.2. Cooling energy savings

When comparing the simulated cooling savings to heating degree days for each location, cooling energy savings were found to decrease continuously with increase in HDD values. This could be a result of less cooling need in colder environment. This trend can be seen in Figure 18.

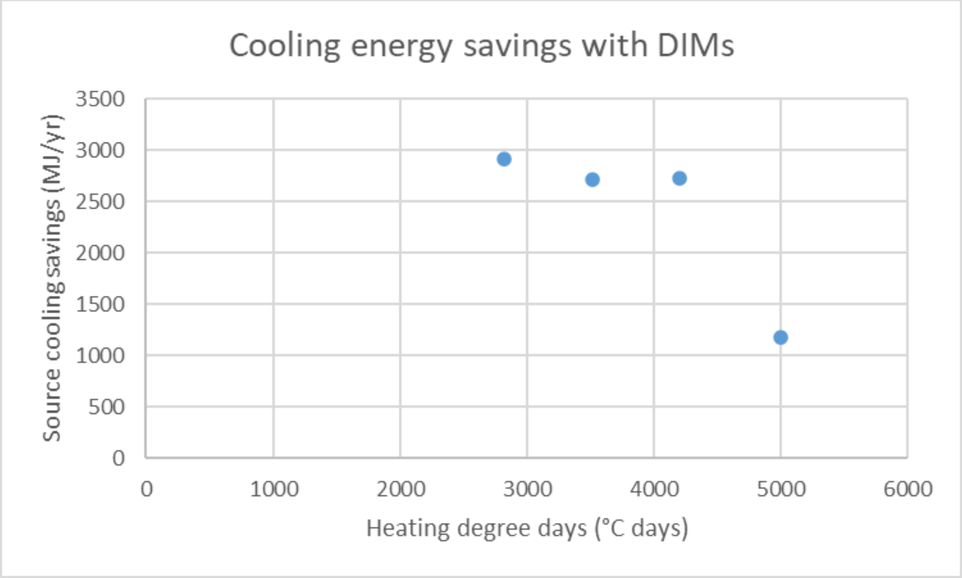

Figure 18. Net cooling energy savings with DIMs by HDD

Cooling energy savings comparison between 2-Step: None/High, code-R and High-R insulation is illustrated in Figure 19. From the plot, it is clear that deployment of DIM contributes more to save cooling energy as it can reduced its insulation level, allowing self-cooling of the house. Model with High-R and Code-R have difficulty emitting trapped heat because of their higher insulation level, forcing them to consume more energy for the cooling.

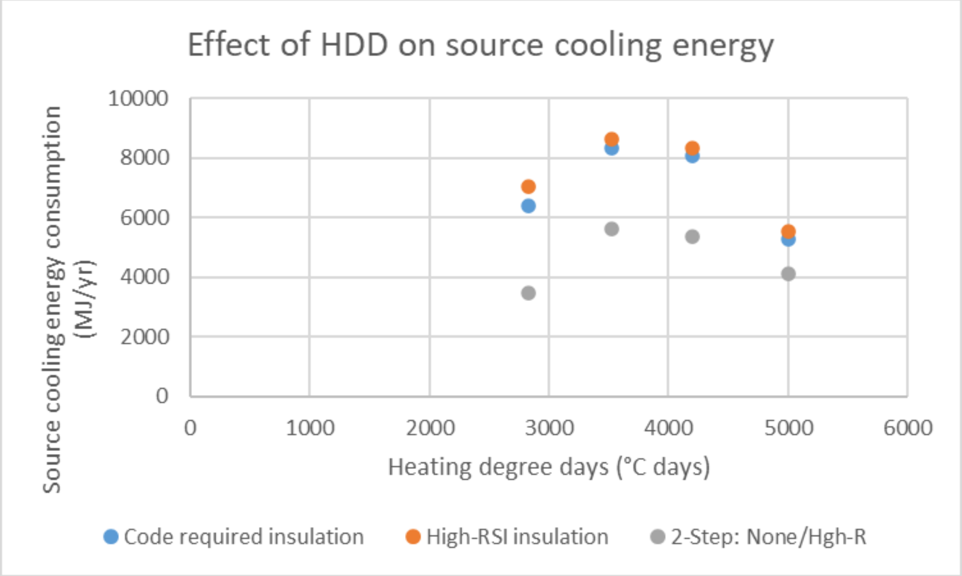

Figure 19. Effect of HDD on source cooling energy

For warmer climates (low HDD values), 2-Step DIMs save energy when compared to code-required insulation. However, this energy savings could also be achieved by using static insulation with a higher R-value. For colder climates, the opposite behaviour is found. Switching to static insulation with a higher R-value does not decrease the cooling load, but a dynamic insulation system will.

3.3 DIMs vs High-R insulation

There is potential energy savings when DIMs are deployed for the prototypical residential building in all Canadian climates considered in the analysis. However, in several of these locations, similar savings could be realized by investing in a higher level of static insulation, which would be more cost effective than a dynamic insulation system.

To determine where DIMs would be more effective than adding more static insulation, the baseline was changed from code required insulation (code-R) to high-R. For example, instead of comparing RSI-0.4/4.76 to RSI-3.17, the level of comparison in this section is RSI-4.76. The assumption is that for dynamic insulation to be a viable technology, RSI-0.4/4.76 must perform better than static insulation with a rating of RSI-4.76.

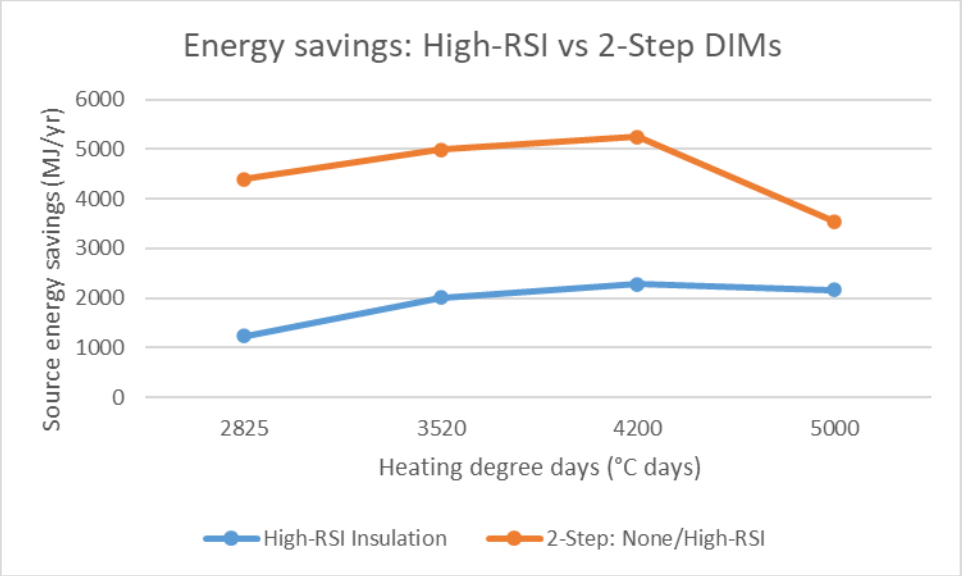

Figure 20. Energy savings: High-RSI vs 2-Step DIMs

In figure 20, source energy savings between 2-Step: None/High vs. High-R is compared. Clearly, DIMs have significant impact in reducing overall energy consumptions for residential buildings. It is also observed that energy savings gap between High-R and 2-step insulation is gradually decreasing with increase in HDD. Possible reason for it might be low cooling requirement with high HDD.

4. Conclusion

This research discusses the potential for energy savings in Canadian residential buildings through the use of variable insulation. The analysis uses an energy simulation tool to get the heating and cooling energy consumptions with the static insulation a well as dynamic insulation. DIMs are applied to the exterior walls of the house and assumed to operate based on seasonal control scheme. Consequently 2-step variable insulation will be either on High-R or Low-R depending upon the month of the operation.

According to the analysis's findings, utilising DIMs can reduce both heating and cooling energy use, but cooling energy savings are more notable. This is particularly true when accounting for equipment inefficiencies and source energy losses. In particular, the use of dynamic insulation can result in yearly energy savings of up to 36% in Canadian residential buildings by lowering the need for space heating and cooling by up to 44% and 33%, respectively. Despite the lower source energy factor, results are found to be in line with the studies carried for US residential buildings. 2-Step variable insulations are tested with different step size and DIM with highest R-value swing is observed to provide the best energy savings.

After studying dynamic insulation for one location, analysis is extended to other three cities to ensure its effectiveness in other climate zones as well. DIMs provided better energy savings compared to code required static insulation however percentage energy savings were observed to be decreasing in colder climates. Energy savings are also compared based on the HDD and heating energy savings were seen to increase gradually with the HDD and opposite was observed for cooling energy savings. Nevertheless, heating energy savings could also be achieved by using static insulation with a higher R-value. For colder climates, the opposite behsaviour is found. Switching to static insulation with a higher R-value does not decrease the cooling load, but a dynamic insulation will. At the end, DIMS were compared to High-R static insulations as they are more cost effective. Though DIMs have shown significant better energy performance compared to High-R, making them more suitable from the energy savings perspective.

Ultimately, the DIM technology and its control strategy needs to be developed for seamless integration with building envelope systems. To be practical, DIMs must be robust enough to handle the demands of a construction site. To be a viable alternative to static insulation systems, DIM installation and operation costs must also be comparable with the potential energy cost savings.

Future work

In this thesis, dynamic insulation was considered only for exterior walls. In climate zones where DIMs have been shown to be effective, future research could be conducted to determine the effect of using variable insulation in the roof, either in addition to or instead of variable wall insulation. Additionally, more than 2-steps can be implemented in DIMs studies to explore full potential of this technology. Moreover, additional analysis needs to be carried out to quantify the potential energy savings of using DIMs in commercial buildings.

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Appendix A – Heating and cooling energy consumption data – Static insulation

1) Vancouver, BC

	RSI - 0.4		RSI - 1.4		RSI - 3.17		RSI - 4.76		RSI - 5.46	
	Heating demand (MJ)	Cooling demand (MJ)	Heating demand (MJ)	Cooling demand (MJ)	Heating demand (MJ)	Cooling demand (MJ)	Heating demand (MJ)	Cooling demand (MJ)	Heating demand (MJ)	Cooling demand (MJ)
Yearly demand (MJ)	72880.59	2777.908	15352.202	4643.828	5772.554	6390.776	3908.7	7023.66	3476.925	7197.904
Yearly demand (MJ)	75658.498		19996.03		12163.33		10932.36		10674.829	
January	13485.217	0	3640.949	0	1637.614	0	1189.477	0	1082.316	0
February	11053.036	0	2729.02	0	1087.366	0	725.079	0	638.724	0
March	9862.549	0	1955.057	0	538.633	0	245.733	0	187.658	0
April	6150.799	0	544.895	0	0	0	0	0	0	0
May	2185.034	329.868	0	407.092	0	722.064	1.111	867.888	1.313	907.088
June	0	415.716	0.909	760.676	0	1150.324	0	1257.144	0	1283.996
July	0	719.516	0	1309.28	0	1596.224	0	1667.764	0	1685.796
August	0.404	653.464	0	1255.576	0	1556.044	0	1631.112	0	1649.928
September	389.658	344.176	3.737	600.544	1.313	1003.128	0.707	1127.392	0.505	1158.556
October	5532.376	315.168	464.499	310.66	0	362.992	0	472.36	0	512.54
November	10404.515	0	2279.065	0	825.372	0	521.564	0	450.46	0
December	13817.002	0	3734.071	0	1682.256	0	1225.029	0	1115.949	0

2) Toronto, ON

	R - 0.4		R - 1.4		R - 3.6		R - 4.76		R - 5.46	
	Heating demand (MJ)	Cooling demand (MJ)	Heating demand (MJ)	Cooling demand (MJ)	Heating demand (MJ)	Cooling demand (MJ)	Heating demand (MJ)	Cooling demand (MJ)	Heating demand (MJ)	Cooling demand (MJ)
Yearly demand (MJ)	105771.24	4919.6	29255.963	6987.988	12647.523	8352.54	10375.326	8619.296	9505.312	8725.92
Yearly demand (MJ)	110690.84		36243.951		21000.063		18994.622		18231.232	
January	23245.251	0	7779.929	0	3999.6	0	3413.396	0	3182.308	0
February	19951.944	0	6468.242	0	3172.208	0	2662.663	0	2463.39	0
March	16017.691	0	4414.104	0	1644.078	0	1263.308	0	1119.686	0

April	8285.03	0	1284.316	0	129.785	0	43.228	0	18.382	0
May	1239.068	499.604	0	677.376	2.02	928.256	1.919	999.796	1.818	1027.824
June	0.505	875.532	0	1325.94	0	1590.736	0	1632.092	0	1647.772
July	0	1339.268	0	1839.852	0	2028.6	0	2052.708	0	2062.116
August	0	1194.424	0	1716.764	0	1931.384	0	1960.392	0	1971.368
September	0	669.928	0.606	1044.876	0	1354.948	0	1411.2	0	1433.74
October	5751.849	340.844	465.004	383.18	0	518.616	0	563.108	0	583.1
November	12100.608	0	2883.146	0	946.774	0	702.253	0	610.343	0
December	19179.294	0	5960.616	0	2753.058	0	2288.559	0	2109.385	0

3) Montreal, QC

	R - 0.4		R - 1.4		R-4.05		R - 4.76		R - 5.46	
	Heating demand (MJ)	Cooling demand (MJ)	Heating demand (MJ)	Cooling demand (MJ)	Heating demand (MJ)	Cooling demand (MJ)	Heating demand (MJ)	Cooling demand (MJ)	Heating demand (MJ)	Cooling demand (MJ)
Yearly demand (MJ)	123354.128	4717.72	37056.496	6693.008	16313.924	8090.292	14847.101	8230.04	13793.772	8333.136
Yearly demand (MJ)	128071.848		43749.504		24404.216		23077.141		22126.908	
January	28082.04	0	9981.022	0	5243.415	0	4870.119	0	4597.116	0
February	23103.043	0	7903.654	0	3925.567	0	3612.063	0	3382.894	0
March	18311.401	0	5422.791	0	2073.833	0	1827.292	0	1652.158	0
April	8938.298	0	1551.36	0	169.276	0	109.08	0	71.811	0
May	1171.499	497.252	0	676.788	2.424	931.588	2.323	967.652	2.222	994.896
June	1.01	856.716	0	1282.036	0	1558.984	0	1581.132	0	1597.008
July	0	1303.792	0	1810.256	0	1999.788	0	2012.332	0	2020.76
August	0	1133.272	0	1664.628	0	1890.028	0	1905.512	0	1916.88
September	0	594.468	2.424	916.888	0	1262.632	0	1296.932	0	1321.432
October	6982.332	332.22	872.135	342.412	0	447.272	0	466.48	0	482.16
November	13912.043	0	3701.852	0	1264.52	0	1103.021	0	988.891	0
December	22852.462	0	7621.258	0	3634.889	0	3323.203	0	3098.68	0

4) Calgary, AB

	R - 0.4		R - 1.4		R-4.76		R - 5.46		R - 6.41	
	Heating demand (MJ)	Cooling demand (MJ)	Heating demand (MJ)	Cooling demand (MJ)	Heating demand (MJ)	Cooling demand (MJ)	Heating demand (MJ)	Cooling demand (MJ)	Heating demand (MJ)	Cooling demand (MJ)
Yearly demand (MJ)	144119.526	2963.324	41080.538	3798.872	15702.47	5274.36	14473.704	5397.84	13261.502	5555.816
Yearly demand (MJ)	147082.85		44879.41		20976.83		19871.544		18817.318	
January	25267.877	0	8687.414	0	4005.761	0	3755.685	0	3503.69	0
February	21312.616	0	7040.104	0	3010.204	0	2795.276	0	2581.055	0
March	19160.912	0	5735.487	0	1976.469	0	1789.821	0	1607.112	0
April	11718.323	0	2575.702	0	412.484	0	333.502	0	260.479	0
May	5609.035	371.224	342.895	422.968	0	617.008	0	633.668	0	657.188
June	1616.101	423.752	0	583.492	0.808	915.712	0.909	948.052	1.01	981.176
July	0	747.74	0	1071.924	0	1423.352	0	1445.304	0	1467.452
August	160.287	664.44	0.909	890.82	0.404	1236.76	0	1271.06	0	1297.52
September	4076.663	433.552	73.932	504.112	0	708.932	0	731.08	0	759.304
October	11285.134	322.616	2336.837	325.556	316.534	372.596	245.632	368.676	180.992	393.176
November	18728.026	0	5697.814	0	2076.055	0	1899.406	0	1724.979	0
December	25184.552	0	8589.444	0	3903.751	0	3653.473	0	3402.185	0

Appendix B – Heating and cooling energy consumption data – 2-Step variable insulation

1) Vancouver, BC

	R - 1.4/3.17		R - 0.4/3.17		R - 1.4/4.76		R - 0.4/4.76		R - 1.4/5.46		R - 0.4/5.46	
	Heating demand (MJ)	Cooling demand (MJ)	Heating demand (MJ)	Cooling demand (MJ)	Heating demand (MJ)	Cooling demand (MJ)	Heating demand (MJ)	Cooling demand (MJ)	Heating demand (MJ)	Cooling demand (MJ)	Heating demand (MJ)	Cooling demand (MJ)
Yearly demand (MJ)	5775.887	4696.16	6161.303	3217.928	3911.528	4805.528	4298.055	3473.12	3479.753	4845.708	3866.482	3552.5
Yearly demand (MJ)	10472.047		9379.231		8717.056		7771.175		8325.461		7418.982	
January	1637.614	0	1637.614	0	1189.477	0	1189.477	0	1082.316	0	1082.316	0
February	1087.366	0	1087.366	0	725.079	0	725.079	0	638.724	0	638.724	0
March	538.633	0	538.633	0	245.733	0	245.733	0	187.658	0	187.658	0
April	0	0	0	0	0	0	0	0	0	0	0	0
May	0	407.092	0	722.064	0	407.092	1.111	867.888	0	407.092	1.313	907.088
June	0.909	760.676	0	415.716	0.909	760.676	0	415.716	0.909	760.676	0	415.716
July	0	1309.28	0	719.516	0	1309.28	0	719.516	0	1309.28	0	719.516
August	0	1255.576	0.404	653.464	0	1255.576	0.404	653.464	0	1255.576	0.404	653.464
September	3.737	600.544	389.658	344.176	3.737	600.544	389.658	344.176	3.737	600.544	389.658	344.176
October	0	362.992	0	362.992	0	472.36	0	472.36	0	512.54	0	512.54
November	825.372	0	825.372	0	521.564	0	521.564	0	450.46	0	450.46	0
December	1682.256	0	1682.256	0	1225.029	0	1225.029	0	1115.949	0	1115.949	0

2) Toronto, ON

	R - 1.4/3.6		R - 0.4/3.6		R - 1.4/4.76		R - 0.4/4.76		R - 1.4/5.46		R - 0.4/5.46	
	Heating demand (MJ)	Cooling demand (MJ)	Heating demand (MJ)	Cooling demand (MJ)	Heating demand (MJ)	Cooling demand (MJ)	Heating demand (MJ)	Cooling demand (MJ)	Heating demand (MJ)	Cooling demand (MJ)	Heating demand (MJ)	Cooling demand (MJ)
Yearly demand (MJ)	12646.109	7123.424	12648.028	5526.024	10374.013	7167.916	10375.831	5642.056	9504.1	7187.908	9505.817	5690.076

Yearly demand (MJ)	19769.533		18174.052		17541.929		16017.887		16692.008		15195.893	
January	3999.6	0	3999.6	0	3413.396	0	3413.396	0	3182.308	0	3182.308	0
February	3172.208	0	3172.208	0	2662.663	0	2662.663	0	2463.39	0	2463.39	0
March	1644.078	0	1644.078	0	1263.308	0	1263.308	0	1119.686	0	1119.686	0
April	129.785	0	129.785	0	43.228	0	43.228	0	18.382	0	18.382	0
May	0	677.376	2.02	928.256	0	677.376	1.919	999.796	0	677.376	1.818	1027.824
June	0	1325.94	0.505	875.532	0	1325.94	0.505	875.532	0	1325.94	0.505	875.532
July	0	1839.852	0	1339.268	0	1839.852	0	1339.268	0	1839.852	0	1339.268
August	0	1716.764	0	1194.424	0	1716.764	0	1194.424	0	1716.764	0	1194.424
September	0.606	1044.876	0	669.928	0.606	1044.876	0	669.928	0.606	1044.876	0	669.928
October	0	518.616	0	518.616	0	563.108	0	563.108	0	583.1	0	583.1
November	946.774	0	946.774	0	702.253	0	702.253	0	610.343	0	610.343	0
December	2753.058	0	2753.058	0	2288.559	0	2288.559	0	2109.385	0	2109.385	0

3) Montreal, QC

	R - 1.4/4.05		R - 0.4/4.05		R - 1.4/4.76		R - 0.4/4.76		R - 1.4/5.46		R - 0.4/5.46	
	Heating demand (MJ)	Cooling demand (MJ)	Heating demand (MJ)	Cooling demand (MJ)	Heating demand (MJ)	Cooling demand (MJ)	Heating demand (MJ)	Cooling demand (MJ)	Heating demand (MJ)	Cooling demand (MJ)	Heating demand (MJ)	Cooling demand (MJ)
Yearly demand (MJ)	16313.924	6797.868	16314.934	5267.108	14847.202	6817.076	14848.111	5322.38	13793.974	6832.756	13794.782	5365.304
Yearly demand (MJ)	23111.792		21582.042		21664.278		20170.491		20626.73		19160.086	
January	5243.415	0	5243.415	0	4870.119	0	4870.119	0	4597.116	0	4597.116	0
February	3925.567	0	3925.567	0	3612.063	0	3612.063	0	3382.894	0	3382.894	0
March	2073.833	0	2073.833	0	1827.292	0	1827.292	0	1652.158	0	1652.158	0
April	169.276	0	169.276	0	109.08	0	109.08	0	71.811	0	71.811	0
May	0	676.788	2.424	931.588	0	676.788	2.323	967.652	0	676.788	2.222	994.896
June	0	1282.036	1.01	856.716	0	1282.036	1.01	856.716	0	1282.036	1.01	856.716
July	0	1810.256	0	1303.792	0	1810.256	0	1303.792	0	1810.256	0	1303.792

August	0	1664.628	0	1133.272	0	1664.628	0	1133.272	0	1664.628	0	1133.272
September	2.424	916.888	0	594.468	2.424	916.888	0	594.468	2.424	916.888	0	594.468
October	0	447.272	0	447.272	0	466.48	0	466.48	0	482.16	0	482.16
November	1264.52	0	1264.52	0	1103.021	0	1103.021	0	988.891	0	988.891	0
December	3634.889	0	3634.889	0	3323.203	0	3323.203	0	3098.68	0	3098.68	0

4) Calgary, AB

	R - 1.4/4.76		R - 0.4/4.76		R - 1.4/5.46		R - 0.4/5.46		R - 1.4/6.41		R - 0.4/6.41	
	Heating demand (MJ)	Cooling demand (MJ)	Heating demand (MJ)	Cooling demand (MJ)	Heating demand (MJ)	Cooling demand (MJ)	Heating demand (MJ)	Cooling demand (MJ)	Heating demand (MJ)	Cooling demand (MJ)	Heating demand (MJ)	Cooling demand (MJ)
Yearly demand (MJ)	15776.099	4039.952	15862.353	4026.428	14547.636	4052.692	14633.991	4093.656	13335.333	4100.712	13421.789	4203.024
Yearly demand (MJ)	19816.051		19888.781		18600.328		18727.647		17436.045		17624.813	
January	4005.761	0	4005.761	0	3755.685	0	3755.685	0	3503.69	0	3503.69	0
February	3010.204	0	3010.204	0	2795.276	0	2795.276	0	2581.055	0	2581.055	0
March	1976.469	0	1976.469	0	1789.821	0	1789.821	0	1607.112	0	1607.112	0
April	412.484	0	412.484	0	333.502	0	333.502	0	260.479	0	260.479	0
May	0	617.008	0	617.008	0	633.668	0	633.668	0	657.188	0	657.188
June	0	583.492	0.808	915.712	0	583.492	0.909	948.052	0	583.492	1.01	981.176
July	0	1071.924	0	747.74	0	1071.924	0	747.74	0	1071.924	0	747.74
August	0.909	890.82	160.287	664.44	0.909	890.82	160.287	664.44	0.909	890.82	160.287	664.44
September	73.932	504.112	0	708.932	73.932	504.112	0	731.08	73.932	504.112	0	759.304
October	316.534	372.596	316.534	372.596	245.632	368.676	245.632	368.676	180.992	393.176	180.992	393.176
November	2076.055	0	2076.055	0	1899.406	0	1899.406	0	1724.979	0	1724.979	0
December	3903.751	0	3903.751	0	3653.473	0	3653.473	0	3402.185	0	3402.185	0