Residential Sector Energy and GHG Emissions Model for the Assessment of New Technologies

by

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I dedicate this dissertation to my wife, Anne Chandler Swan.

It is primarily her support which has enabled me to continue my University education for ten years. I am most grateful that she never let the world stop for me. Every single year of the last decade has been marked by something unique and significant, the majority occurring because she decides, and then makes it so. This year is certainly no exception as she carries our first child.

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Abstract

Worldwide, the residential sector is a major consumer of energy. Both the rate at which we consume energy and our use of non-renewable energy resources have come under pressure to change. These changes may occur to some extent by conservation techniques. However, due to living standard expectations, these changes will primarily rely on technology. Many technological opportunities exist to reduce the conventional energy consumption and greenhouse gas (GHG) emissions of the residential sector, such as: improving energy efficiency, introducing alternative energy conversion technologies, and increasing the use of renewable energy resources.

The accurate estimate of the impact that a new technology has on residential sector energy consumption and GHG emissions requires a versatile, reliable, detailed, and high-resolution analytical model. Such models account for the wide range of climate, energy supply, and housing stock characteristics, and are useful for decision makers to evaluate and parametrically compare a wide range of energy efficiency measures and technology strategies when applied to the residential sector.

This dissertation presents the development of a new energy consumption and GHG emissions model of the Canadian residential sector. This new model is detailed with regard to the housing stock, comprehensive with regard to the treatment of end-uses (including thermodynamic behaviour and occupant behaviour), and possesses the capability, resolution, and accuracy to assess the impact upon energy consumption and GHG emissions due to the application of alternative and renewable energy technologies to the residential sector. The new model is titled the Canadian Hybrid Residential End-Use Energy and GHG Emissions Model (CHREM).

The CHREM advances the state-of-the-art of residential sector energy consumption and GHG emissions modeling by three principal contributions: i) a database of 16,952 unique house descriptions of thermal envelope and energy conversion system information that statistically represent the Canadian housing stock; ii) a “hybrid” modeling approach that integrates the bottom-up statistical and engineering modeling methods to account for occupant behaviour, and provide the capacity to model alternative and renewable energy technologies, such as solar energy and energy storage systems; and iii) a method for the accumulation and treatment of energy and GHG emissions results.

List of Abbreviations and Symbols Used

A	floor area
AB	Alberta
AC/h	air changes per hour (with subscript pressure rating in pascals)
AEEI	autonomous energy efficiency index
AFN	air flow network
AL	appliances and lighting
ALC	appliances, lighting and cooling
an	annual
ANN	artificial neural network
app	appliance
ASHP	air source heat pump
ASHRAE	American Society of Heating, Refrigeration and Air-Conditioning Engineers
AT	Atlantic region (provinces: Newfoundland and Labrador, Nova Scotia, Prince Edward Island, New Brunswick)
B	billing data
b	constant
BC	British Columbia
BEAM	Built Environment Analysis Model
C	appliance ownership (presence or count)
C_{p}	specific heat
c	coefficient
CBECS	Commercial Buildings Energy Consumption Survey
CD	conduction
CDA	conditional demand analysis
CHREM	Canadian Hybrid Residential End-use Energy and GHG Emissions Model
CHS	Canadian housing stock
COP	coefficient of performance
CSDDRD	Canadian Single-Detached and Double/Row Housing Database
CV	convection
CVS	central ventilation system
CWEC	Canadian Weather for Energy Calculations
DG	double-glazed

DHW	domestic hot water
dis	disposable
DR	double row house type
E	energy consumption
e	end-use group
EGHD	EnerGuide for Houses Database
EIF	emission intensity factor
ELA	effective leakage area (with subscript pressure rating in pascals)
EM	engineering method
EPI	energy performance index
ESP-r	The ESP-r building simulation program
f	fuel type
G	ground
GA	genetic algorithm
GDP	gross domestic product
GHG	greenhouse gas
GIS	geographical information systems
GSHP	ground source heat pump
GWP	global warming potential
HA	heat advection
HAP	Hourly Analysis Program
HDD	heating degree days
HRV	heat recovery ventilator
I	income
i	array element location
l	length
LW	long wave
MB	Manitoba
mo	monthly
NB	New Brunswick
NEMS	National Energy Modeling System
NF	Newfoundland and Labrador
NN	neural network

NRCan	Natural Resources Canada
NS	Nova Scotia
OT	Ontario
Pc	price
PE	Prince Edward Island
PR	Prairies region (provinces: Manitoba, Saskatchewan, and Alberta)
QC	Quebec
R	appliance rating
R^2	multiple correlation coefficient
r	aspect ratio
ref	reference
REUM	Residential Energy Use Model
S	housing stock
SC	space cooling
SD	single detached house type
SG	single-glazed
SH	space heating
SHEU-XX	Survey of Household Energy Consumption (XX denotes year)
SK	Saskatchewan
SM	statistical method
SS	sensible heat energy storage
SW	short wave
T	temperature
t	time or period of time
TG	triple-glazed
U	use factor
UEC	unit energy consumption
V	array of interaction variables
Vol	volume
XML	extensible markup language
η	efficiency
ρ	density

Acknowledgements

It is a rare thing to find someone so dedicated and supportive of your research, that through those interactions you learn life lessons. This has been the case with my supervisor, Dr. V. Ismet Ugursal of Dalhousie University. He is an outstanding individual from whom I learned to be polite, and yet straightforward. Dr. Ugursal never hesitated to put my academic, professional, and personal interests first, no matter what the expense. Looking back on the last four years, it is apparent that his suggestions, advisement, and recommendations were all made with my best interest in mind. I am grateful to have had this opportunity to conduct research with Dr. Ugursal, and I will carry the life lessons with me into the future.

("Lukas, do you remember the story of the wolf?")

Dr. Ian Beausoleil-Morrison, my co-supervisor of Carleton University, has guided much of my research related to the ESP-r simulator. Early on, he directed me down a path that provided traction, knowledgably introducing critical modeling components, and connecting me with many supportive colleagues. Dr. Beausoleil-Morrison always critically examined my research, providing alternative perspectives and arguments that caused me to learn.

(He also taught me how to dress for conferences.)

The research for this dissertation was conducted as part of the Solar Buildings Research Network. This NSERC strategic research network, led by Dr. Andreas Athienitis of Concordia University, consists of a body of 24 researchers and 100 graduate students from 10 different Canadian universities. This network was critical to my academic development by introducing me to many of my colleagues, and allowing me the opportunity to present at a variety of conferences and working sessions. It greatly enriched my experience as a graduate student.

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Chapter 1 Introduction

Much of human society may be characterized as dense centers of energy consumption. As population continues to grow, and societies continue to evolve, ever increasing demands are placed on our conventional energy sources. Carbon based fossil fuels presently constitute the majority of the World conventional energy sources (IEA 2009), and Canada is no exception to this trend (OEE 2006b). These fossil fuels are limited in supply (i.e. non-renewable) and their use causes the release of significant amounts of air, water, and soil contaminants, as well as non-cyclic greenhouse gasses (GHG). It is under this context that focus has been placed on how we use energy, with the objective to reduce consumption and displace fossil fuels with renewable energy resources.

Energy consumption may be broadly grouped into sectors, with each sector having a number of end-uses. An example of these sectors is shown for Canada in Figure 1.1a.

- The residential sector requires energy to support end-uses related to occupant health and comfort in the living space. The principal end-uses are space heating (SH), space cooling (SC), domestic hot water heating (DHW), and appliances and lighting (AL). An estimate of the contribution of each of these end-uses to the total residential sector is shown for Canada in Figure 1.1b.
- The commercial/institutional sector has similar end-uses to the residential sector, with additional energy consumption attributed to a variety of business related equipment. The commercial/institutional sector covers a wide range of activities such as retail trade, office space, education, and health care, each with its own particular characteristics of energy consumption.
- The industrial sector also requires SH, SC, and AL, but is dominated by energy consumption attributable to manufacturing processes. These processes, such as mining, refining, forestry, textiles, and equipment manufacture, range considerably in energy intensity. Certain industries are so energy intense that they have agreements with utilities to shut down during periods of peak demand.
- The transportation sector is notably different, as it is a mobile use of energy. This sector accounts for cars, trucks, air, rail, and marine transport. Nearly all energy consumption in this sector is related to the vehicular motion itself.
- The agriculture sector requires energy for the growth or processing of plants and animals. This energy consumption tends to be associated with equipment, including farm vehicles for harvest.

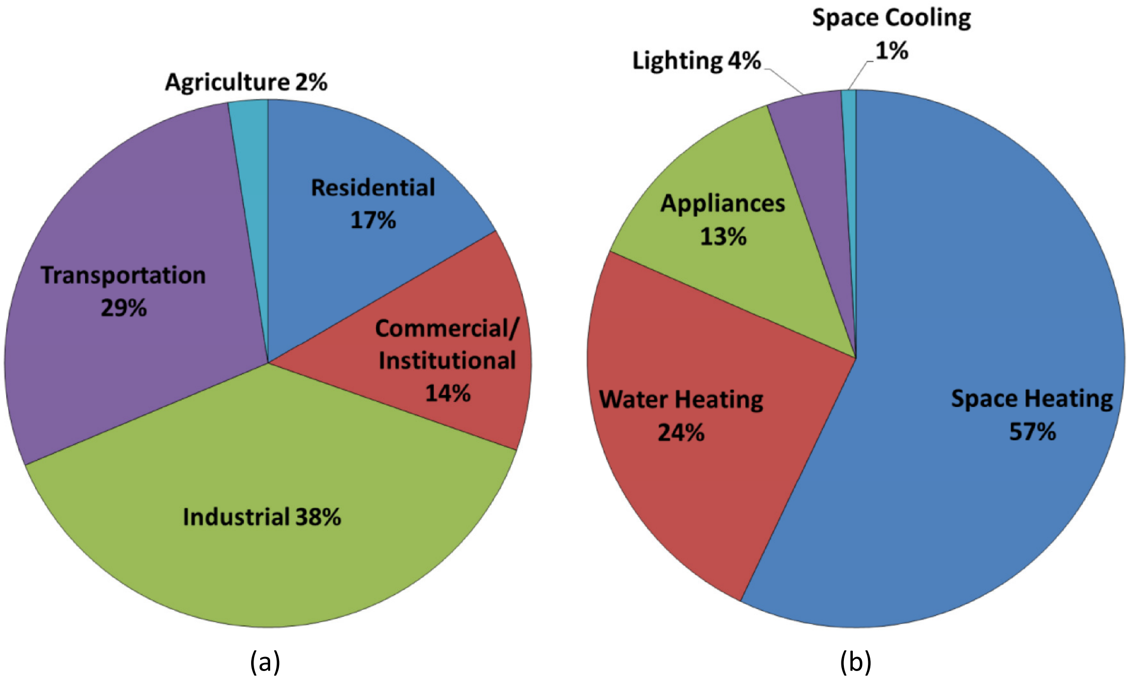

Figure 1.1 Estimates of the Canadian end-use energy consumption shown by (a) sector, and (b) for the residential sector end-uses (OEE 2006b)

Of these energy consuming sectors, the residential sector is the most standardized with respect to end-uses. While the commercial/institutional, industrial, and agriculture sectors have a wide variety of end-uses corresponding with the business type, nearly all energy consumed in the residential sector is attributed to either SH, SC, DHW, or AL. In contrast with the variety of vehicles in the transportation sector, the energy intensity of specific dwellings in the residential sector tends not to vary more than an order of magnitude.

This standardized aspect to residential sector end-uses is a welcome characteristic in the consideration of methods to reduce conventional energy consumption. If a certain technological change is made to a dwelling which results in a considerable reduction of energy consumption, it is likely that other dwellings in the region may also achieve some reduction using the same technology. There are certain characteristics of the Canadian residential sector which support the implementation of new technologies, including renewable energy technologies:

- Houses require a mix of electricity and heat. This requirement of mixed energy types allows for the implementation of a variety of technologies, including co-generation units which supply both electricity and heat.

- The vast majority of Canadian occupants own their own home (OEE 2006). This creates a vested interest in the energy performance of house. It also eases accessibility to the facility for technology installations, and may provide leverage for financing such an installation.
- Housing is long-term, with the expected lifetime of most dwellings being 100 years or more. This long term outlook allows a homeowner to make significant investments in the upgrade of a dwelling.
- The housing stock has relatively low energy consumption per unit floor area in comparison with other sectors (OEE 2006b). This is essentially due to the lack of equipment or manufacturing process that is found in the commercial/institutional and industrial sectors. For the majority of the housing stock, there is also significant roof space per dwelling. The combination of low energy consumption per unit floor area, and significant roof space, presents the opportunity of using solar renewable energy to provide a substantial portion of the end-use energy consumption.

Because of these characteristics, the housing stock, and in particular the Canadian housing stock (CHS), is of interest for the assessment of technology additions that are intended to offset conventional energy consumption. The residential sector in Canada is estimated to be responsible for approximately 17% of the national end-use energy consumption and 16% of the national GHG emissions (OEE 2006b). Consequently, any national strategy to reduce energy consumption and the associated GHG emissions must address the residential sector to be effective.

1.1 An Overview of the Canadian Housing Stock

Although the end-uses are consistent, the magnitude of energy consumption and the specific contribution of the four end-uses (SH, SC, DHW, and AL) vary considerably throughout the CHS. This is primarily due to the differences in climate, energy supply, and building characteristics among Canada's regions, which are shown in Figure 1.2. These regional variations affect the impact of particular technologies as applied to the CHS. This will result in a technology being more suitable to one region than another, and influencing energy consumption and GHG emissions to varying degrees.

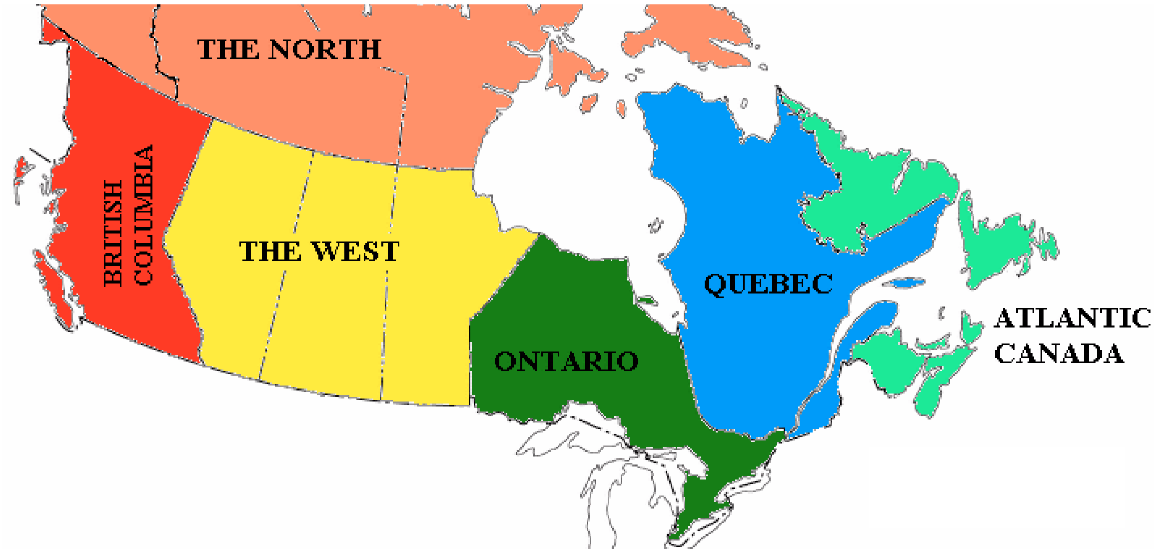

Figure 1.2 Major Canadian regions (source: www.canadainfolink.ca)

There are four major house types in Canada:

- Single-detached dwellings are standalone structures which do not share walls with other dwellings.
- Attached dwellings which share one or two common walls with other dwellings, but are otherwise similar to single detached dwellings. Examples of attached dwellings include duplexes and row housing.
- Apartments form part of a building containing several dwelling units. Apartments share walls, ceiling, and floor with other dwellings and are typically serviced by a central building plant system.
- Mobile homes are designed and built for transport and are typically located on a temporary foundation.

Throughout the last century, the principal change in house thermal envelopes has been the level of insulation and airtightness of the floors, walls, ceilings, windows, and doors. Newer homes tend to have significantly better insulating properties than older homes. Figure 1.3 shows the distribution of houses by construction period. It is apparent that older homes constitute a substantial portion of the CHS. Therefore, to have a significant effect on the energy consumption of the residential sector, upgrades to the existing housing must be considered.

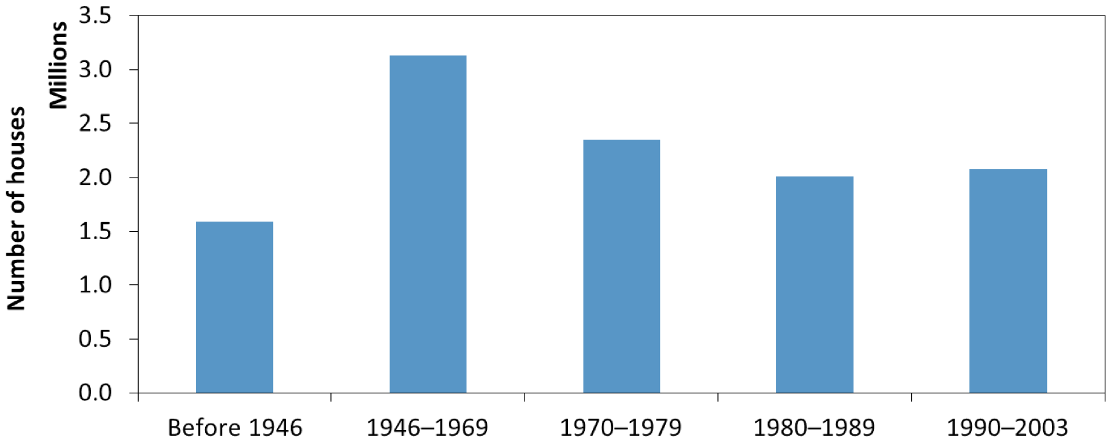

Figure 1.3 Distribution of the CHS by construction period (OEE 2006)

The energy sources which service the houses vary by region. Typical energy sources include: electricity, natural gas, heating oil, and wood. Electricity may be used for all end-uses, and dominates the SC and AL energy consumption. Regional differences primarily appear when comparing the energy sources used for SH and DHW:

- Atlantic Canada uses a combination of heating oil, electricity, and wood.
- Quebec primarily uses electricity.
- Ontario, the West, and British Columbia primarily use natural gas.

Finally, the regions themselves have differing climatic conditions which strongly affect SH and SC energy consumption. As shown in Figure 1.1b, the end-use energy consumption of the CHS is dominated by SH. This is due to the cold climate. A representation of the heating differences required in Canada is shown in Figure 1.4 through the use of heating degree days. The regions of Atlantic Canada and British Columbia experience a warmer heating season than the interior regions.

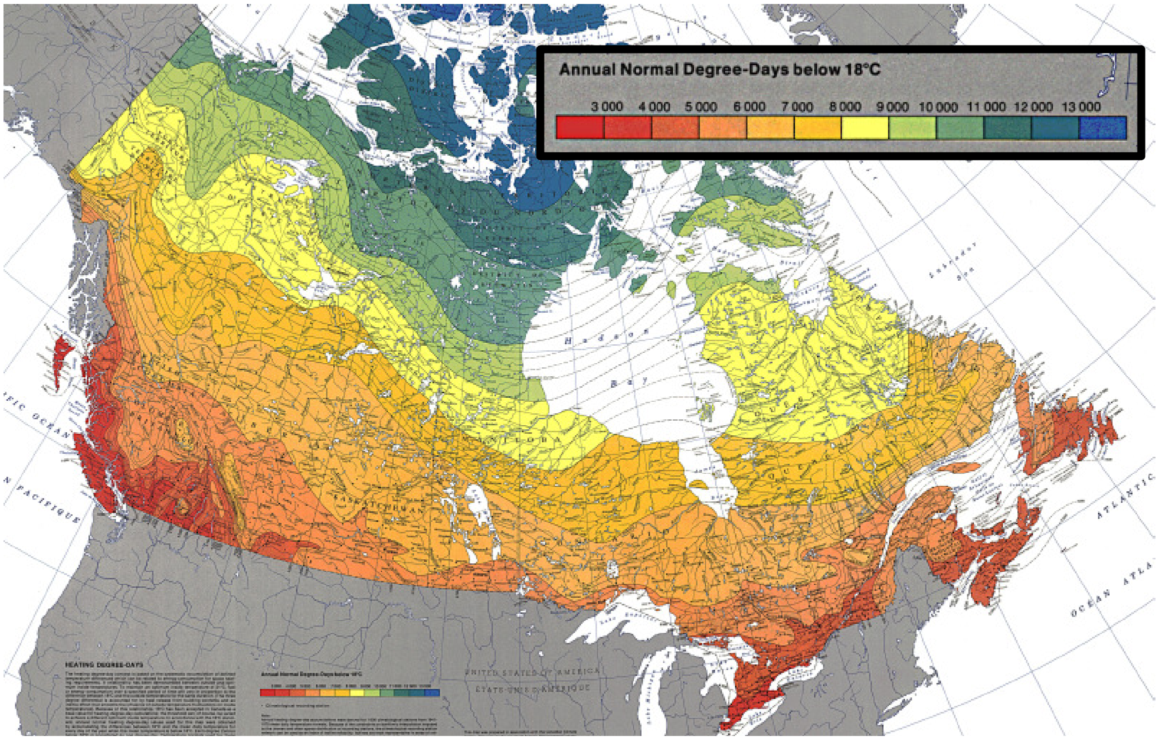

Figure 1.4 Map showing the variation of HDD across Canada (source: NRCan)

1.2 Examples of Technologies for the Reduction of Conventional Energy Consumption

Conservation is perhaps the easiest and most cost effective solution to reducing energy consumption. However, there are expectations to maintain comfort and living standards which limit the extent to which conservation measures can be imposed. The addition of technologies will be required to significantly affect overall energy consumption of the CHS. A reduction of energy consumption and the associated GHG emissions of the residential sector can be achieved by a combination of strategies that includes: improving end-use energy efficiency, introducing alternative energy conversion technologies, and increasing the use of renewable energy resources.

The improvement of end-use energy efficiency may be achieved by many different measures. For example, additional insulation may be blown in to existing walls and ceilings. Windows may be replaced with multi-glazed and coated versions. Recently, Lomanowski and Wright (2009) examined the use of integrated blinds located within window glazing layers to reduce SC energy consumption. Airtightness may be improved by taking sealing measures around common leakage points (e.g. windows and doors). Improvement of end-use energy efficiency may also be achieved by selecting appliances and/or energy conversion equipment with improved efficiency or effectiveness. For example, the use of heat-recovery ventilators provides for fresh air while transferring much of the heat from the exhaust airflow to the intake airflow. New appliances, such as refrigerators, have increased insulation, and new clothes-washers extract more water prior to a drying cycle. Compact fluorescent light bulbs use approximately one-quarter the energy of equivalent incandescent bulbs. Conventional heating systems may be replaced with advanced designs, such as condensing furnaces. A new thermostat may include temperature setback control algorithms.

Alternative energy conversion technologies may be deployed to dramatically affect energy consumption. For example, the use of heat pumps provides a multiplier effect from the purchased energy to the energy delivered within the home. Heat pumps can use ambient air, water, or soil as the source of this extra delivered energy. Co-generation systems may be used to produce both electricity and heat, taking advantage of the dual energy type requirement of all houses within the CHS. Co-generation systems capitalize on the inherent inefficiency of heat engines. The mechanical power is used to generate electricity, and the low-grade heat contained in the exhaust gasses is used for SH or DHW.

There are a variety of methods of integrating renewable energy technologies into houses. Passive technologies may be employed to increase the capture and utilization of solar energy. For example, increasing the thermal mass of specific areas in the house will store absorbed solar energy for use at a later period (e.g. overnight). This increase in mass may be the simple addition of concrete, or may involve embedded phase-change materials such as those under investigation by Zhang et al. (2008). Active technologies come in a broader range. Solar thermal collectors can be used for SH or DHW. A characteristic of solar thermal based renewable energy methods (both passive and active) is the need for thermal energy storage. Solar photovoltaic panels or small wind turbines are other active renewable energy systems, ones which generate electricity. An example of a flexible solar photovoltaic panel that is intended as roofing material is shown in Figure 1.5.

Researchers are now investigating new building materials which incorporate multiple renewable energy technologies (Liao et al. 2007, Candanedo and Athienitis 2010, Candanedo et al. 2010). So-called "building integrated photovoltaic/thermal panels" replace conventional roofing with a photovoltaic module backed by an air-ducting system. Absorbed solar radiation that is not converted to electricity by the photovoltaic module becomes heat, which is carried into the dwelling via the air-ducting system to support SH needs.

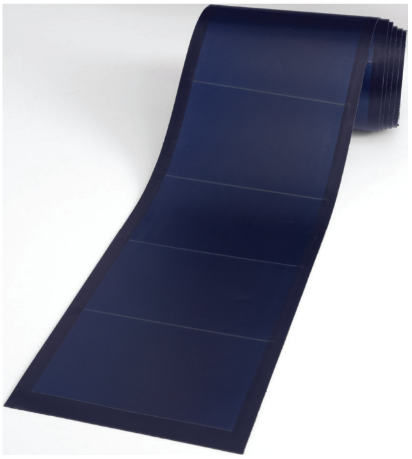

Figure 1.5 Flexible photovoltaic panel for use as an integrated roofing material (source: Uni-solar)

1.3 Assessment of the Impacts of Technologies upon the CHS

From the perspective of policy development, such as government initiatives and incentives, it is important to estimate the potential impact that new technologies can have on energy consumption and GHG emissions. Such an assessment is not trivial for Canada. The wide range of variation found in the CHS limits the applicability of technologies to a certain subset of houses. The performance of new technologies, such as alternative, renewable, and energy storage devices, varies considerably throughout the day, season, and year as a function of energy source or demand. The addition of technologies can have complex interrelated effects on the end-use energy consumption of houses. For example, improving the efficiency of lighting reduces the internal heat gain from lights, necessitating an increase in the SH end-use energy consumption. Not only does this affect the energy consumption due to specific equipment efficiencies, it may also affect GHG emissions in a distinctly different manner depending upon the utilized energy sources. The use of electricity will result in dramatically different GHG emissions depending upon the generation energy source. The energy sources used for electricity generation vary by Canadian province. Whereas Nova Scotia primarily relies on coal for electricity generation, Quebec primarily relies on dammed hydro.

The accurate estimate of the impact on energy consumption and GHG emissions due to new technologies requires a versatile, reliable, detailed, and high-resolution analytical model. Such models are useful for decision makers, energy analysts, energy suppliers, and utilities to evaluate and parametrically compare the impact of a wide range of energy efficiency measures and technology strategies on the energy consumption and GHG emissions of the residential sector. The results of such an analysis can be utilized to develop policy and programs to support and/or promote dwelling upgrades or new technologies that meet energy consumption or GHG emissions reduction targets.

Numerous residential sector energy modeling methodologies have been developed over the past three decades. Each methodology has distinct strengths, weaknesses, data requirements, capabilities, and applicability. Several of these modeling methodologies have been applied to the CHS with success. There are two general methodologies employed to model the residential energy consumption: "top-down" and "bottom-up", as shown in Figure 1.6. A comprehensive review of energy modeling methodologies and the models themselves is presented in Chapter 2. The following subsections provide an introduction to these methods.

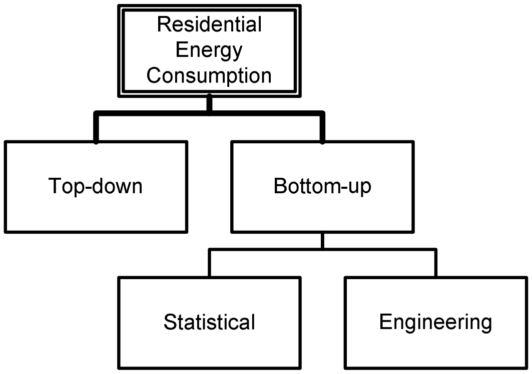

Figure 1.6 Residential energy consumption modeling methodologies

1.3.1 Top-down Modeling Approach

The top-down approach utilizes historic aggregate energy consumption information submitted by energy suppliers, and regress the energy consumption of the housing stock as a function of top-level variables. These variables include macroeconomic indicators (e.g. gross domestic product, unemployment, and inflation), energy price, and general climate. The top-down approach is used to provide long-term projections in the absence of discontinuities such as energy supply and pricing shocks, and technological breakthroughs. Because of its reliance on historical information, the top-down method is not suitable for assessing the impact on energy consumption caused by new technologies.

Examples of top-down models include the energy demand model of residential and commercial sectors of Asian mega-cities (Tooru et al. 2002), the National Energy Modeling System of the U.S. Department of Energy (EIA 2005), and the residential energy demand system for Spain (Labandeira et al. 2006).

1.3.2 Bottom-up Modeling Approach

The bottom-up approach to modeling residential energy consumption explicitly accounts for the end-uses (SH, SC, DHW, and AL) within the sector by estimating them for a specific group of houses. These results are then extrapolated to be representative of national levels. The bottom-up approach consists of two distinct categories: the statistical method and the engineering method, as shown in Figure 1.6.

The bottom-up *statistical method* utilizes a regression technique and a variety of known indicator variables to attribute total measured dwelling energy consumption to individual end-uses. As with the top-down method, the requirement of energy consumption information limits the ability of the statistical method in predicting the impact of new technologies. However, the statistical method is capable of accounting for demographics and the effects of occupant behaviour. The energy consumption influenced by occupant behaviour is significant (e.g. how often the clothes-dryer is used) and has been found to vary dramatically between households (Nicol 2001, Seryak and Kissock 2000).

Examples of bottom-up statistical models include the Princeton scorekeeping model (Fels 1986) that was applied to the USA by Hirst et al. (1986), the conditional demand analysis model used by Parti and Parti (1980) for San Diego, and the adaptive neural network technique that Yang et al. (2005) applied to a building in Montreal.

The bottom-up *engineering method* utilizes appliance ratings and expected use level, as well as thermodynamic and heat transfer relationships, to explicitly calculate the energy consumption of individual end-uses. The use of fundamental thermodynamics and heat transfer allows the engineering method to assess energy consumption in absence of historic energy consumption information. This enables the engineering method to assess new technologies, a unique characteristic among modeling methods. However, the engineering method suffers from its rudimentary treatment of occupant behaviour. It is safe to say that engineering estimates of appliance ratings and expected occupant use levels do not capture the variety and variability of actual occupant behaviour.

Examples of bottom-up engineering models include the application of survey data sources to the residential sector of Delhi by Kadian et al. (2007), an archetype based model for the USA by Huang and Broderick (2000), and a model of Norway's housing stock by Larsen and Nesbakken (2004) that is based on 2,013 dwellings.

1.4 Present Status of Energy and GHG Emissions Modeling of the CHS

To quantify and understand the impacts that technologies have on the CHS, and to influence the take-up of these technologies, a number of surveys, programs, and energy models have been developed specifically for Canada. These works initiated in the early 1980's and continue today.

1.4.1 Surveys

Groups within Natural Resources Canada (NRCan) have commissioned a multitude of surveys on the CHS. In 1993, the first of four national Survey of Household Energy Use (SHEU-93) surveys was conducted (Statistics Canada 1993). Subsequent SHEU surveys were carried out in 1997, 2003, and 2007 (OEE 2000, 2006, 2010). These surveys assessed the present housing stock from the perspectives of thermal envelope, energy conversion equipment, and energy consumption. The SHEU was complemented by further surveys such as the Survey of Canadian New Household Equipment Purchases 1994 & 1995 (NEUD 1997), the Survey of Houses Built in Canada in 1994 (NEUD 1997b), and the 1994 Home Energy Retrofit Survey (NEUD 1997c). All of these surveys include thousands of samples and representation from each province or major region.

The major strength of surveys is that they give an unbiased portrait of the present housing stock. This data can be used for assessment of appliance penetration levels, and can provide the source data for certain energy models. The surveys often acquire billing data and this provides a means for calibrating energy models. However, surveys have a set of objectives and a limited scope. This often leads to the provision of only a portion of the data required for energy modeling.

1.4.2 Building Energy Estimation Software Tools and Programs

To quantify and characterize building energy performance, NRCan developed a building energy assessment tool. The software tool, conceived in 1982, is named HOT2000 (CANMET 2008). HOT2000 conducts a monthly bin type energy analysis on low-rise dwellings using a non-directional dependent house description. HOT2000 was originally developed as a validation tool for low energy buildings designed to meet the requirements of the R-2000 energy use and air quality program (OEE 2005).

NRCan also initiated the EnerGuide program to provide incentive to homeowners who had their dwelling audited and modeled, and then proceeded with energy related dwelling upgrades (Blais et al. 2005). To facilitate this program, an offshoot of the HOT2000 software called HOT2XP was developed (CANMET 2008b). The HOT2XP program instituted directional dependency to the house description.

Over 200,000 houses were evaluated in the EnerGuide program, resulting in the EnerGuide for Houses Database (EGHD). It contains the details of each home energy audit, including thermal envelope properties and energy conversion equipment information (CANMET 2006). The EGHD is described in detail by Blais et al. (2005).

The major strength of the EGHD is the level of detail and total number of dwellings. The information contained in the database is suitable for conducting detailed building energy performance simulation. However, the EGHD does not include occupancy characteristics or billing data. The HOT2XP and HOT2000 software used for energy analysis of the EGHD perform suitably for standardized assessment of SH and SC energy consumption for conventional houses of the CHS. However, these software suffer from an inability to appropriately model alternative and renewable energy technologies. This inability stems from the monthly bin-type analysis technique which does not consider the variability of renewable energy or energy storage characteristics.

To account for recent technological developments, energy storage mechanisms, and renewable energy technologies, new software is presently being developed by NRCan. This HOT3000 software will replace the HOT2000 software for upcoming energy programs sponsored by the Canadian Federal Government (CANMET 2010). HOT3000 will utilize the

ESP-r building simulation engine, which is capable of simulation time-steps of one hour or less, and modeling of advanced technologies (Haltrecht et al. 1999, ESRU 2007, Clarke 2001). The ESP-r simulator uses numerical heat and mass balance methods applied at discrete time steps to a finite volume representation of the building. ESP-r has been extensively tested and verified (e.g. Strachan et al. 2009).

1.4.3 Top-down Energy Models

Using much of the data acquired by its own surveys, NRCan developed the Residential End-Use Model (REUM). The estimates of REUM are published by the Canadian government in the Energy Use Data Handbook (OEE 2006b). The REUM relies on aggregate energy consumption data reported by Statistics Canada, which is originally obtained from major energy suppliers across the nation. The REUM allocates this consumption to end-uses based on housing stock characteristics, estimates of unit energy consumption, and a number of indicators such as climate and energy price. The REUM also includes an assessment of GHG emissions based on the mix of energy sources.

The principal strength of the REUM is its aggregate energy billing data. These data likely account for the majority of all energy consumed within the sector. By incorporating certain stock characteristics and indicator variables, the model provides an indication of the fluctuation in end-use energy consumption and GHG emissions throughout time. As the REUM is a top-down model, it is incapable of assessing new technologies.

1.4.4 Bottom-up Energy Models

Between 1994 and 2005, the Canadian Residential Energy End-use Data and Analysis Centre (CREEDAC), with support from NRCan, developed a series of bottom-up energy and emissions models for the CHS. The primary objective was to expand the state of the knowledge of residential energy use within Canada, and to examine the impacts of technological upgrades. The following bottom-up models were all developed at CREEDAC.

1.4.4.1 Engineering Method Models

The Canadian Residential Energy End-use Model (CREEM) was developed to study and analyze the characteristics of the residential end-use energy consumption in Canada, and to evaluate the impact of various energy efficiency measures (Farahbakhsh et al. 1998, Farahbakhsh 1997). The model makes use of the Modified STAR-HOUSING database (Ugursal and Fung 1996, Scanada 1992) and the 1993/94 "200-House Audit" project database (NRCan 1994) to create 16 archetypes, representative of a range of houses found in the CHS. The SHEU-93 (Statistics Canada 1993) was used to augment these archetypes with unique house information, creating 8,767 house descriptions.

HOT2000 was used to estimate the annual unit energy consumption (UEC) for each of the 8,767 CREEM houses. Energy billing data were available for 2,524 of these houses, and this data was used to calibrate the model. As the CREEM is based on the statistically representative SHEU-93 houses, the results were extrapolated to estimate the energy consumption characteristics of the CHS. Using the CREEM model, Guler et al. (2001) and Guler (2000) studied the impact of energy efficiency upgrades to the CHS. They found energy savings potential for upgrades of heating systems to be 8%, basement insulation to be 4%, and programmable thermostats to be 2%.

Fung (2003) further refined the CREEM model and extended it to incorporate GHG emissions. Estimates of appliance ratings and use factors were provided to account for the effects of occupant behaviour on the household energy consumption. The GHG emissions were calculated by multiplying the energy consumption by energy source specific GHG emission intensity factors (EIF). Constant factors were used for fossil fuels consumed on-site (i.e. at the dwelling), whereas average monthly provincial factors were used to account for the electricity generation energy source mix.

The CREEM model demonstrated many new techniques for analyzing the CHS. It modeled thousands of houses to capture the variety of the housing stock, and used a bottom-up engineering technique to assess the impacts of numerous energy efficiency upgrades. It also implemented a GHG emissions assessment technique. However, the CREEM relies on the HOT2000 monthly bin-type energy analysis software, and is thus incapable of assessing alternative (e.g. co-generation) or renewable energy technologies. Furthermore, variation in house building thermal envelope properties were limited to the number of archetypes. The CREEM also imposed appliance ratings and use factors which fail to encompass the variety of effects caused by occupant behaviour. The GHG emissions model accounts for the present status of the CHS by using the *average* GHG EIFs. But it does not adequately capture the effect on GHG emissions due to upgrades or technologies which cause an incremental change in *marginal* electricity generation. This difference is discussed further in section 1.4.5.

1.4.4.2 Statistical Method Models

Cognizant of the CREEM engineering method limitations at capturing the effects of occupant behaviour, CREEDAC initiated research into statistical models. Aydinalp-Koksal and Ugursal (2008), Aydinalp et al. (2004, 2003b, 2002) and Aydinalp (2002) used the SHEU-93 dataset and two distinctly different techniques to develop bottom-up statistical models of the energy consumption of the CHS. The first approach was to use a neural network (NN) regression technique to determine the relationship between residential energy consumption and a large number of input variables. The NN technique is a simplified mathematical information handling method, similar to that of a biological neural network. The second technique was conditional demand analysis (CDA), which uses appliance ownership variables and exploits differences in ownership among the samples to determine the contribution of each appliance to the residential energy consumption.

Both of these techniques regress the measured dwelling energy consumption onto input variables. CDA employs linear regression which seeks to minimize the estimation error by modifying the variable coefficients. These coefficients represent the rating and use of appliances. The NN allows for significant interaction between the input variables by having a number of hidden “neurons” which are influenced by each input. The weights and bias of each neuron are determined by minimizing the estimation error. Both models can calculate the energy consumption of a dwelling given its characteristics. By regressing the energy consumption onto input variables, these statistical techniques have the ability to account for demographic factors and occupant behaviour.

Aydinalp-Koksal and Ugursal (2008) found that the bottom-up CDA, NN, and engineering methods of modeling the energy consumption of the CHS were of similar accuracy. They identified that the NN technique always had a slightly higher prediction capability, owing to the high level of interconnectivity it allowed between input variables. However, the NN is cannot be used for technology assessment due to its statistical method. Aydinalp-Koksal and Ugursal (2008) proposed that because of the unique strengths of the bottom-up engineering and statistical methods, a hybrid modeling methodology should be developed.

1.4.5 GHG Emissions Models related to Electricity Generation

Because the addition of new technologies to the CHS can cause an incremental change in electricity consumption, there is the need to determine which generating energy source is affected by that incremental change. For this purpose, GHG emissions models related to electricity generation are interested in the *marginal* generation GHG EIF. Three recent models of GHG emissions have been conducted using electrical generation information.

Marbek (2006) attempted to correlate the hourly Ontario energy price paid by wholesale customers to the electricity generation energy source. Using knowledge of the change in price, the energy source responding to the incremental change would be identified. They developed three techniques in their correlation process, but none produced distinct results. They were successful in identifying coal by a very low price; however, natural gas and hydro were largely indistinguishable. As an alternative, they used a probability distribution method to estimate the seasonal price-setting energy sources of Ontario, and the effective GHG EIF.

NRCan (2007) investigated the GHG EIFs of Ontario for the base generation and the marginal generation at different levels of demand. Although their methodology is not discussed, they found that the marginal generation is relatively unaffected by demand. They identify that the marginal GHG EIF of Ontario is typically two to three times that of the base generation GHG EIF.

Recently, Farhat and Ugursal (2010) conducted a comprehensive review of the electrical generation aspects of Canada. They discuss the base and marginal generation and show the wide variation among Canadian provinces. Using annual and monthly generation data they calculate the GHG EIF for both average (combination of base and marginal generation) and marginal generation. These values may be used to identify the impact upon GHG emissions caused by an incremental change in electricity consumption.

1.5 Advancing the State-of-the-art of Residential Sector Energy Consumption and GHG Emissions Modeling

Based on the preceding sections, the following arguments are made regarding the present status of energy consumption and GHG emission models of the CHS:

1) The residential sector in Canada is responsible for approximately 17% of the national end-use energy consumption and 16% of the national GHG emissions (OEE 2006b). Consequently, any national strategy to reduce energy consumption and the associated GHG emissions must address the residential sector to be effective. The accurate estimate of the impact on energy consumption and GHG emissions due to new technologies requires a versatile, reliable, detailed, and high-resolution analytical model.

2) The characteristics of the CHS vary significantly. This is primarily due to the differences in climate, energy supply, and building characteristics among Canada's regions.
3) The addition of technologies will be required to significantly affect overall energy consumption of the CHS. This can be achieved by a combination of strategies that includes: improving end-use energy efficiency, introducing alternative energy conversion technologies, and increasing the use of renewable energy resources.
4) The bottom-up approach to energy modeling is the only method that can accurately estimate the impact of new technologies on the energy consumption and GHG emissions of the CHS.
5) Present bottom-up models of energy consumption and GHG emissions of the CHS are lacking in the following areas:
    a) They rely on a limited variety of thermal envelope data. The thermal envelope dramatically affects the SH energy consumption, the largest end-use in the CHS.
    b) They are incapable of assessing the impact of alternative and renewable energy technologies.
    c) The bottom-up engineering models provide only a rudimentary estimate of occupant behaviour. This inhibits their ability to accurately estimate DHW and AL energy consumption.
6) The ESP-r building energy performance simulator is capable of estimating the impact of new technologies on the energy consumption of a building (Clarke 2001).
7) Aydinalp-Koksal and Ugursal (2008) proposed that a hybrid modeling method should be developed to overcome the limitations in present energy consumption models of the CHS. Such a hybrid model would rely on the bottom-up engineering and statistical methods.
    a) The engineering method provides for the specific ability to assess the impact that new technologies have on energy consumption and GHG emissions.
    b) The statistical method provides for the specific ability to assess the impact that occupant behaviour has on DHW and AL use.
8) A set of electricity generation GHG EIFs for both the average and marginal generation have been developed for each province of Canada by Farhat and Ugursal (2010). The marginal generation values may be incorporated into a model to assess the impact that an incremental change in electricity consumption will have on GHG emissions.

Considering the capabilities of the existing models, there is a need for a comprehensive modeling tool that can be used to study the impacts of alternative and renewable energy technologies on the energy consumption and GHG emissions of the CHS. This dissertation advances the state-of-the-art of residential sector energy consumption and GHG emissions modeling by addressing each of the arguments listed above.

1.5.1 Objective

The principal objective of this dissertation is the development of a new energy consumption and GHG emissions model of the CHS. This new model is comprehensive with regard to the end-uses, detailed with regard to the housing stock, and possesses the capability, resolution, and accuracy to assess the impact upon energy consumption and GHG emissions due to the application of alternative and renewable energy technologies to the CHS. The new model is titled the Canadian Hybrid Residential End-Use Energy and GHG Emissions Model (CHREM). A simplified CHREM flowchart is shown below in Figure 1.7. A detailed CHREM flowchart is provided in Figure 8.1 (Chapter 8, page 245). The following is a list of principal attributes that is required of the CHREM to achieve the model objectives:

- The CHREM must use a statistically representative database of the CHS, suitable for detailed building energy performance simulation. The database must contain sufficient unique house information to capture the variety of characteristics found in the CHS. It must allow for the identification of potential penetration levels of new technologies to the existing housing stock.
- The CHREM must employ a hybrid modeling approach that utilizes the strengths of different modeling methods to estimate the energy consumption of the major end-uses. The bottom-up statistical method is used to account for the effect of occupant behaviour on the DHW and AL end-uses. The bottom-up engineering method is used to enable the capacity for modeling alternative and renewable energy technologies. Because of the interrelation between end-uses, these two modeling methods must be integrated.
- The CHREM must have the ability to individually distinguish the change in energy consumption and GHG emissions for each end-use and energy source due to the application of a new technology to the CHS. Consideration must be given to the treatment of incremental changes in the electricity consumption.

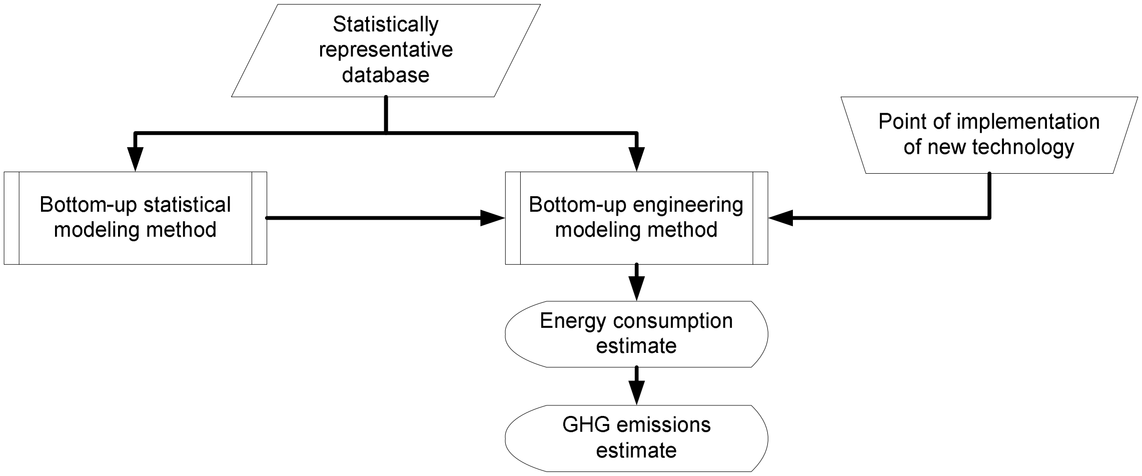

Figure 1.7 Simplified CHREM flowchart

The CHREM will be made available in the public domain for research use. Access to the CHREM can be obtained by contacting the author (Lukas.Swan@Dal.Ca).

1.5.2 Outline of the Dissertation

This dissertation presents the detail of the development of the CHREM. It also includes a case study on windows to demonstrate the unique capabilities of the CHREM. The dissertation is organized as follows:

> Chapter 2 reviews and critically examines the existing methods and models used to estimate the energy consumption and GHG emissions of the residential sector.
>
> Chapter 3 presents the CHREM housing database, which consists of 16,952 detailed house descriptions that are representative of the CHS. The large number of houses in the database accounts for the wide variety of characteristics found in the CHS. It also allows for the identification of houses which are suitable for specific technology applications. Each unique house description came from an energy audit of a real Canadian house. The audit characterized the building thermal envelope and its energy conversion systems. The database contains sufficient information to develop a thermodynamically representative house that is suitable for detailed building energy performance simulation. Geometric information is included which enables the assessment of directionally dependent solar energy technologies, and solar gains that are admitted through windows.
>
> Chapter 4 presents the CHREM bottom-up statistical method, which constitutes the first half of the “hybrid” modeling approach. The statistical method relies on the CHREM database, and employs the NN technique to estimate the annual use of DHW and AL. These specific end-uses are strongly affected by occupant behaviour. The annual use results are then distributed onto representative timestep use profiles. The timestep profiles allow the AL and DHW use estimates to be included within the CHREM bottom-up engineering method. This inclusion allows for the interrelated energy consumption effects of end-uses as described in section 1.3.
>
> Chapter 5 presents the CHREM bottom-up engineering method, which constitutes the second half of the hybrid modeling approach. The engineering method relies on the CHREM database and the statistical method timestep use profiles of DHW and AL, to create a representative thermodynamic description of each house. This detailed description includes: geometrical layout; specific treatment of each thermal zone; properties and dimensions of each material layer of the floors, walls, ceilings, windows, and doors; air-leakage characteristics; and specification of all heating, ventilation, and air-conditioning equipment. The engineering method utilizes the ESP-r building energy performance software to conduct annual simulation of each house, and estimates the end-use energy consumption.
>
> Chapter 6 presents the CHREM results accumulation methods and values. These are used to assess the energy transfer mechanisms within the house, and energy consumption attributable to each specific end-use. The GHG emissions are calculated from the monthly end-use energy consumption with respect to the energy source EIF. In the case of electricity, the provincially specific average or

marginal electricity generation EIF is used. The energy consumption and GHG emissions estimates are compared to other models and verified against billing data.

Chapter 7 provides a demonstration of the capabilities of the CHREM. The contribution of windows to the end-use energy consumption of the CHS is estimated. Two window upgrade scenarios are modeled, and the impact on energy consumption and GHG emissions is estimated.

Chapter 8 concludes the dissertation with a summary of the contributions to the state-of-the-art of housing stock energy consumption and GHG emissions modeling. A list of recommendations is provided for future research using the CHREM, and of opportunities to expand and further develop the CHREM.

Chapter 2 Review of Residential Sector Energy Consumption Modeling Techniques

This chapter was previously published as:

Swan LG, Ugursal VI (2009). Modeling of end-use energy consumption in the residential sector: A review of modeling techniques. Renewable and Sustainable Energy Reviews 13(8). 1819–1835. DOI: 10.1016/j.rser.2008.09.033.

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Lukas Swan is the principal researcher and author of the article. He conducted the research as part of his PhD. Thus, while he received supervision and guidance from his supervisor Dr. Ugursal, he carried out the work, wrote the published article, communicated with the editor of the journal, and carried out the necessary revisions before publication. Minor grammatical changes have been made to integrate the article within this dissertation.

2.1 Abstract

There is a growing interest in reducing energy consumption and the associated greenhouse gas emissions in every sector of the economy. The residential sector is a substantial consumer of energy in every country, and therefore a focus for energy consumption efforts. Since the energy consumption characteristics of the residential sector are complex and inter-related, comprehensive models are needed to assess the technoeconomic impacts of adopting energy efficiency and renewable energy technologies suitable for residential applications.

The aim of this chapter is to provide an up-to-date review of the various modeling techniques used for modeling residential sector energy consumption. Two distinct approaches are identified: top-down and bottom-up. The top-down approach treats the residential sector as an energy sink and is not concerned with individual end-uses. It utilizes historic aggregate energy values and regresses the energy consumption of the housing stock as a function of top-level variables such as macroeconomic indicators (e.g. gross domestic product, unemployment, and inflation), energy price, and general climate. The bottom-up approach extrapolates the estimated energy consumption of a representative set of individual houses to regional and national levels, and consists of two distinct methodologies: the statistical method and the engineering method.

Each method relies on different levels of input information, different calculation or simulation techniques, and provides results with different applicability. A critical review of each method, focusing on the strengths, shortcomings and purposes, is provided along with a review of models reported in literature.

2.2 Introduction

Nationally, energy consumption of the residential sector accounts for 16% to 50% of that consumed by all sectors, and averages approximately 30% worldwide as shown in Figure 2.1. This significant consumption level warrants a detailed understanding of the residential sector's consumption characteristics to prepare for and help guide the sector's energy consumption in an increasingly energy conscience world; conscience from standpoints of supply, efficient use, and effects of consumption. In response to climate change, high energy prices, and energy supply/demand, there is interest in understanding the detailed consumption characteristics of the residential sector in an effort to promote conservation, efficiency, technology implementation and energy source switching, such as to on-site renewable energy.

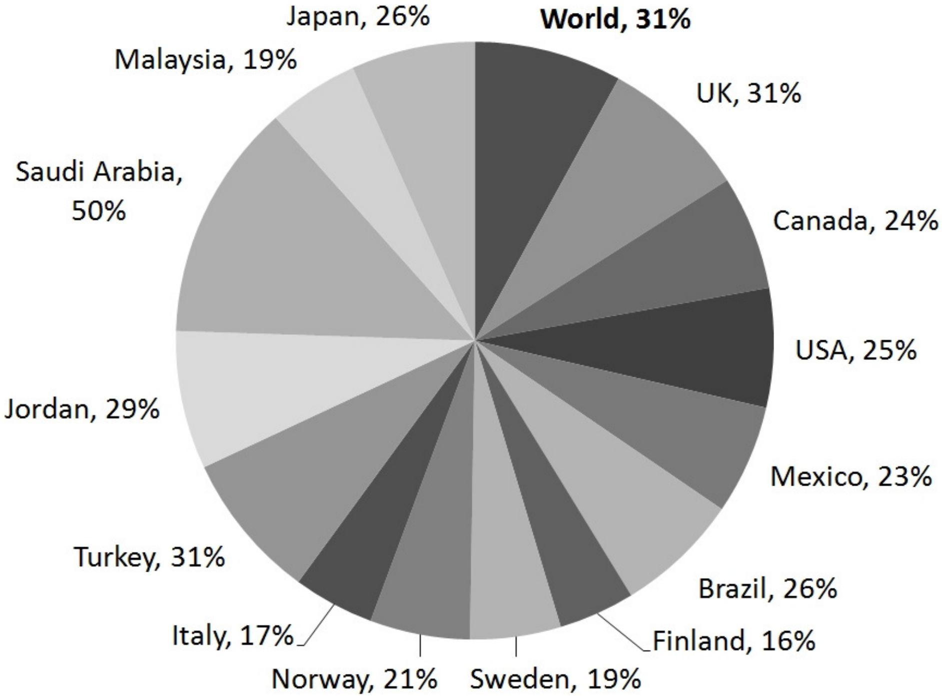


Figure 2.1 Residential energy consumption shown as a percentage of national energy consumption and in relative international form (Saidur et al. 2007)

Energy consumption of other major sectors such as commercial, industrial, agriculture and transportation are better understood than the residential sector due to their more centralized ownership, self-interest, and expertise in reducing energy consumption, and high levels of regulation and documentation. The residential sector is largely an undefined energy sink due to the following reasons:

- The sector encompasses a wide variety of structure sizes, geometries, and thermal envelope materials.
- Occupant behaviour varies widely and can impact energy consumption by as much as 100% for a given dwelling (Seryak and Kissock 2003).
- Privacy issues limit the successful collection or distribution of energy data related to individual households.

The residential sector uses secondary energy. Secondary energy is that received in suitable form for use by the consuming systems to support the living standards of occupants. The major end-use groups of secondary energy are:

- Space heating (SH) and space cooling (SC) – energy required to support thermal losses incurred across the building envelope due to conduction and radiation, as well as air infiltration/ventilation in an effort to maintain the living space at a comfortable temperature and air quality.
- Domestic hot water (DHW) – energy required to heat water to a comfortable or appropriate temperature for occupant and appliance uses.
- Appliances and lighting (AL) – energy consumed to operate common appliances (e.g. refrigerator, coffee maker) and for the provision of adequate lighting.

The degree to which these groups affect the overall energy consumption is highly dependent on climate, physical dwelling characteristics, appliance and system characteristics, ownership, and occupant behaviour.

The total energy consumption of a dwelling is that required to support all energy consuming end-uses, inclusive of the losses due to appliance and system efficiencies. The end-uses may have complex interrelated effects with regards to energy consumption. For example, the energy consumption of most common appliances results in heating of the conditioned living area. The energy consumption can be supplied by one or more secondary energy sources and includes on-site generation and passive solar gains. The sum of each dwelling’s energy consumption for a given area (e.g. city, country) results in a regional or national residential sector energy consumption, the modeling of which is the topic of interest for this review.

Energy consumption modeling of buildings seeks to quantify energy requirements as a function of input parameters. Models may be used for a variety of reasons, the most common being the determination of regional or national energy supply requirements (macro scale) and the change in energy consumption of a particular dwelling due to an upgrade or addition of technology (micro scale). Modeling of this nature is useful as it can guide decisions of policy regarding the residential stock, both old and new. By quantifying the consumption and predicting the impact or savings due to retrofits and new materials and technology, decisions can be made to support energy supply, retrofit and technology incentives, new building code, or even demolition and re-construction.

Residential energy models may focus on a thermal zone, building, neighbourhood, city, state or province, region, or nation. The level of detail of input parameters is a function of data availability, model focus and purpose, and assumptions. Increased detail allows for a more comprehensive investigation of particulars, although accurate assumptions may significantly ease the modeling process and provide suitable results.

Emphasis of this review is placed on models that are or could be used to model the residential sector energy consumption. Energy consumption models of this scope involve an approximation of the residential stock and a methodology for estimating the energy consumption of the stock. Such models are useful to formulate policy decisions regarding the residential stock, both old and new. By quantifying the consumption and predicting the impact or savings due to construction/demolition, retrofits and new materials and technology, decisions can be made to support energy supply, retrofit and technology incentives, new building codes, or even demolition and re-construction. This review of residential sector energy consumption models introduces the modeling techniques, reviews the published literature, and concludes with an analysis of the strengths and weaknesses of the techniques.

2.3 Objective

The objective of this chapter is to provide an up-to-date review of the various techniques used for modeling residential sector energy consumption. Two distinct approaches are identified: top-down and bottom-up. Each technique relies on different levels of input information, different calculation or simulation techniques, and provides results with different applicability. A critical review of each technique, focusing on the strengths, shortcomings and purposes, is provided along with a review of models reported in literature.

2.4 Modeling Methodologies

Residential energy models rely on input data from which to calculate or simulate energy consumption. The level of detail of the available input data can vary dramatically, resulting in the use of different modeling techniques which seek to take advantage of the available information. These different modeling techniques have different strengths, weaknesses, capability, and applicability.

2.4.1 Types and Sources of Information

Depending on the modeling methodology to be used, the input data required to develop residential energy models includes information on the physical characteristics of the dwellings, occupants and their appliances, historical energy consumption, climatic conditions, and macroeconomic indicators. The information can be collected independently or concurrently, can be national aggregate or individual dwelling values, and vary greatly in level of detail. The basic information collection method is by survey, the results of which are published in raw or analyzed form.

The preliminary estimate of the total residential sector energy consumption is usually published by governments which compile gross energy values submitted by energy providers (examples are Canada (OEE 2006b), USA (EIA 2006), UK (UK 2007), and China (China 2005)). These estimates provide indicators as to sector energy consumption but may be inaccurate as they do not account for unreported energy or on-site generation. A more detailed source of energy consumption data, typically on a monthly basis and for each dwelling, is the billing records of energy suppliers (e.g. monthly dwelling electricity bill). However, with no additional housing information these energy consumption values are difficult to correlate due to the wide variety of dwellings and occupants.

To provide more detailed information than the above aggregate values, housing surveys are conducted. These surveys target a sample of the population to determine building and occupant characteristics and appliance penetration levels (examples are Canada (OEE 2006), USA (EIA 2001), and UK (UK 2007b)). Macmillan and Kohler (2004) conducted a worldwide review of such surveys. Surveys typically attempt to define the house geometry and thermal envelope, ownership of appliances, occupants and their use of appliances and preferred settings, and demographic characteristics. In addition, surveys may attempt to obtain the energy suppliers' billing data (described above) and alternative energy source information (e.g. unreported wood usage) to correlate the energy consumption of the house with its characteristics identified during the survey. This allows for calibration through reconciliation of a model's predicted energy consumption with actual energy billing data. This level of information is superior to the previously mentioned energy supplier values; however, it is limited due to collection difficulties and cost, and therefore it is imperative that the selected sample be highly representative of the population. Also, occupant descriptions of their appliance use are highly subjective and can be influenced by the season during which the survey takes place (OEE 2006). Examples of surveys which have been condensed for the purpose of energy simulation are Persily et al. (2006) and Swan et al. (2009b).

Elimination of subjective appliance usage estimation is achieved by "sub-metering". This method places energy metering devices on the large energy consuming appliances within the household to determine both their component of the house energy consumption and their usage profile as a function of time. This level of information is rare due to its prohibitive cost.

Estimated total sector energy, individual billing data, surveys, and sub-metering have been used to varying degrees in the development of residential energy consumption models. The determination of which information is used depends on availability and model's purpose. The purpose of models ranges widely and may be directed towards determining supply requirements, price and income elasticity, and the energy consumption impacts of upgrades, technologies, or changes to behavioural patterns.

2.4.2 Techniques used to Model Residential Energy Consumption

Techniques used to model residential energy consumption can broadly be grouped into two categories, "top-down" and "bottom-up". The terminology is with reference to the hierarchal position of data inputs as compared to the housing sector as a whole. Top-down models utilize the estimate of total residential sector energy consumption and other pertinent variables to *attribute* the energy consumption to characteristics of the entire housing sector. In contrast, bottom-up models *calculate* the energy consumption of individual or groups of houses and then extrapolate these results to represent the region or nation.

Groupings of top-down and bottom-up techniques for modeling residential energy consumption are shown in Figure 2.2 and are discussed in the following sections.

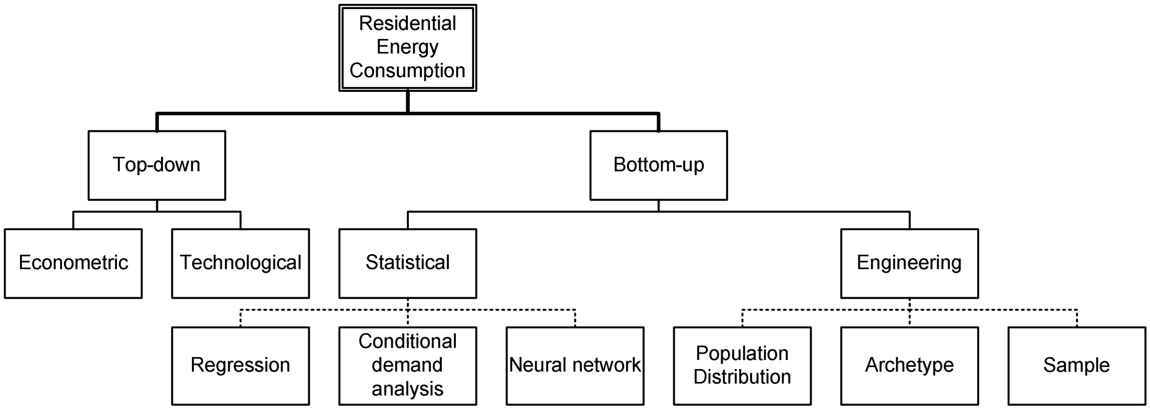


Figure 2.2 **Top-down and bottom-up modeling techniques for estimating the regional or national residential energy consumption**

2.4.2.1 Overview of the Top-down Approach

The top-down approach treats the residential sector as an energy sink and does not distinguish energy consumption due to individual end-uses. Top-down models determine the effect on energy consumption due to ongoing long-term changes or transitions within the residential sector, primarily for the purpose of determining supply requirements. Variables which are commonly used by top-down models include macroeconomic indicators (gross domestic product (GDP), employment rates, and price indices), climatic conditions, housing construction/demolition rates, and estimates of appliance ownership and number of units in the residential sector.

Figure 2.2 shows two groups of top-down models: *econometric* and *technological*. Econometric models are based primarily on price (e.g. energy and appliances) and income. Technological models attribute the energy consumption to broad characteristics of the entire housing stock such as appliance ownership trends. In addition there are models which utilize techniques from both groups.

Top-down models operate on an equilibrium framework which balances the historical energy consumption with that estimated based on input variables. The strengths of top-down modeling are the need for only aggregate data which are widely available, simplicity, and reliance on historic residential sector energy values which provide "inertia" to the model. As the housing sector rarely undergoes paradigm shifts (e.g. electrification, energy shocks), a weighted model provides good prediction capability for small deviations from the status quo. For example, if housing construction increased the number of units by 2%, an increase in total residential energy consumption of 1.5% might be estimated by the top-down model, as new houses are likely more energy efficient. If this construction was increased to 10% of the units the top-down model could have difficulty in producing an appropriate estimate as the vintage distribution of the housing stock would have changed significantly.

The reliance on historical data is also a drawback as top-down models have no inherent capability to model discontinuous advances in technology. Furthermore, the lack of detail regarding the energy consumption of individual end-uses eliminates the capability of identifying key areas for improvements for the reduction of energy consumption.

2.4.2.2 Overview of the Bottom-up Approach

The bottom-up approach encompasses all models which use input data from a hierarchal level less than that of the sector as a whole. Models can account for the energy consumption of individual end-uses, individual houses, or groups of houses and are then extrapolated to represent the region or nation based on the representative weight of the modeled sample. The variety of data inputs results in the groups and sub-groups of the bottom-up approach as shown in Figure 2.2.

Statistical methods (SM) rely on historical information and types of regression analysis which are used to attribute dwelling energy consumption to particular end-uses. Once the relationships between end-uses and energy consumption have been established, the model can be used to estimate the energy consumption of dwellings representative of the residential stock. *Engineering* methods (EM) explicitly account for the energy consumption of end-uses based on power ratings and use of equipment and systems and/or heat transfer and thermodynamic relationships.

Common input data to bottom-up models include dwelling properties such as geometry, envelope fabric, equipment and appliances, climate properties, as well as indoor temperatures, occupancy schedules and equipment use. This high level of detail is a strength of bottom-up modeling and gives it the ability to model technological options. Bottom-up models have the capability of determining the energy consumption of each end-use and in doing so can identify areas for improvement. As energy consumption is calculated, the bottom-up approach has the capability of determining the total energy consumption of the residential sector without relying on historical data. The primary drawback caused by this level of detail is that the input data requirement is greater than that of top-down models and the calculation or simulation techniques of the bottom-up models can be complex.

In all cases the bottom-up models must be extrapolated to represent the housing sector. This is accomplished using a weighting for each modeled house or group of houses based on its representation of the sector.

A notable capability of the bottom-up approach is its ability to explicitly address the effect of occupant behaviour and "free energy" gains such as passive solar gains. Although free energy gains have historically been neglected during residential analysis, they are now a common design point as focus is placed on alternative energy technologies. Statistical methods attribute all of the *measured* energy consumption to end-uses and in doing so incorporate the occupant's behaviour with regards to use and settings of appliances. However, if all energy sources are not accounted for, the end-use energy consumption estimates are de-rated by this consumption difference. Based in its physical principle roots, the EM has the ability to capture the additional energy consumption level based on requirements, inclusive of free energy. However, occupant behaviour must be estimated which is difficult as behaviour has been shown to vary widely and in unpredictable ways.

The following sections examine the modeling techniques by reviewing published models. The applicability, basic methodology, and major conclusions found by the researchers are listed. There is a tendency towards chronological order to facilitate understanding of the modeling technique development stream and contributions by the authors. Certain techniques were found to follow a clear development stream (e.g. conditional demand analysis) while others contain a wide variety of techniques and are discontinuous. Emphasis is placed on modeling technique development and less on the simple application to a new region.

2.5 Top-down Models

The use and development of the top-down modeling approach proliferated with the energy crisis of the late 1970's. In an effort to understand consumer behaviour with changing supply and pricing, broad econometric models were developed for national energy planning. These models require little detail of the actual consumption processes. The models treat the residential sector as an energy sink and regress or apply factors that affect consumption to determine trends. Most top down models rely on similar statistical data and economic theory.

As the housing stock in most regions is continuously undergoing improvement and increase, simply modeling the energy consumption solely as a function of economic variables is short-termed. Hirst et al. (1977) initiated an annual housing energy model of the USA. Their model relied on econometric variables and included a component for growth/contraction of the housing stock. Their work was expanded and improved over the following years resulting in an econometric model which had both housing and technology components (Hirst 1978, Hirst and O'Neal 1980). The housing component evaluates the number of houses based on census data, housing attrition and new construction. The technology component increases or decreases the energy intensiveness of the appliances as a function of capital cost. The economic component evaluates changes in consumption based on expected behavioural changes and efficiency upgrades made to the technology component. Finally, market penetration is considered a function of income and demand/supply. The simulation model combines the changes in outputs of the components and estimates the energy consumption given historic energy consumption values. The authors felt their model was sensitive to major demographic, economic, and technological factors, but recognized the need to continually update all assumed information to improve quality.

Saha and Stephenson (1980) developed a similar model for New Zealand although it had a technological focus. Their economic and housing components drive separate analysis of SH, DHW, and cooking, and are added to obtain total consumption. Their basic energy balance, as shown in Equation 2.1, determines the annual energy consumption of each fuel used to support each end-use group as a function of stock, ownership, appliance ratings, and use. Using historical data, their prediction capability was excellent throughout the 1960’s and 1970’s although there is significant divergence toward the latter half of the 1970’s. This may be due to the model not accounting for shifts in home insulation levels.

$$E_{\mathrm{an},e,f} = S \cdot C_{e,f} \cdot R_{e,f} \cdot U_{e,f} \tag{2.1}$$

Where:

E is the annual energy consumption of end-use group e, corresponding to fuel type, f,

S is the level of applicable housing stock,

C is the appliance ownership level,

R is the rating of all appliances within an end-use group, and

U is a use factor.

Haas and Schipper (1998) recognized that energy consumption of the housing stock is poorly modeled by only a few econometric indicators. They identified “irreversible improvements in technical efficiency” which are a result of consumer response that not only reduces energy consumption due to rising price, but responds by making upgrades to their dwelling. Consequently a subsequent reduction in price would not cause a perfectly elastic rebound. To quantify this asymmetrical elasticity, they developed econometric models for the USA, Japan, Sweden, West Germany, and the UK based on the time periods of: 1970–1993, 1970–1982, and 1982–1983. They found very flat (nearly zero) rebound of energy consumption after periods of increased price, suggesting the typical price elasticity is a diluted average. They also state saturation of appliances can lead to reduced income elasticity and they found limited correlation between increasing technological efficiency leading to increased energy use. When the authors included technological energy intensity in their model (using a bottom up approach based on individual appliance ratings) they found reduced error and that the irreversible share of price elasticity became hidden in the coefficient of intensity.

Two tier econometric models that evaluate choice of system (discrete) and utilization (continuous) are common. Nesbakken (1999) developed such a model for Norway, testing sensitivity and stability across a range of income and pricing. The author considered three years of expenditure surveys and energy consumption to determine differences along the time dimension. Their findings were consistent with negative price elasticity and maximization of utility. Different income groups resulted in similar findings although the responses were slightly higher for higher income groups.

Bentzen and Engsted (2001) revived simple economic modeling of residential energy consumption. They tested the following three annual energy consumption regression models for Denmark:

$$E_{\mathrm{an},t} = b + c_1\, E_{\mathrm{an}.t-1} + c_2\, I_{\mathrm{disp},t} + c_3\, Pc_t \tag{2.2}$$

$$E_{\mathrm{an},t} = b + c_1\, E_{\mathrm{an}.t-1} + c_2\, I_{\mathrm{disp},t} + c_3\, Pc_t + c_4\, HDD_t \tag{2.3}$$

$$E_{\mathrm{an},t} = b + c_1\, E_{\mathrm{an}.t-1} + c_2\, I_{\mathrm{disp},t} + c_3\, Pc_t + c_4\, HDD_t + c_5\, Pc_{t-1} \tag{2.4}$$

Where:
E is the annual energy consumption for year, t,
I is the disposable household income,
Pc is the price of energy,
HDD is the heating degree days,
b is a constant, and
c are coefficients.

From 36 years of data they found that, in all three cases, long term energy consumption was strongly affected by income and lagged energy consumption, and lagged pricing trumped current pricing. Their findings indicate that future energy price must increase with income to maintain the current consumption level.

Using aggregate national residential energy values, Zhang (2004) compared international values of unit energy consumption (UEC) to determine to potential changes in the sector's energy consumption. The author calculated the UEC for various regions of China based on energy consumption and the number of residences, and compared the Chinese UEC with those of other countries. The results indicate that when normalized for heating requirements based on climate (i.e. heating degree days, HDD), Japan uses approximately half the UEC of the USA and Canada, as shown in Figure 2.3. This may be attributed in part to the high ratio of apartment buildings in Japan (40%). China is closer to one quarter of the North American UEC, owing to limited adoption of space heating devices. The paper also discusses the potential of the Chinese residential sector following the North American or Japanese energy consumption characteristics. Interestingly, the model identified that although China is growing, the secondary energy consumption of the residential sector has remained constant due to switching away from coal as a fuel.

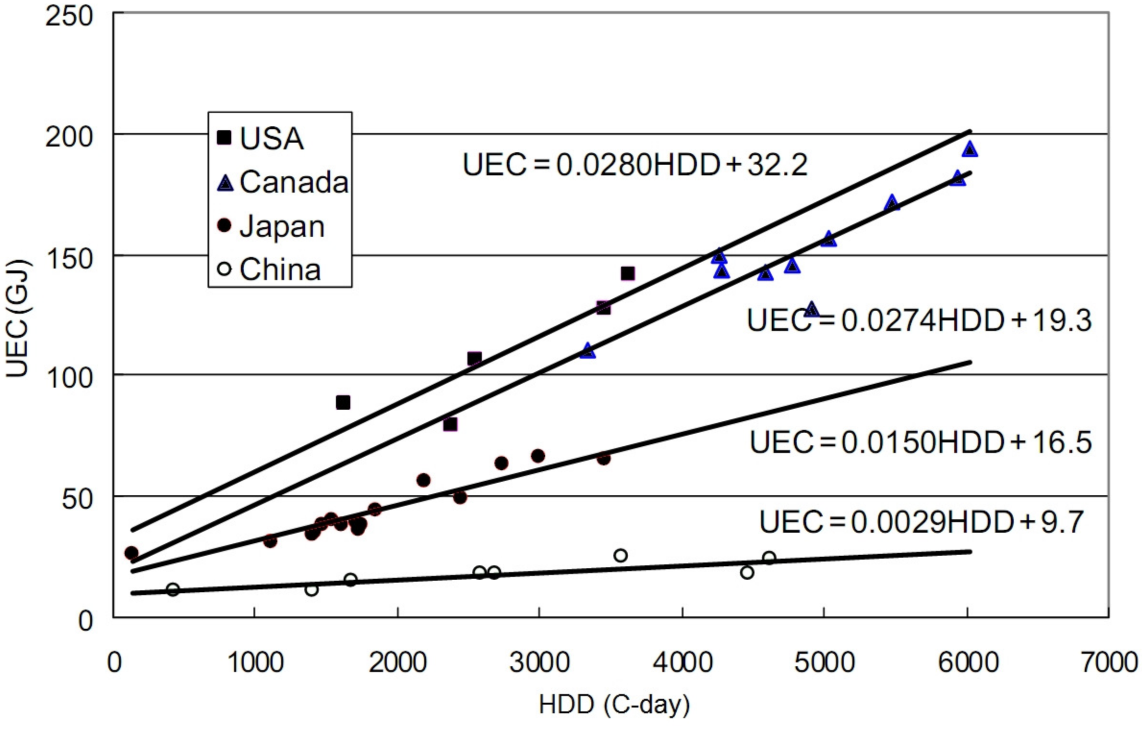


Figure 2.3 Comparison of National UEC values (Zhang 2004)

Ozturk et al. (2004) and Canyurt et al. (2005) proposed the use of genetic algorithms (GA) to determine the relationships between Turkish residential-commercial energy consumption and the following: GDP, population, import/export, house production, cement production and appliance sales. GA models utilize concepts of biology and Darwin's theory of survival of the fittest. Initiated chromosomes (potential solutions) are assessed on the basis of fit (sum of squared errors) to determine their level of participation. Chromosomes are crossed to exchange potential solution characteristics (coefficients of input variables) with the potential of mutations to account for solutions which were not part of the initial population. The authors' GA model estimates the coefficients of the linear model based on the aforementioned variables and their combinations. The resultant model had excellent fit with the calibration information and their projections through the year 2020 were similar to other models. They note the benefits of the GA as requiring limited information and easy development.

The National Energy Modeling System (NEMS) incorporates a current econometric energy model of the USA housing stock (EIA 2005). The model is used for mid-term forecasting and policy analysis. It includes five components: housing stock forecast, technology, appliance stock forecast, building shell integrity, and distributed generation equipment. The appliance stock component places emphasis on appliance lifetime and saturation levels, functions which have been studied in depth for Canada by Young (2008). The distributed generation component indicates that emphasis is being placed on the integration of non-traditional energy sources; it looks at system cost, efficiency, penetration parameters, and solar insolation levels. The calculated energy consumption is then fed back into the NEMS for use with other models and overall energy supply prediction.

Using the entire building register of Goteborg (68,200 buildings) and energy data from the largest energy supplier, Tornber and Thuvander (2005) developed an energy model of the building stock. The energy data was measured at metering stations, and was distributed among connected buildings on the basis of building use and age. The model utilizes geographical information systems (GIS) to visually assist the assessment of the consumption rates of different energy sources throughout Goteborg. Although they were unable to directly link the energy consumption to individual buildings, their spatial model clearly identifies energy use within groups of buildings and may be used for identification of high consumption areas.

Labandeira et al. (2006) extended a regression model by developing a six equation demand model of Spanish residential energy consumption. Separate equations were developed for energy consumption associated with: electricity, natural gas, propane, automotive fuel, public transport, and food. They found that these products are price inelastic. They regressed the energy consumption of over 27,000 houses as a function of demographic, macroeconomic, and climate variables. They experienced reduced multicollinearity problems as their dataset covered an extended period of time (changing appliances ownership) and this also provided longer term elasticity assessment.

Siller et al. (2007) created a model of the Swiss residential sector to test the impacts of renovations and new construction in an attempt to achieve energy consumption and greenhouse gas emissions targets. Their model is based on the effective reference area which is a measure of the effective heated area and is calculated based on census data. They developed modeling matrices which account for the renovation of buildings and if demand is met, new construction of buildings. In calculating energy consumption they use building type, energy standards, efficiency, and heat demand per area. The update of the housing stock is through new construction and renovation, of which the latter is only occasionally realized. They point out that these estimates have a strongly affect model uncertainty.

Balaras et al. (2007) constructed a renovation model of the Hellenic housing stock. Using an assessment of the housing stock and current energy consumption figures, they estimated the impact of fourteen different energy conservation measures that were applied to houses in need of refurbishment. They found the housing stock lacking in insulation and predicted that adding insulation to the stock would save 49% of current space heating energy consumption.

2.6 Bottom-up Models

The bottom-up approach was developed to identify the contribution of each end-use towards the aggregate energy consumption value of the residential stock. This refines the understanding of the details associated with the energy consumption.

There are two distinct categories used in the bottom-up approach to evaluate the energy consumption of particular end-uses. The SM utilizes dwelling energy consumption values from a sample of houses and one of a variety of *techniques* to regress the relationships between the end-uses and the energy consumption. SM models can utilize macroeconomic, energy price and income, and other regional or national indicators, thereby gaining the strengths of the top-down approach. The EM relies on information of the dwelling characteristics and end-uses themselves to calculate the energy consumption based on power ratings and use characteristics and/or heat transfer and thermodynamic principles. Consequently, the engineering technique has strengths such as the ability to model new technologies based solely on their traits. Once developed, the bottom-up models may be used to estimate the energy consumption of houses representative of the residential stock and then these results can be extrapolated to be representative of the regional or national residential sector.

2.6.1 Statistical Method

The vast quantity of customer energy billing information stored at the major energy suppliers worldwide is an unprecedented data source for energy modeling. Researchers have applied a variety of SM techniques to utilize this and other information to regress the energy consumption as a function of house characteristics. A capability of the SM techniques is their ability to discern the effect of occupant behaviour. This is of benefit to residential modeling as occupant behaviour has been found to range widely and is poorly represented by simplified estimates (Seryak and Kissock 2003, Lutzenhiser 1992, Emery and Kippenhan 2006).

The three well documented techniques, all of which use a sample of houses, are regression, conditional demand analysis, and neural networks.

The regression technique uses regression analysis to determine the coefficients of the model corresponding to the input parameters. These models regress the aggregate dwelling energy consumption onto parameters or combinations of parameters which are expected to affect energy consumption. The model is evaluated based on goodness of fit. Input variables which are determined to have a negligible effect are removed for simplicity. Based on the combinations of inputs, the model’s coefficients may or may not have physical significance.

The conditional demand analysis (CDA) technique performs regression based on the presence of end-use appliances. By regressing total dwelling energy consumption onto the list of owned appliances which are indicated as a binary or count variable, the determined coefficients represent the use level and rating. The primary strength of this technique is the ease of obtaining the required input information: a simple appliance survey from the occupant and energy billing data from the energy supplier. However, it does require a dataset with a variety of appliance ownership throughout the sample. This technique exploits the differences in ownership to determine each appliance’s component of the total dwelling energy consumption. In order for the CDA technique to produce reliable results, and depending on the number of variables used, data from hundreds or even thousands of dwellings are required.

The neural network technique utilizes a simplified mathematical model based on the densely interconnected parallel structure of biological neural networks. The technique allows all end-uses to affect one another through a series of parallel “neurons”. Each neuron has a bias term and array of coefficients that are multiplied by the value of the preceding layer’s neurons. Similar to regression models it seeks to minimize error and may apply scaling and activation functions to account for non-linearity. As it is a parallel model, the coefficients have no physical significance.

2.6.1.1 Regression

In an effort to identify unusual metering occurrences (e.g. broken meter) and evaluate the level of households with more than one energy source for space heating, Hirst et al. (1986) used the Princeton scorekeeping model (Fels 1986) with monthly or bimonthly energy supplier billing data. They examined the weather and non-weather sensitive elements of the household energy consumption of dwellings by regressing the energy billing data onto a non-weather dependent constant and a weather dependent coefficient based on HDD, as shown in Equation 2.5. They left the reference temperature for determination of the HDD as a variable, to be adjusted between 4 °C and 24 °C in an effort to reduce error and increase the multiple correlation coefficient (R^2). The adjustment of T_{ref} was shown to be effective by Jones and Harp (1980) who reduced it from the accepted value of 18.0 °C to 16.9 °C and achieved more representative results for the space heating requirements of Oklahoma.

$$E_{\text{an},t} = b + c\ HDD_{\text{t}}(T_{\text{ref}}) \tag{2.5}$$

Where:
E is the annual energy billing data from period, t,
HDD is the heating degree days with reference temperature, T_{ref},
b is constant, and
c is a coefficient.

The coefficients in the above model were termed “fingerprints” and directed towards determining unusual metering occurrences and identifying the use of alternative space heating fuels when comparing the monthly measured house energy consumption to that predicted by the model. Recently, a similar analysis was conducted by Raffio et al. (2007) with the goal of identifying energy conservation potential within a regional area. A similar model with “energy signature” coefficients was developed. These coefficients were compared regionally and also evaluated over the course of the seasons for the identification of patterns which can be used to assess potential energy conserving changes. The authors give examples such as the application of DHW conserving devices to dwellings with high non-weather dependent energy consumption, and the application of programmable thermostats to high balance point T_{ref} buildings. While the model cannot determine the impact of these changes, it may identify the potential for application. The primary advantages of this model are simplicity, only requiring billing data, and the capability of normalized comparison across many different residences using a sliding scale which is continuously updated from new billing data. Utilizing larger sets of billing data, the models can become descriptive of a nation.

Tonn and White (1988) developed a regression model with four simultaneous equations: separate equations of electricity use associated with SH and AL, wood use, and indoor temperature. Data was sourced from 100 sub-metered homes that utilized wood heat. In an attempt to encompass occupant behaviour they conducted an extensive survey (300 questions) which asked questions related to goals and motivations, and occupants self-defined socioeconomic response. Their desire was to determine the motivation or ethical considerations in energy use. They developed 30 different regression models, consecutively eliminating variables with insignificant impact. Their four regression equations achieved R^2 values ranging from 0.80 to 0.91. While housing characteristics played a distinct role in the models, they found ethical motivations outweigh economic motivations. They found education level and age of the head of household not to affect any of the four equations.

Douthitt (1989) constructed a model of residential space heating fuel use in Canada by regressing consumption as a function of present and historic fuel price, substitute fuel price, total fuel consumption, and a vector of building structure, climatic, and occupant characteristics. Using 370 records, they achieved R^2 values equal to 0.52 (natural gas), 0.76 (heating oil), 0.37 (electricity with natural gas available), and 0.79 (electricity with no natural gas available). The author found that the sample with energy source alternatives achieve near unity price elasticity, the implication being towards fuel subsidies being ineffective at reducing annual fuel cost per house. Income elasticity was also very unitary, indicating that providing subsidies (in effect income) to low-income families would result in increased usage.

Fung et al. (1999) adopted the regression techniques of Douthitt (1989) to determine the impact on Canadian residential energy consumption due to energy price, demographics, and weather and equipment characteristics. They found both short and long term fuel price elasticity to be negative, although the long term was larger in magnitude. Income elasticity was found to be insignificant. These results were similar for each end-use group (i.e. SH/SC, DHW, AL).

2.6.1.2 Conditional Demand Analysis

Parti and Parti (1980) developed the CDA method given the availability of a detailed survey of appliance and occupants of over 5,000 households and their corresponding monthly electrical billing data from the electricity utility in San Diego. They recognized the limitations inherent to an engineering model that approximates occupant behaviour based on theoretical considerations and therefore they attempted to determine the use level of individual appliance based on regression methods. They proposed a *conditional demand regression equation* based on the indication of appliance ownership and expected relations with other house characteristics such as floor area or demographic factors gathered from a survey.

Their regression equation, one for each month of a year of billing data, take the form

$$E_{\mathrm{mo}} = \sum_{i} \sum_{app} c_{app,i} \left(V_i C_{app} \right) \tag{2.6}$$

Where:

E is the monthly electrical energy consumption,

C is a variable indicating appliance presence or count for appliances, app,

V is a set of interaction variables with elements, i, such as the number of occupants, income, and floor area, and

c is a coefficient.

The appliance at $app = 0$ is unspecified to account for appliances whose presence were not explicitly surveyed and the interaction variable when $i = 0$ accounts for appliance energy consumption unrelated to interactions with other surveyed information.

Parti and Parti (1980) specified conditions to limit use of the significant appliances to help in regression coefficient determination. These included disallowing air conditioning from November through March and space heating from July through August. They considered the dominant electrical end-uses: air conditioning, space heating, water heating, and common appliances which include dishwasher, cooking range, dryer, and refrigerators and freezers. The interaction variables corresponding to end-use groups are shown in Table 2.1.

Table 2.1 Interaction variables which have an effect on the energy consumption of particular appliances or equipment (Parti and Parti 1980)

	Appliances and equipment			
Interaction variable	Common	Refrigerator	DHW	SH/SC
Occupant count	√	√	√	
Electricity price	√		√	√
Household income	√		√	√
Floor area				√
SH/SC per unit area				√

The final model coefficients were indicative of appliance use and resulted in R^2 values ranging from 0.58 to 0.65. As the regression model included demographic variables, the authors were able to determine econometric effects such as income and energy price elasticity. In comparison with engineering estimates, their CDA model under predicts energy consumption of space heating and over predicts energy consumption of water heating and common appliances. The authors believe they could incorporate solar technologies, but recognize the need for sufficient samples and associated annual dwelling energy consumption data. They see the benefits of the CDA method including the disaggregation of energy consumption by end-use without sub-metering and the inclusion of behavioural aspects within the coefficients.

Using 15 minute interval load data from 100 Los Angeles electricity customers, Aigner et al. (1984) utilized the CDA method to determine hourly regression equations. Based on constant appliance dummy variables, they found the regression resulted in inadequate coefficients. For example, the magnitude of coefficients (indicating use level) changed throughout the day with load level, but the relationship between different appliances did not, indicating that the coefficients represent an average use level and are not indicative of the daily use profile. To promote differences in the coefficients, the authors imposed restrictive windows of appliance use; specifically, laundry and cooking devices were excluded over the period of 2 AM to 5 AM. Their results compared to actual occupant load profiles better than conventional CDA.

Caves et al. (1987) developed a CDA model of the residential electricity energy consumption of Los Angeles customers by incorporating prior information through the use of Bayesian inference in an effort to reduce unreasonable or negative coefficients estimated by the conventional CDA method. The prior information was developed by using the EM to model appliances and systems and estimate load profiles. These profiles were used to calculate coefficients of use, similar to the CDA coefficients. A typical CDA model, based on a sample of 129 houses with daily energy consumption information (excluding weekends) for the summertime in Los Angeles was constructed using a method similar to Parti and Parti (1980). Given the confidence levels of the EM coefficients and the CDA method coefficients, these weighted values are combined using Bayesian techniques to estimate final coefficients of the CDA regression model. This combination approach reduces the multicollinearity effects which can result in negative or unreasonable coefficients; however, it relies on engineering estimates of occupant behaviour.

Bartels and Fiebig (1990) and Fiebig and Bartels (1991) propose an alternative method that incorporates sub-metered end-use energy consumption of a subset of the sample into the CDA model. This was accomplished by removing the energy consumption and independent variables of the measured appliances within the sub-metered subset of houses. In doing this, they reduced the regression requirements of the subset and weighted the regression of the coefficients of the remaining sample. One advantage of this method is that the elimination of certain end-use consumption of the sub-metered subset increases the resolution and therefore the confidence level of the estimates of non-metered appliances. This is an improvement over using the EM to determine estimates of certain end-uses based on occupant behaviour.

Lafrance and Perron (1994) furthered the CDA method by incorporating energy consumption data from three different years over a decade for Quebec. This allowed for the determination of changes in annual energy consumption as a function of changing appliance stock (specifically the addition of electric space heat), and long term pricing response. The database they used was significantly larger than previous efforts, approximately 100,000 samples in total, and contained additional information such as weather relations (heating and cooling degree days), cords of wood (an important energy source for space heating in

Quebec), water heater characteristics and certain demographics. These qualities increased the R^2 coefficient to a range of 0.55 to 0.70.

Their CDA model for each year of available data allowed them to identify changing ownership which evolved to larger, more consuming appliances throughout the period. Strong relationships were identified between incentive activities and appliance penetration. They found the CDA method could estimate the space heating energy consumption associated with wood as an energy source better than engineering estimates. This is due to direct occupant control over wood burning devices (e.g. damper control) and also the wide range of efficiency during operation. The authors identify a multicollinearity issue, the inability to determine which of two or more near linear related independent variables are having an impact on the dependent variable (energy consumption). They found that the nearly ubiquitous presence of the refrigerator and small unspecified appliances made it difficult to determine their impacts. They suggest improving the estimation by further distinguishing certain appliances by their characteristics (e.g. age, size, and number of doors of a refrigerator). Furthermore, they identify that the net energy consumption of the households, as determined by billing data, is not inclusive of passive energy gains and therefore is not representative of the actual consumption of the house, only the net measured consumption. However, this does not impede the relative comparison of two appliances as the passive gains remain identical.

Hsiao et al. (1995) combined the work of Caves et al. (1987) and Bartels and Fiebig (1990) by utilizing sub-metered end-use energy consumption as the Bayesian inference prior information. The approach used a small set (49 households) of direct metered end-use data and a larger set which included billing and survey information from Ontario Hydro customers (347 households). The prior information is formed from the mean and variance of the end-use data, thereby providing values which incorporate behavioural aspects better than simple EM estimation.

Bartels and Fiebig (2000) further improved upon this modeling technique development stream by increasing “efficiency” of sub-metering by conducting a review of the house appliance survey prior to the sub-metering measurement. They identified houses which would contribute the most to the model by being sub-metered. Based on a preliminary review of 1901 house appliance surveys the authors chose 250 appropriate houses and certain appliances to sub-meter. Sub-metering was also focused on freezers and lighting, areas which posed significant difficulty due to multicollinearity in all previous CDA efforts. Given excellent sub-metered data they attempted to extend their annual model to a half-hour model (48 CDA equations per day); however this resulted in a drop in the R^2 values from 0.66 to 0.34.

Lins et al. (2002) developed a national CDA model for Brazil featuring 10,818 dwellings based on monthly energy consumption. As the model covered a wide north-south geographical area with varying climatic conditions, they found it difficult to obtain R^2 greater than 0.5.

Aydinalp-Koksal and Ugursal (2008) constructed a national residential CDA model based on over 8,000 records from a 1993 Canadian national residential energy consumption survey (Statistics Canada, 1993). To be applicable to the entire energy consumption of the Canadian residential sector, the authors developed three CDA models corresponding to the dominant energy sources in Canada: electricity, natural gas, and oil. As the survey data was highly detailed, new descriptive variables were added to the CDA equations including: programmable thermostats, heat recovery ventilation, heating equipment efficiency, windows and doors, aerators and laundry loads. They mention that the number of independent variables should be limited to facilitate regression and reduce poor approximations of smaller appliances which may be indistinguishable.

The three CDA models achieved R^2 values ranging from 0.79 to 0.89 which may be a result of their annual model that averages the daily and seasonal effects. Certain end-uses were under or overestimated similar to Parti and Parti (1980). The authors examined socioeconomic effects using the model. The effects were linear, which caused concern as the model was driven to extremity values such as one occupant. Interestingly, the presence of children and adults equivalently affected the electricity consumption of common appliances, lighting, and space cooling. The CDA models were compared to detailed NN and EM models conducted on the same database. The CDA method always under predicted the NN model, and under predicted the EM in the AL, cooling, and SH categories, but not the DHW category. The authors note that the CDA model coefficients are more transparent and their implications better understood in comparison with the NN method.

2.6.1.3 Neural Network

The use of NN methods in modeling residential energy consumption has historically been limited, possibly due to the computational and data requirements or the lack of physical significance of the coefficients relating dwelling characteristics to total energy consumption. Because of their ability to capture non-linear characteristics, NN models have been used to forecast the varying electrical loads seen by utilities. Aydinalp et al. (2002) provides a review of the literature and discusses the development of NN models for electrical load forecasting purposes, stating that hundreds of models have been developed. They further report that modeling of energy consumption of individual buildings using NN originated and evolved throughout the 1990's beginning with commercial buildings and progressing in complexity. Specifically noted is an hourly building energy simulation contest reported by Kreider and Haberl (1994) in which the top contenders used "connectionist" methods (e.g. NN).

A simplified NN is shown in Figure 2.4. Interconnectivity between each characteristic is found at hidden neurons. Coefficients for each input to a hidden or output neuron are included in respective vectors "$\overline{V}$". The neurons are also biased by the term "b". For a particular NN arrangement (3:2:1 shown in the figure) and appropriate scaling and activation functions, the coefficient vector and bias are adjusted using a variety of techniques to minimize error of the model. Once the values are determined, the model can be used calculate the energy consumption as a function of different inputs.

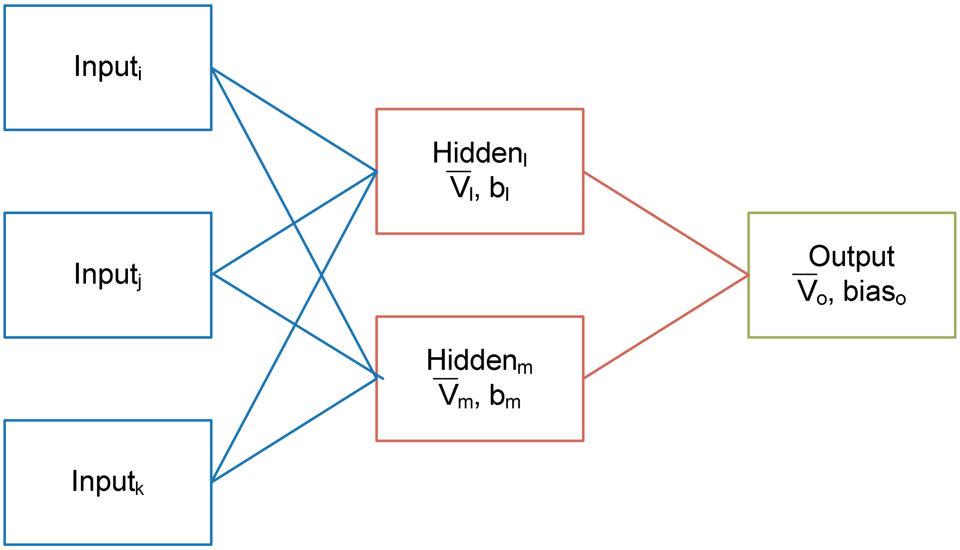


Figure 2.4 Simplified NN with three inputs, two hidden neurons with coefficient arrays "$\overline{V}$" and bias "b", and one output

Issa et al. (2001) introduced the application of NN modeling to the residential energy consumption of a region. They described the development of a NN model that uses energy performance index (EPI) and conditioned floor areas of a group of dwellings with billing data. The EPI is an assigned energy efficiency rating based on housing components. Their NN model bridged the gap between actual energy consumption and the EPI rating. No results were declared.

Mihalakakou et al. (2002) created an energy model of a house in Greece using the NN methodology based on atmospheric conditions. Inputs included air temperature and solar radiation and the NN was trained using five years of hourly energy consumption data. Results of predicted energy consumption for the dwelling were excellent on an hourly basis. This can be attributed to the unprecedented amount of hourly "training" data used to calibrate the model. Sadly, while multiyear data was available, dates were not indicated as an input to the NN and therefore annual changes were not accounted for. This method may be extrapolated on a monthly basis using energy supplier billing data to a region of houses. It would therefore become a tool to estimate the variation in energy consumption between cold or warm years.

Aydinalp et al. (2002, 2003) introduced a comprehensive national residential energy consumption model using the NN methodology. They divided it into three separate models: appliances, lighting, and cooling (ALC); DHW; and SH. To differentiate the electrical energy consumption for ALC from DHW and SH, only houses which used natural gas or oil for heating loads were used to train the ALC model. The NN models used the 1993 Canadian national residential energy consumption survey (Statistics Canada 1993).

The ALC NN model utilized appliance and heating system information, as well as demographic information for a total of 55 inputs. They trained the model using the annual ALC electricity consumption billing data and inputs from a 741 household "training dataset". The network was optimized by varying properties such as learning algorithm, scaling interval, and hidden layers, which were evaluated by maximizing the R^2 values. Once the network properties were determined it took 182 training cycles to achieve the final nodal coefficients and bias values.

A "testing set" of 247 houses was used to compare the ALC NN model with the EM. Prediction capabilities of the NN surpassed that of the EM, with R^2 values of 0.91 and 0.78, respectively when compared to the metered energy consumption. The authors commented on the ability of the NN to determine an individual appliance's component of the aggregate energy consumption by simply removing its presence from the modeled house. Appliance values compared well with other studies, but were not compared to sub-metered data.

Specifically, the refrigerator consumption was not found to be rational, indicating an appliance saturation issue similar to that of the CDA method. As demographic factors were included as inputs, socioeconomic response was analyzed. It was found that ALC energy consumption increased as a second order polynomial as a function of household income.

Aydinalp et al. (2004) extended the NN methodology from ALC loads of the Canadian residential sector to loads due to SH and DHW. This was accomplished using similar methods to those described above, using the remaining dataset that contained alternative energy sources. The ALC NN was also used to remove the ALC component when solving for SH and DHW provided by electricity sources. Values of R^2 were again higher than corresponding EM models based on the same data; however, Figure 2.5 shows the SH energy consumption predicted by the NN has a biased error. A socioeconomic analysis was conducted and both SH and DHW energy consumption were found to vary linearly with income.

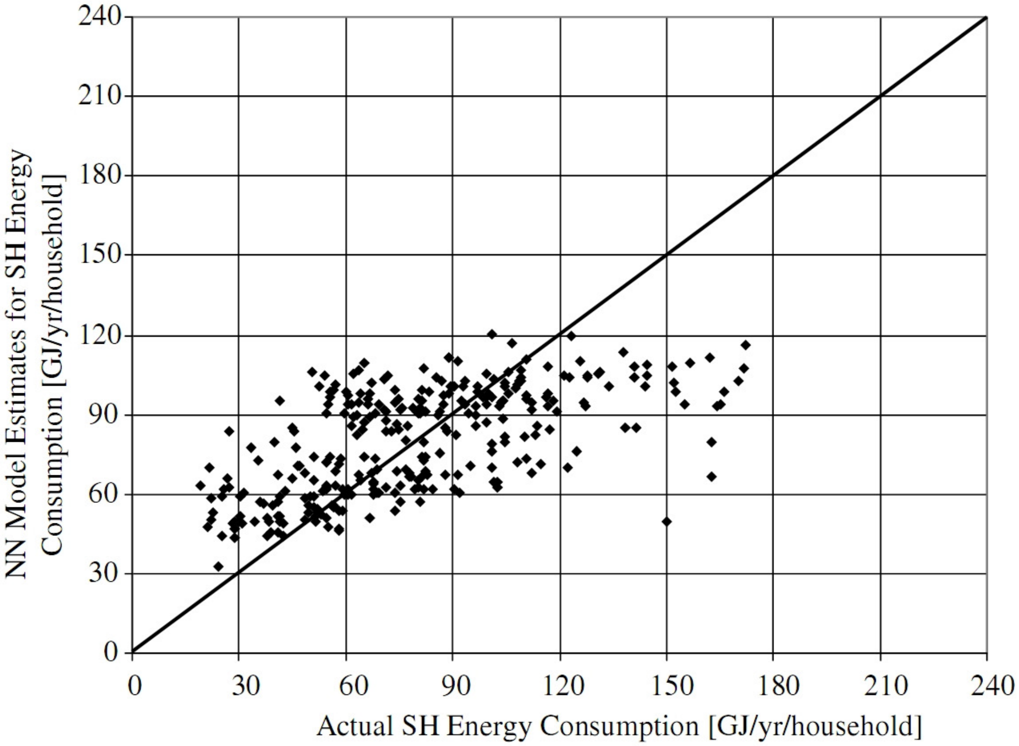


Figure 2.5 Comparison of SH energy consumption using the NN technique to actual SH energy consumption (Aydinalp et al. 2004)

Yang et al. (2005) presented a technique for an "adaptive" NN which functions by accumulating additional energy data or using a sliding window of recent energy data. This extends upon the static predictions made by conventional NN, and allows for the coefficients and bias to be updated as new information becomes available. They found that given a previously trained network, the updating of the coefficient and bias values to represent new data takes less time as the initial values are close to the final state. This technique could be applied for continuous update, similar to that of the top-down technique used by the NEMS (EIA 2005).

2.6.2 Engineering Method

The EM accounts for energy consumption of the end-uses based on their ratings or characteristics. The EM is the only method that can fully develop the energy consumption of the sector without any historical energy consumption information. Models can be as simple as an estimate of SH based on the climate through the use of HDD or as detailed as a complete thermodynamic and heat transfer analysis on all end-uses within the dwelling. As it functions based on the physics of the end-uses, the EM has the highest degree of flexibility and capability with regard to modeling new technologies which have no historical consumption data. However, occupant behaviour must be assumed. As occupant behaviour varies widely, this is difficult to estimate. Three EM techniques are identified in this review: distributions, archetypes, and sample.

The distributions technique utilizes distributions of appliance ownership and use with common appliance ratings to calculate the energy consumption of each end-use. As end-uses are typically calculated separately, this technique does not account for interactions amongst end-uses. The product of appliance ownership, appliance use, appliance rating, and the inverse of appliance efficiency results in the energy consumption. By aggregating the appliance consumptions on a regional or national scale the residential energy consumption is estimated.

The archetypes technique is used to broadly classify the housing stock according to vintage, size, house type, etcetera. It is possible to develop archetype definitions for each major class of house and utilize these descriptions as the input data for energy modeling. The energy consumption estimates of modeled archetypes are scaled up to be representative of the regional or national housing stock by multiplying the results by the number of houses which fit the description of each archetype.

The sample technique refers to the use of actual sample house data as the input information to the model. This allows for the capture of the wide variety of houses within the stock and can be used to identify regions with high energy consumption. If the sample is representative of the regional or national housing stock, the stock energy consumption can be estimated by applying appropriate weightings to the results. As the variety of houses varies widely, this technique requires a large database of representative dwellings.

2.6.2.1 Distributions

EM models can be constructed by using regional or national distributions of appliance ownership and use, and determining the end-use energy consumption. While they rely on national assessments of appliance penetration and can incorporate historic energy consumption, their level of disaggregation (by end-use) allows them to be considered bottom-up. As the number of houses and appliance penetration distributions are known, the resultant energy consumption is considered to be representative of the region or nation.

Capasso et al. (1994) developed an appliance use profile of the Italian residential sector based on distributions determined from housing surveys. Demographic and lifestyle data combined with engineering data of a wide range of appliances was used to calculate total house energy consumption. Their model was applied to the region and compared well with load recordings.

Jaccard and Baille (1996) developed a model of Canadian provinces using the INSTRUM-R simulation tool. The inputs to the model include historic energy consumption, price, behavioural parameters, distribution levels of technologies, and quantification of appliance unit energy consumption, cost, and availability. The simulation tool then explicitly models the energy consumption of each appliance, the sum of which is considered to be the residential energy consumption. Functions are included to retire old housing stock and also to test the housing stock for retrofit potential. Based on the potential it simulates the purchase of new appliances. The authors detail the advanced life cycle cost assessment features of the model which do not assume perfect knowledge across space and time, thereby limiting a single technology capturing 100% of the market. They consider this to be a strong asset of the model as it more appropriately simulates the regional technology choices.

Using a combination of distributions and micro-level data sources, Kadian et al. (2007) developed an energy consumption model of the residential sector of Delhi. They used a simplified end-use consumption equation to incorporate the penetration and use factors of all households, similar to Equation 2.1 although extended to individual end-uses. They included end-uses such as lighting, water heating, air conditioning, refrigeration, cooking, washing, and certain subjective loads. The sum of the end-use energy consumption was input into the Long Range Energy Alternatives Planning (LEAP) system to incorporate variables such as population, income, and increasing number of houses.

Saidur et al. (2007) created a non-space heat residential energy model of Malaysia based on different researchers' distribution estimates of appliance ownership, appliance power rating and efficiency, and appliance use (there is no SH requirement in Malaysia). Their estimate of national annual energy consumption is the summation of the product of each appliance's variables and reciprocal of efficiency. Furthermore, they conducted an exergy analysis to complement their efficiency analysis. The exergy analysis allowed for a comparative tool by which to gauge different energy sources and conversion devices based on a reference state. They found an overall energy efficiency of 69% and exergy efficiency of 30% for Malaysia, as shown in Table 2.2. They state the gap in efficiencies is due to a mismatch of input and output quality levels (i.e. high temperature energy resources were used for low temperature applications). This is dominated by the refrigerator and air conditioner.

Table 2.2 Overall energy and exergy efficiency of the residential sector (Saidur et al. 2007)

Country	Year	Overall Energy Efficiency	Overall Exergy Efficiency
China	2005	–	10
Canada	1986	50	15
USA	1970	50	14
Brazil	2001	35	23
Italy	1990	–	2
Japan	1985	–	3
Sweden	1994	–	13
Turkey	2004–2005	81	22
Norway	2000	–	12

2.6.2.2 Archetypes

The EM can be applied to a limited set of dwellings that represent classes of houses found in the residential sector, commonly referred to as "archetypes". Depending on the level of detail, modeling of archetypes can capture the interconnectivity of appliances and end-uses within the house which is not possible using models based on distributions. Parekh (2005) describes the process of developing archetypes for energy simulation. The author outlines three basic criteria in generating archetypes: geometric characteristics, thermal characteristics, and operating parameters. Using housing surveys and available housing data, geometric and thermal characteristics are correlated to arrive at various groupings found within the housing stock. Data from these archetype groups was examined for minimum, average, and maximum values for use in determining representative characteristics of each archetype for use with building simulation programs.

As the archetype modeling method typically involves a highly detailed integrated simulation of a house, its development progressed with computer and software capabilities. As the number of archetypes is limited, they are the input of choice for EM models as they reduce simulation time as compared with the sample technique which models each house within a database.

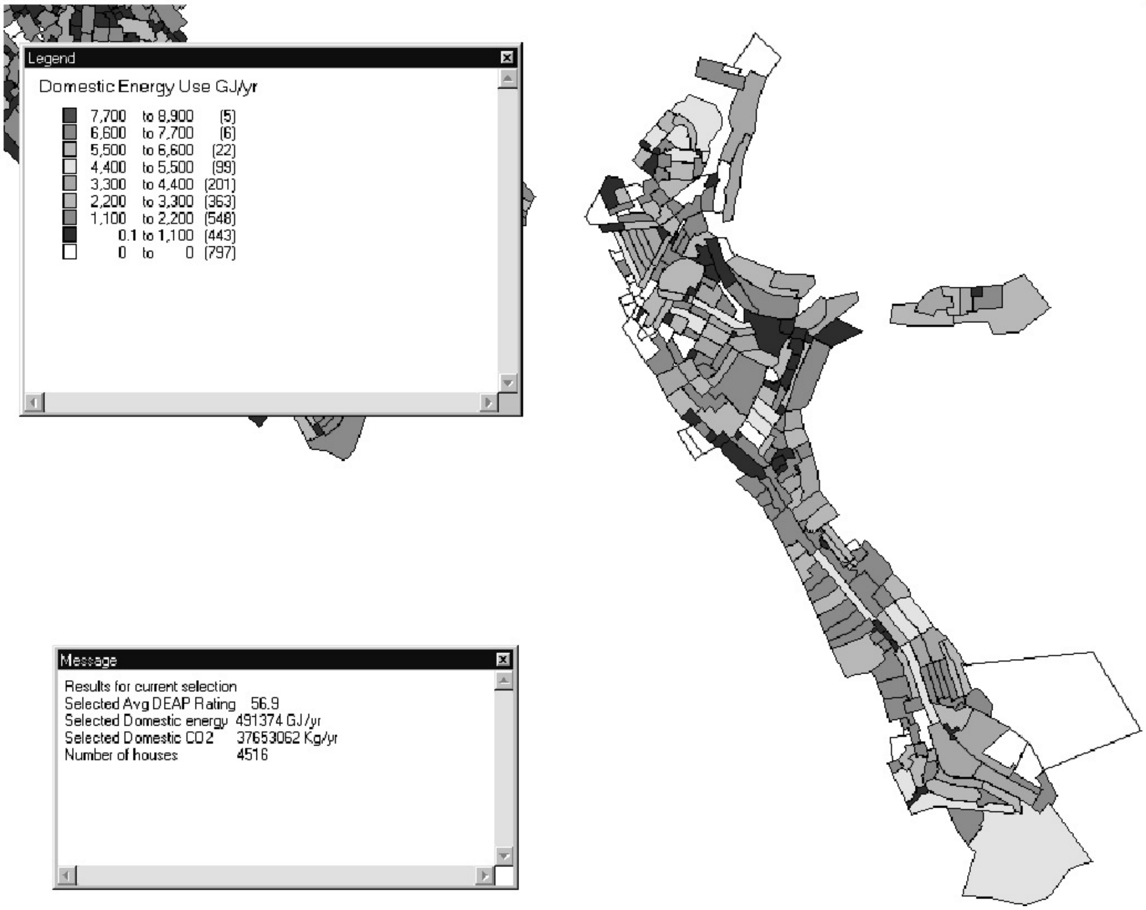
MacGregor et al. (1993) developed the Nova Scotia residential energy model using three insulation/infiltration levels and nine dwelling types, resulting in 27 archetypes. They used typical values of occupancy, appliances, and lights, and evaluated the energy consumption of each archetype using the Hourly Analysis Program (HAP) developed by Carrier Corporation (2008). Energy consumption values were extrapolated to provincial levels based on the estimated number of dwellings represented by each archetype. The results were found to be in agreement with regional top down estimates. The model was used to evaluate the potential for energy savings and economic benefits of introducing small-scale fluidized-bed furnaces for residential space and DHW heating.

Kohler et al. (1997) developed a mass, energy, and monetary flow model of the German building sector. They recognized the building stock as the largest economic, physical, and cultural capital of industrialized countries, although the stock is not yet well quantified. To overcome this lack of data, they decomposed survey data into basic elements and classed them. While they state they are “reference” buildings and not “typical”, they are associated with “age-use” classifications characteristic of archetypes. Each group was broken down into detailed elements such as window type. Using these elements they developed building specifications which comprise the materials and operations with respect to the building. Included in their model was retirement and replacement of both buildings and appliances. The authors found their bottom-up model was in agreement with other studies and energy surveys.

Huang and Broderick (2000) developed an EM model of space heating and cooling loads of the American building stock using 16 multifamily and 45 single-family “prototypical” residential buildings. These archetypes were simulated in 16 different regions; some archetypes were simulated in as many as six regions. The authors utilized DOE-2.1, a building energy simulation program supported by the USA Department of Energy (DOE2 2008). Building heating and cooling loads were disaggregated to show the contributions from the walls, roof, windows, infiltration, and internal gains by setting the thermal conductivity of each component to zero. They also included plant efficiencies, accounting for part-load efficiency and air-conditioner efficiency; however, only furnace/air-conditioner plants were modeled owing to the source of the archetypes from the Gas Research Institute. The authors utilized building population estimates provided by the U.S. Residential Energy Consumption Survey (EIA 2001) to scale their results up to a national value. This was accomplished by normalizing the archetypes' energy consumption by heated floor area and multiplying by the national floor area value.

Jones et al. (2001) developed an energy and environmental prediction model which utilized GIS techniques. They used a unique technique that augments archetypes with additional information based on a "drive-pass" survey. The model employs the UK Standard Assessment Procedure to simulate a dwelling based on building fabric, glazing, ventilation, water heating, space heating, and fuel costs. To reduce information collection time and effort, residences with similar characteristics were grouped and modeled by an archetype. The augmentation process was accomplished by using GIS to estimate building area, historical sources to estimate age, and the drive-pass (the process of assessing building characteristics from the sidewalk) to determine storeys, chimneys, and the ratio of window to wall area.

Using the developed archetypes (five age groups and twenty built forms) augmented with individual characteristics, Jones et al. (2001) simulated the energy consumption of each dwelling in Neath Port Talbot, UK. Using GIS they illustrate the high consumption areas and those dwellings which have high potential for upgrades, as shown in Figure 2.6.



```
Results for current selection
Selected Avg DEAP Rating   56.9
Selected Domestic energy  491374 GJ/yr
Selected Domestic CO2     37653062 Kg/yr
Number of houses          4516
```

Figure 2.6 Domestic energy intensity of individual residences in Neath Port Talbot (Jones et al. 2001)

Shipley et al. (2002) developed archetypes of different Canadian government building types to represent over 3500 buildings. The archetypes were based on categories such as type, floor area, and age. They developed the Commercial Energy and Emissions Analysis Model which utilizes ASHRAE's modified bin method, which is described by Knebel (1983). Archetypes reduced their simulation efforts as the average building accounted for the large group of diverse buildings. They calibrated the model using supplied energy consumption information from a subset of the buildings and used the model to determine the impacts of building envelope improvements.

Carlo et al. (2003) took a different approach to the development of archetypes to represent Brazilian commercial buildings. Using previous simulation results of 512 buildings, the authors determined the primary variables of a building energy regression equation to be roof area ratio, façade area ratio, and internal load density. Combinations of these variables were used to develop 12 archetypes which were augmented with additional variables for parametric simulation. This resulted in 695 prototype buildings which were simulated in DOE-2.1 to determine their energy consumption. The results were used in the assessment of potential building code changes.

Shimoda et al. (2004) developed a residential end-use energy consumption model on the city scale for Osaka, Japan. They developed 20 dwelling types and 23 household (occupant) types to represent the variety of houses within the city. Each dwelling type (not detailed in the paper) was modeled using conductive heat transfer analysis; however, each dwelling was considered to have identical insulation levels based on 1997 commercial offerings. This identical insulation level is a major drawback. Households were developed based on the number of family members, appliance ownership levels, and appliance ratings. Each archetype was simulated and multiplied by the number of dwellings it represents. The authors found two interesting results from their technique: the total estimated residential energy use is less than historical values because “unreasonable” energy use (e.g. leaving lights on) was not accounted for, and estimated unit energy consumption is larger than statistical values which they attribute to surveys focusing on larger families.

Wan and Yik (2004) took an alternate approach to archetypes and focused on solar gains. After conducting a survey of typical housing characteristics in Hong Kong including floor plan, they developed a single archetype of 40 m^2 floor area with a rectangular living and dining room, two bedrooms, kitchen, and a bathroom. They applied typical characteristics including wall thickness, window to wall ratio, glass thickness, and wall absorptivity. To introduce variety, they rearranged the floor plan layout and orientation while maintaining the size and room geometries; this resulted in different window areas facing the sun. In addition they specified different family types and use profiles. They utilized two simulation engines: HTB2 (Alexander 1994) for heat-transfer and BECRES (Yik et al. 2000) for air-conditioning. They found their estimates of air conditioner energy consumption to be large when compared to historical statistics and they decreased this difference by reducing appliance usage and ownership level within the dwellings. After the modification the predicted energy consumption compared well with statistics.

Yao and Steemers (2005) developed a model based on four typical UK housing topologies: flat, semi-detached, detached, and mid-terraced. Using national appliance ownership distributions, average appliance use, and average appliance rating, the authors generated random daily aggregate appliance energy consumption profiles. They used the thermal resistance method developed by the Martin Centre to calculate heating losses. They generated a regional profile based on 100 generated households and found it to be in agreement with national statistical data.

Palmer et al. (2006) developed a model of the UK housing stock using 431 archetypes. They used the BREDEM-8 Building Research Establishment tool (Anderson et al. 2001) which is a monthly heat flux simulation program to model the required SH and DHW heating energy consumption. Occupant and appliance heat gains are calculated based on distributions and DHW consumption is based on typical values. Their model encompasses trends of construction/demolition and demographic changes to estimate the energy consumption of the residential sector through 2050.

Petersdorff et al. (2006) modeled the EU-15 building stock by examining five standard buildings with eight insulation standards. They used Ecofys's Built Environment Analysis Model (BEAM) to calculate the heating demand for three climatic regions. The three house types included in the model were terrace, small apartment, and large apartment. The eight insulation standards applied to the buildings were determined based on typical values for the climatic conditions and building vintage found in EU countries. The authors modeled different scenarios of retrofit and construction/demolition, and attempted to extend the model to smaller housing types. They found their models corresponded well with statistical data.

To extend the archetype methodology beyond its typical position of limited variety, Nishio and Asano (2006) developed an archetype generation tool based on the Monte Carlo technique. The authors utilized numerous statistics, surveys, and conventional datasets from Japan to define both the distribution and range of housing variables. Their house generator uses the Monte Carlo technique to define attributes for each archetype based on probability assumptions. It then develops hourly patterns of energy consumption for common activities, and aggregates and applies these on a monthly basis as a function of the proposed family composition. While the number of generated houses is variable, the generator relies on 34 different family types and 47 different climatic regions. In an example, they generate and analyze 10,000 houses.

Clarke et al. (2008) focused on the main determinants of energy demand within the Scottish building stock to create representative thermodynamic classes. Using the following determinants and their value or level, they developed 3,240 classes: insulation level (6), capacity level (2), capacity position (3), air permeability (3), window size (3), exposure (5), and wall to floor area ratio (2). Each class was modeled using the building performance simulation software ESP-r (ESRU 2002, Clarke 2001) to determine the thermal energy requirements of the dwelling. System information such as heating/cooling, ventilation, DHW, and lighting was then applied to calculate the total energy consumption of the dwelling. The results were incorporated into a tool for comparative analysis and assessment of the impact of improvement measures upon the stock.

2.6.2.3 Samples

While archetypes provide a limited representation of the regional or national housing stock due to the limited variety of archetypes that can reasonably be defined, the use of actual house samples with the EM can realistically reflect the high degree of variety found in the actual housing stock, provided that the sample size is sufficiently large. As this form of EM modeling is data intensive, its application has been limited.

Farahbakhsh et al. (1998) developed a model of the Canadian housing stock based on 16 archetypes augmented with data from 8,767 actual houses. As the house data came from a national housing survey database that is statistically representative of the Canadian housing stock, weights of house representation were provided for the purpose of scaling the consumption up to provincial and national values. An individual house input file was generated for each of the 8,767 houses and simulated using Natural Resources Canada's HOT2000 monthly bin type building simulation software (CANMET 2008). As energy billing data was available for 2,524 houses, these were used in the calibration procedure to correct data conversion errors in the input files. The national consumption estimate was found to be in agreement with other studies. Using this national residential energy model, Guler et al. (2001, 2008) studied the impact and economic analysis of energy efficiency upgrades on energy consumption and greenhouse gas emissions. They found energy savings and greenhouse gas reduction potential for upgrades of heating systems to be 8%, basement insulation to be 4%, and programmable thermostats to be 2% (approximate values reported here). Using the energy costs at that time, the major upgrades were not found to be economically feasible. Aydinalp et al. (2000) updated the model of Farahbakhsh et al. (1998) by using housing data from 1997 and found that the UEC had increased by 1.8%.

Larsen and Nesbakken (2004) developed a model of Norway's housing stock using household information from 2,013 dwellings. They describe the simulation engine, ERÅD, and identify its fundamental weakness as the high number of numerical inputs. Significant efforts were required to calibrate the model which is not desirable as the engineering technique should calculate appropriate initial values. They note that while it is possible to account for every end-use in an engineering model, unspecified end-uses must be estimated. Instead, this was accounted for by calibrating the known end-uses, resulting in a slight overestimate of each end-use contribution. The authors found SH and DHW to be approximately 42% and 24% of total consumption, respectively.

Two other sample EM models deal with commercial buildings. Ramirez et al. (2005) modeled 2,800 commercial premises of California using a modified version of eQuest building simulation software which is based on the DOE2 simulation engine (DOE2 2008b). Combining survey information from all 2,800 buildings, their energy billing data, sub-metered data from 500 buildings, and current year weather data from 20 stations, the authors modified predefined footprint templates to represent each building. The model numerically and visually displayed the hourly results of each building simulation. Calibration was conducted on each building model by a simulation specialist and consisted mainly of verifying significant end-uses and their ranges. Final alterations were made by adjusting schedules and operating hours. During the calibration process it was found that occupation, or lack thereof, of the building has unexpected impacts. Specifically, the assumption that AL are turned off at the end of the business day was found to be false.

Griffith and Crawley (2006) developed a similar model. They modeled 5,430 buildings that comprise the Commercial Buildings Energy Consumption Survey Database (CBECS) and included weighting factors for extrapolation to national results for the USA. However, their focus was the "technical potential" of the sector (i.e. the lowest feasible energy consumption) and thus the 2005 building code requirements were applied to each building. Additional information not included in the CBECS was developed using ASHRAE standards and pseudo-random application of average parameter distributions, such as infiltration. They developed a rule based pre-processor to translate the parameters into "shoebox" building input files for simulation by the USA Department of Energy's EnergyPlus software (USDOE 2008). Simulations were conducted on a computer cluster. They determined that the high number of building records was a disadvantage as it required significant computing capability. They recommend this technique only when results must reflect national implications on a limited number of scenarios. They recommend a smaller database size for high numbers of parametric simulations.

Swan et al. (2008) has developed a national residential energy model of Canada using a detailed database of nearly 17,000 houses. The housing database, described by Swan et al. (2009c), is a selected subset from a national home energy audit program database that characterised the thermal envelope of each dwelling, including an air tightness test. The database of houses descriptions has been converted to detailed house models for building energy simulation using the software ESP-r (ESRU 2002, Clarke 2001). The detailed house descriptions and high resolution simulation (one hour time-step) allow for an assessment of the impact on energy consumption due to the application of new technologies to appropriate houses.

2.7 Critical Analysis of Top-down and Bottom-up Approaches

The top-down and bottom-up approaches each have distinct similarities and differences, as well as advantages and disadvantages. Two of the most critical issues that characterize these approaches are the required input information and the desired range of modeled scenarios.

2.7.1 Strengths and Weaknesses of the Top-down Approach

Top-down approaches are relatively easy to develop based on the limited information provided by macroeconomic indicators such as price and income, technology development pace, and climate. Top-down models heavily weigh the historical energy consumption which is indicative of the expected pace of change with regards to energy consumption. This weighting may be seen in Equation 2.4. Models that evaluate from a regional or national scope are useful for estimating the required energy supply and the implications of a changing economy. They falter when discontinuity is encountered. Examples of such situations include technological breakthroughs or severe supply shocks, the latter being most pronounced due to the slow turnover rate of the housing stock. Contrary to other studies and with respect to a practical sense given today's energy environment, Haas and

Schipper (1998) clearly identified non-elastic response due to "irreversible improvements in technical efficiency". This exemplifies the importance of including a representative technological component in top-down models. Jaccard and Bailie (1996) discussed the notable dichotomy that top-down models estimate high abatement costs for reducing carbon dioxide emissions whereas bottom-up models' estimates are notably lower. They attribute this to economists' over-reliance on the autonomous energy efficiency index (AEEI) and the elasticity of substitution (ESUB). The NEMS has included both a *technology* and *distributed-generation* component (EIA 2005). This indicates that top-down modeling systems are now attempting to account for the uptake of new technologies. While these techniques may account for future technology penetration based on historic rates of change, they do not provide an indication of the *potential* impacts of such technologies and are therefore not helpful in the development of policy or incentive to encourage them.

2.7.2 Strengths and Weaknesses of the Bottom-up Approach

Bottom-up statistical techniques bridge the gap between detailed bottom-up end-use energy consumption models and regional or national econometric indicators. These techniques are capable of encompassing the effects of regional or national economic changes while indicating the energy intensity of particular end-uses. The primary information source of the bottom-up SM is energy supplier billing data. While this is private information, the sheer quantity and quality of this information warrants further compilation and use. By disaggregating measured energy consumption among end-uses, occupant behaviour can be accounted for. This is a distinct advantage of the SM over the EM. Of the three bottom-up SM techniques, common regression is the least favoured as the utilized inputs vary widely among models, limiting their comparison. In contrast, CDA is focused on simplifications of end-uses and is therefore easily ported to other locations and its predictions are comparable among different studies. As appliances currently on the market vary widely in size and less in technology, the addition of such information could be beneficial for future CDA studies. Although the NN technique allows for the most variation and integration between end-uses, resulting in the highest prediction capabilities (Aydinalp et al. 2003), its coefficients have no physical significance. This is a severe drawback. Estimation of individual end-uses was demonstrated by removing their presence in the NN model. However, due to the interconnectivity between each end-use, the removal of many end-uses, individually or simultaneously, reduces the level of confidence in the resulting predictions. Furthermore, bias of the energy estimation error was found when using the NN technique. Aydinalp-Koksal and Ugursal (2008) provide a detailed review and comparison of specific CDA, NN, and EM models.

Bottom-up EM techniques rely on more detailed housing information. These models explicitly calculate or simulate the energy consumption and do not rely on historical values, although historical data can be used for calibration. Larsen and Nesbakken (2004) developed both engineering (samples) and statistical (CDA) models to compare their results. They noted that the engineering technique requires many more inputs and has difficulty estimating the unspecified loads, but while the statistical technique reduces both of these issues it is hampered by multicollinearity resulting in poor prediction of certain end-uses.

If the objective is to evaluate the impact of new technologies, the only option is to use bottom-up EM techniques. This is a point of emphasis because compared to taxation and pricing policies, technological solutions are more likely to gain public acceptance to reduce energy consumption and the associated greenhouse gas emissions. The EM is capable of modeling on-site energy collection or generation such as active or passive solar and co-generation technologies.

The most apparent drawback of the EM is the assumption of occupant behaviour. Because the effect of occupant behaviour can significantly impact energy consumption, the assumption of occupants' activities is not trivial. Statistical techniques based on monthly data are capable of incorporating the effects of occupant behaviour, although they may be inappropriately applied to end-uses. Also, the high level of expertise required in the development and use of the EM may be considered a drawback. The computational limitations discussed by Griffith and Crawley (2006) regarding large numbers of simulations are no longer critical as the data processing capability of computers is continuing to increase rapidly.

To address the shortcomings of both the EM and the statistical based models, research was conducted by Swan et al. (2009b) to develop a "hybrid" EM and NN model for the Canadian housing sector that will incorporate a NN model to predict the highly occupant sensitive DHW and AL energy consumption, while using the EM to predict the SH and SC energy consumption.

2.7.3 Attributes and Applicability of the Modeling Approaches

The important attributes of the three major residential energy modeling approaches, namely the top-down, bottom-up statistical and bottom-up engineering, are shown in Table 2.3.

Table 2.3 Positive and negative attributes of the three major residential energy modeling approaches

Modeling approach	Positive attributes	Negative attributes
Top-down	• Long term forecasting in the absence of any discontinuity • Inclusion of macroeconomic and socioeconomic effects • Simple input information • Encompasses trends	• Reliance on historical consumption information • No explicit representation of end-uses • Coarse analysis
Bottom-up statistical	• Encompasses occupant behaviour • Determination of typical end-use energy contribution • Inclusion of macroeconomic and socioeconomic effects • Uses billing data and simple survey information	• Multicollinearity • Reliance on historical consumption information • Large survey sample to exploit variety
Bottom-up engineering	• Model new technologies • “Ground-up” energy estimation • Determination of each end-use energy consumption by type, rating, etc. • Determination of end-use qualities based on simulation	• Assumption of occupant behaviour and unspecified end-uses • Detailed input information • Computationally intensive • No economic factors

Each approach meets a specific need for energy modeling which corresponds to its strongest attribute:

- Top-down approaches are used for supply analysis based on long term projections of energy demand by accounting for historic response.
- Bottom-up statistical techniques are used to determine the energy demand contribution of end-uses inclusive of behavioural aspects based on data obtained from energy bills and simple surveys.
- Bottom-up engineering techniques are used to explicitly calculate energy consumption of end-uses based on detailed descriptions of a representative set of houses, and these techniques have the capability of determining the impact of new technologies.

Given today's energy considerations that encompass supply, efficient use, and effects of energy consumption leading to the promotion of conservation, efficiency, and technology implementation, all three modeling approaches are useful. Top-down models are the clear winner in supply considerations as they are heavily weighted by historical energy consumption which places their estimates of supply within reason. Bottom-up statistical models can account for occupant behaviour and use of major appliances, which leads to the identification of behaviours and end-uses which cause consumption of unwarranted quantities of energy. Lastly, bottom-up engineering models may identify the impact of new technologies based on their characteristics and account for the wide degree of variety within the housing stock.

As the effects and limitations of conventional energy sources (i.e. fossil fuels) are widely acknowledged, alternative energy sources and technologies are continuously being investigated and developed. To determine the impacts of such new developments requires a bottom-up model. This is further exemplified by the focus being placed on efficiency and on-site energy collection and generation at individual houses. During this period of rapid technological development and implementation, the bottom-up techniques will likely provide much utility as policy and strategy development tools.

Chapter 3 Database of House Descriptions Representative of the Canadian Housing Stock for Coupling to Building Energy Performance Simulation

This chapter was previously published as:

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

3.1 Abstract

The development of a simulation tool that can accurately characterize the energy performance of the Canadian housing stock would enable detailed studies to predict the impact of energy saving upgrades and technologies on a national scale. Such a tool requires a detailed database of house descriptions that collectively represent the entire housing stock. Such a database has been assembled by selectively extracting measured and observed data collected by professionals who conducted on-site audits of 200,000 houses. The auditors' data were extracted to statistically match key parameters (location, house type, vintage, geometry, and heating system) with a broad-based random survey of the Canadian stock. The result is a database comprised of nearly 17,000 detailed records of single-detached, double, and row houses. Each of these house records represents approximately 500 houses in the Canadian stock and contains sufficient data to enable the accurate characterization of its energy performance through building performance simulation.

3.2 Introduction

In Canada, the housing stock sector constitutes over 17% of the Canadian end-use energy consumption (OEE 2006b). This consumption is composed of domestic appliance uses, lighting, ventilation, cooling, and heating. As its climate dictates significant heating energy, Canada has had incentive programs in place for over three decades to support upgrades or the addition of technologies to the housing envelope and the space heating systems through the R-2000, EnerGuide, and ecoAction programs (OEE 2004, 2005, 2007). As residential energy consumption is further scrutinized, a nationally and regionally representative energy model of the Canadian housing stock (CHS) is required to estimate the impact that upgrades or additions of technology may have on energy consumption and associated greenhouse gas (GHG) emissions.

In order to develop such an energy model there is a need for a representative database of houses. It must contain data on each house of sufficient detail for use with sophisticated building energy simulation software that is capable of high resolution simulation (time step of one hour or less) to realistically predict the performance of renewable energy technologies.

Key to the database is a large number of houses which represent the CHS. This should encompass the variety of housing styles, construction materials and techniques, heating equipment, and weather conditions. The database must also properly distinguish vintage, allowing for determination of impacts to houses within selected age groups. Quantifications such as these may be used in the assessment of changes to the national building or energy codes. Incorporating the wide variety of houses of the CHS, while remaining regionally representative, allows for targeted application of upgrades or technologies to meet desired reductions in energy consumption or GHG emissions.

This chapter describes the development process and characteristics of a new database that represents the Canadian stock of single-detached, double, and row houses. The database is both nationally and regionally representative with respect to the parameters used in its development. This database forms the foundation of a tool based upon building performance simulation for accurately predicting the end-use energy and related environmental emissions of the CHS.

3.3 Data Sources

To develop a residential database for energy simulation that statistically represents and is inclusive of the wide variety of houses of the CHS requires detailed data on house characteristics for a large number of dwellings. These requirements are met by the EnerGuide for Houses Database (EGHD) and the Survey of Household Energy Use 2003 (SHEU-03).

3.3.1 EnerGuide for Houses Database

The EGHD (CANMET 2006) is the culmination of over 200,000 requested home energy audits that were conducted from 1997 through 2006. The audits, performed by professional auditors, measured and observed the house geometry, construction fabric, air-tightness, and heating/cooling equipment. Blais *et al.* (2005) describes in detail the EnerGuide objectives and the development of the EGHD. The basis for the audit was to estimate each house's annual energy consumption, using Natural Resources Canada (NRCan) software HOT2XP® (CANMET 2008), and to identify and quantify the energy savings of dwelling upgrades for federal and provincial incentive programs.

The audit measured and accounted for the following: location and orientation, house type, geometry, number of storeys, foundation type, presence of an attic, construction materials including windows and doors, blower door test results (air-tightness), and domestic hot water (DHW) and space heating system information.

The EGHD only includes single-detached (SD) and double and row (DR) houses. SD is defined as an entirely separated standalone single housing unit. DR is similar, but shares one or more walls with another house. The EGHD does not include apartments or mobile home dwelling types. While this is a limitation, the SD and DR dwellings types represent 80% of the CHS by units, as shown in Figure 3.1. From a national housing energy perspective, the SD and DR house types represent more than 85% of the sector's energy consumption (OEE 2006). This is because the other significant dwelling type, apartments, typically has fewer walls exposed to ambient conditions and less floor area per dwelling.

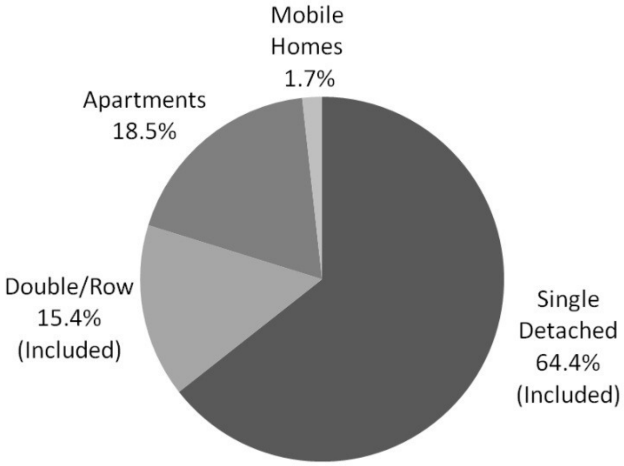

Figure 3.1 Distribution of the CHS by type (OEE 2006). House types included in the EGHD are noted.

The EGHD is unprecedented due to its size and parameter inclusion which provides far more detail than most housing databases. For example, the 200,000 records of the EGHD are equal to nearly 2% of the entire population of Canadian residential units, whereas the 50,000 records of the 2005 American Housing Survey (US Census Bureau 2006) is equal to only one twentieth of a percent of the population of US residential units.

A “dataset” composed of 187,821 complete house records from the EGHD, each with over 161 distinct data fields, was provided for this project by NRCan. This data provides the highly detailed information of actual dwellings for use as the source data for this project. However, as the home energy audits of the EGHD were requested by homeowners for incentive purposes, the database is biased and unrepresentative of the CHS. To overcome this bias, a comparison and selection algorithm was developed that used statistically representative descriptive parameters of the CHS as described in subsection 3.4 below.

3.3.2 Survey of Household Energy Use 2003

The SHEU-03 is a housing survey which was designed to quantify the energy use characteristics of the CHS and assess the effectiveness of federal energy efficiency programs over time (OEE 2006). The SHEU was conducted in 1993, 1997, and 2003 and is expected to be continued. SHEU-93 provided a baseline for comparison and was the most detailed SHEU survey. Subsequent SHEU surveys have focused more on the level of recent upgrads within dwellings to assess the impact of programs which support energy efficiency measures.

Statistics Canada conducts SHEU surveys on randomly selected dwellings based on regional population distribution. In this fashion the data is considered unbiased and representative of the CHS. The data for the 2003 survey was collected from 4,551 dwellings. The SHEU survey is similar in nature to the USA Residential Energy Consumption Survey (RECS) conducted by the USA Energy Information Administration (EIA 2001), which surveys a similar number of dwellings. RECS includes additional survey information beyond SHEU, although it is not nearly as statistically significant. RECS has a house representation level of 1:25,359, whereas SHEU has a house representation level of 1:2,439.

The survey results of SHEU were extrapolated to the entire CHS of 11.1 million dwellings. SHEU-03 lists parameters such as dwelling type and floor area, but does not include detailed information such as construction materials (most notably insulation) or infiltration/ventilation values which are desirable for energy simulation. Furthermore, individual house records are not publicly available, eliminating the possibility of using the SHEU-03 database directly for energy simulation.

The results of a statistical analysis of the SHEU-03 database are published as parameter distribution tables as a function of Canadian region or dwelling type (OEE 2006a). Parameter distribution tables further discretized by both Canadian region and dwelling type were provided for this project by the Office of Energy Efficiency (OEE) of NRCan. As they are unbiased and representative of the CHS, the SHEU-03 parameter distributions are used as a guide, and the basis of comparison, for the selection of dwellings from the EGHD.

3.4 Methodology

The EGHD dataset is the source from which a subset of nationally and regionally representative houses was selected with respect to certain descriptive house parameters. The selection is based on comparison with the national and regional parameter distributions of the CHS as defined by SHEU-03. This selection technique keeps each detailed house record unmodified and intact and in an open format (delimited ASCII) suitable for a variety of uses.

As it was recognized that the selection procedure would result in fewer houses than the original EGHD dataset, and to limit the number of house records in an effort to promote a reasonable batch energy simulation computational time of less than one day[1], a subset of 18,000 to 20,000 house records was desired. This is approximately a 10:1 reduction from the original 187,821 EGHD dataset house records.

3.4.1 Inspection of the EGHD

The received dataset of the EGHD was initially inspected for duplicates caused by resubmission. Using the individual record filenames, 7,772 duplicates records were found, and the earlier of the two records was discarded to account for an energy auditor resubmitting to correct a previous error. Filenames were checked for adequate structure (10 alphanumeric characters) resulting in the removal of 173 records. Filenames are of utmost importance as they provide the identification of each house for comparison of future

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[1] Annual hourly energy simulation (engineering type) time is estimated to be 6-12 hours using two dual-processor (1.86 Ghz) quad-core computers.

energy simulation investigations. The filename structure includes an alphabetic fifth character which indicates if the file is a first audit ("A"), or a subsequent audit after upgrades or modifications were made to the house (e.g. "B"). Table 3.1 shows the distribution of these audit levels. Of the remaining EGHD dataset, 72% are individual houses, of which 38% underwent upgrades and re-evaluation during the EnerGuide program. As incentive was provided for upgrades, and the level of upgrades of the EnerGuide program is not considered representative of the CHS, only initial energy audits ("A" records) were considered for the subset database. This reduced the remaining EGHD dataset to 129,389 records.

Table 3.1 Distribution of house audit sequence in the EGHD dataset

Filename audit sequence	Dwelling count	Percent of EGHD dataset	Percent of "A" audits
A	129,389	71.9%	100.0%
B	49,134	27.3%	38.0%
C	36	0.0%	0.0%
Other	1,317	0.7%	

The remaining set was then divided into the five distinct Canadian regions defined by SHEU-03. They are:

- Atlantic (provinces of Newfoundland and Labrador, Prince Edward Island, Nova Scotia, and New Brunswick)
- Quebec
- Ontario
- Prairies (provinces of Manitoba, Saskatchewan, and Alberta)
- British Columbia

House records from the territories (Nunavut, Northwest Territories, and Yukon) were discarded due to their low population and limited data. This further reduced the EGHD dataset by 1,013 records.

The following key parameters of the houses were tested for validity: vintage, storeys, living space floor area, and DHW and space heating energy sources. Entries that had unrealistic values were discarded. Houses constructed prior to 1900 and houses with floor area less than 25 m^2 were the dominant parameters which resulted in the discarding of 6,919 houses. Of the original EGHD dataset 121,456 house records remained: 112,066 SD and 9,390 DR type houses.

The distributions of SD and DR houses of the remaining EGHD dataset are shown as a function of region in Figure 3.2. As the EGHD only includes these dwelling types, the summation of SD and DR values is considered 100%. To provide reference to the CHS, SHEU-03 distributions (also totalled for SD and DR types only) are shown as a thick black outline in Figure 3.2.

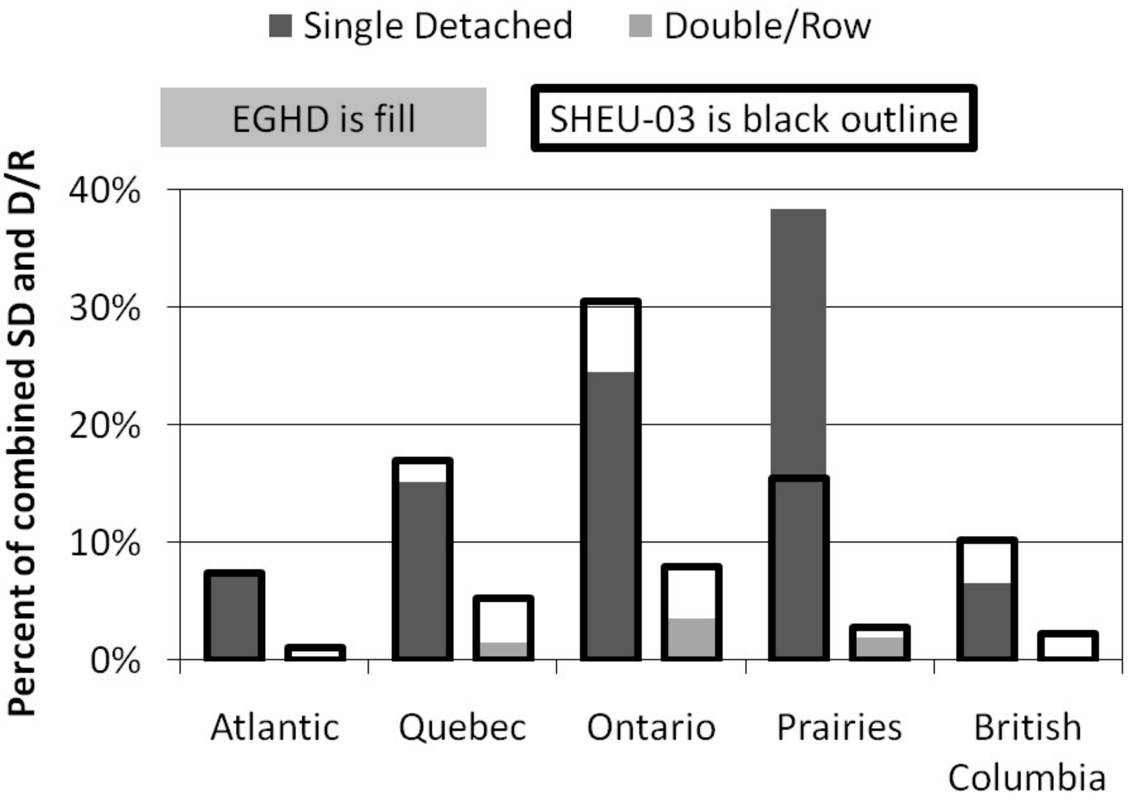


Figure 3.2 Regional distribution of SD and DR houses in the EGHD dataset and SHEU-03

Figure 3.2 shows that in comparison with SHEU-03, the EGHD is lacking DR houses and the SD type is overrepresented in the Prairies region. Aydinalp *et al.* (2001) found different SD distributions, indicative of regional marketing changes of the EnerGuide program throughout its operating period. This regional analysis by house type shows that the EGHD dataset must undergo significant reduction of overrepresented house records to achieve distributions representative of the CHS, as defined by SHEU-03.

3.4.2 Selection Parameters

Following a review and critical analysis of the data available in SHEU-03, the following "selection parameter" distributions were chosen as the reference in selecting house files from the EGHD:

- House type (SD or DR)
- Region (Atlantic, Quebec, Ontario, Prairies, British Columbia)
- Vintage (1900–1945, 1946–1969, 1970–1979, 1980–1989, 1990–2003)
- Storeys (1 through 3 including half storeys)
- Living space floor area (25–56 m^2, 57–93 m^2, 94–139 m^2, 140–186 m^2, 187–232 m^2, 232–300 m^2; excluding basement or crawl space)
- Space heating energy source (electricity, natural gas, oil, wood, propane)
- DHW energy source (electricity, natural gas, oil)

Parameters such as number of occupants and temperature set-points were not used in the selection process as they were typically left as the default value in the EGHD. This was due to the standardized testing protocols of the EnerGuide program established for comparison purposes.

The SHEU-03 parameter distributions of SD houses are listed on a regional scale and considered reliable; however, due to limited data, SHEU-03 does not consider the regional estimates for DR housing to be reliable. Therefore, in the case of vintage, storeys, and living space floor area, the national DR parameter distributions were applied to each region. The regional DR energy source distributions were set equal to the regional SD energy source distributions. These assumptions were considered appropriate due to the more uniform construction of DR dwellings across the nation, and the similar utility and fuel service received by both housing types within a region.

EGHD house records which regionally matched the SHEU-03 selection parameter distributions were selected to form a nationally and regionally representative subset database called the *Canadian Single-Detached & Double/Row Housing Database* (CSDDRD).

3.4.2.1 Selection of Houses from the EGHD

The selection of houses for the CSDDRD was accomplished using a forward progressing compare and select/discard algorithm. Prior to the algorithm being invoked, the EGHD was randomly shuffled to remove the influence of chronological or provincially ordered submissions. The algorithm uses two steps: (1) the definition of parameter distributions, and (2) the selection of dwellings.

3.4.2.1.1 Definition of Parameter Distributions

The ratio of SD to DR houses defined by SHEU-03 was used to calculate the number of SD and DR houses for the CSDDRD to achieve a desired total of 18,000–20,000 houses. The number of SD houses was set to 15,000. This required 3,590 DR house records to maintain a ratio equivalent to SHEU-03, resulting in a total 18,590 desired houses for the CSDDRD.

SHEU-03 specifies the regional distribution of houses by type, which was used to calculate the regional distributions for each selection parameter for the SD and DR houses of the CSDDRD. Table 3.2 shows the regional distribution for the SD type. It can be seen that the regional distribution of CSDDRD and SHEU-03 houses are equivalent, and that the total number of desired SD houses in the CSDDRD is 15,000.

Table 3.2 SHEU-03 and desired CSDDRD SD house distribution

Region	SHEU-03	% of SHEU-03	CSDDRD	% of CSDDRD
Atlantic	662,335	9%	1,381	9%
Quebec	1,513,497	21%	3,157	21%
Ontario	2,724,438	38%	5,683	38%
Prairies	1,381,219	19%	2,881	19%
British Columbia	910,051	13%	1,898	13%
Total	7,191,540	100%	15,000	100%

Using the same approach, the desired number of houses was calculated for each element of the selection parameters, forming arrays. An example parameter is *DHW Energy Source* and its elements are *electricity*, *oil*, and *natural gas* as shown in Table 3.3. Table 3.3 shows that the 1,381 Atlantic SD houses defined in Table 3.2 have been distributed by DHW elements equivalent to that specified by for the Atlantic region by the SHEU-03 DHW selection parameter.

Table 3.3 SHEU-03 and desired CSDDRD DHW parameter distribution for the Atlantic region SD house type

DHW energy source	SHEU-03 (Atlantic)	% of SHEU-03 (Atlantic)	CSDDRD (Atlantic)	% of CSDDRD (Atlantic)
Electricity	487,023	76%	1,043	76%
Oil	157,855	24%	338	24%
Natural Gas	0	0%	0	0%
Total	644,878	100%	1,381	100%

An organizational chart of the example DHW selection parameter for the Atlantic region is shown in Figure 3.3. The numerical value is the desired number of houses and the percentage value corresponds to that defined by SHEU-03. There are 50 distinct selection parameter array sets accounting for two house types, five regions and five selection parameters.

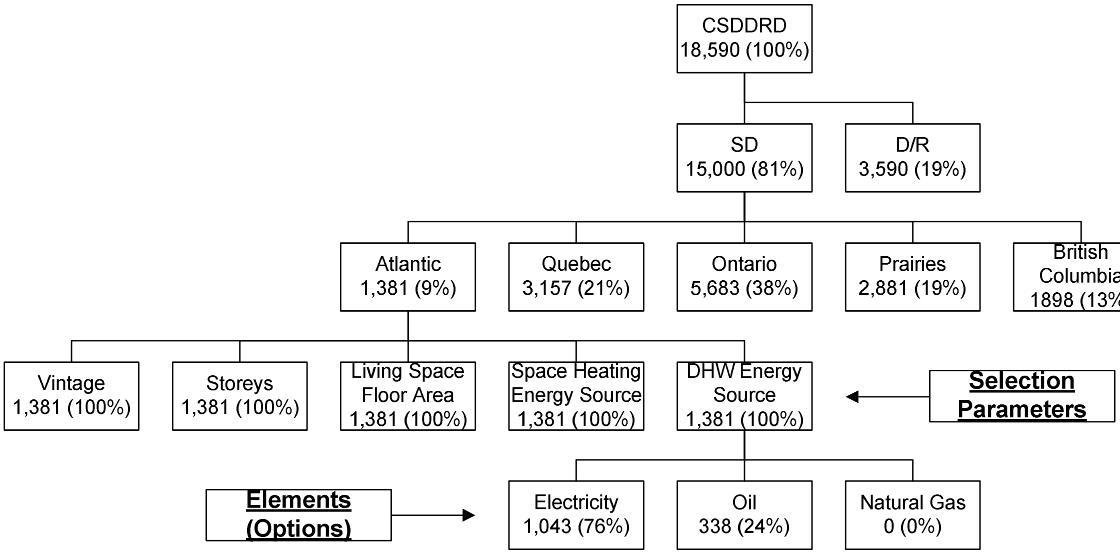


Figure 3.3 Organizational chart of desired selection parameter array

3.4.2.1.2 Dwelling Selection

A computer program was written that consecutively progresses through the EGHD dataset, evaluating the parameters of each house record and comparing them to the selection parameter arrays.

If a house record's parameter values matched a desired element for every selection parameter for the appropriate region and house type, the house was added to the subset database and the corresponding element in each parameter array was decremented. As houses continued to be selected, the arrays decremented to zero, limiting any further selection of houses with similar characteristics. This process eliminates the possibility of over-representing houses with particular characteristics. If a parameter option was not available (e.g. natural gas in the example of Table 3.3), or if that option had been decremented to zero by previously selected house records, the house record under review was discarded.

The consecutive nature of this technique has a limitation: the first house record encountered in the EGHD dataset which fits with the desired distributions is selected for the

CSDDRD. Because of this, a certain popular parameter option may fill, limiting the selection of subsequent house records that have desired characteristics as well as the popular filled characteristic. This was encountered for houses with underrepresented characteristics. Assigning weights to underrepresented houses (i.e. counting each underrepresented house as two or more) was not desirable due to the correlation between house parameters and the reduction of the total number of houses in the CSDDRD. Instead, this problem was addressed by initially sorting the EGHD dataset in such a way that house files with underrepresented parameters were placed at the beginning of the dataset. This forced these records to be encountered first. While this gives preference to houses with underrepresented characteristics, it does not bias the CSDDRD because the selection parameter arrays limit the inclusion of these houses to the value which is desired.

3.4.2.2 Characteristics of the CSDDRD

A comparison of the regional distributions of the two house types with SHEU-03 is shown in Figure 3.4. The CSDDRD distribution closely matches that of SHEU-03. Figure 3.4 may be compared to the original EGHD dataset distribution shown in Figure 3.2.

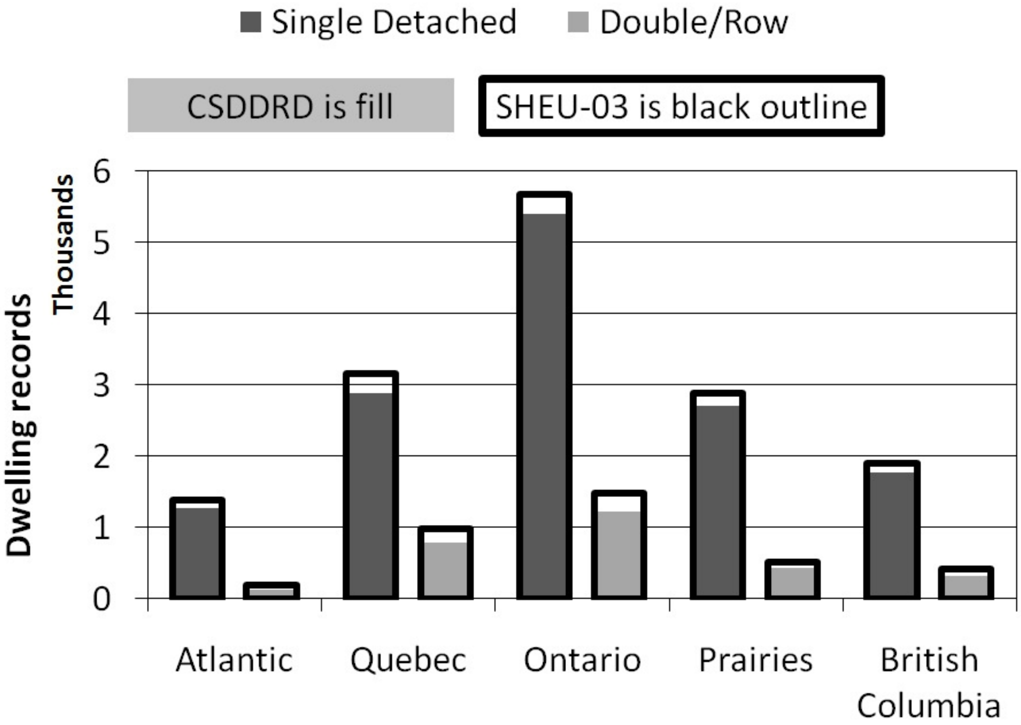


Figure 3.4 CSDDRD region and house type distributions compared to SHEU-03

As described, certain parameter options limited the complete fill of the arrays and therefore the CSDDRD has fewer houses than desired. The CSDDRD is comprised of 14,030 SD and 2,922 DR house records. This totals 16,952 records which, based on the selection parameters, statistically represent the 8.9 million SD and DR houses of the CHS.

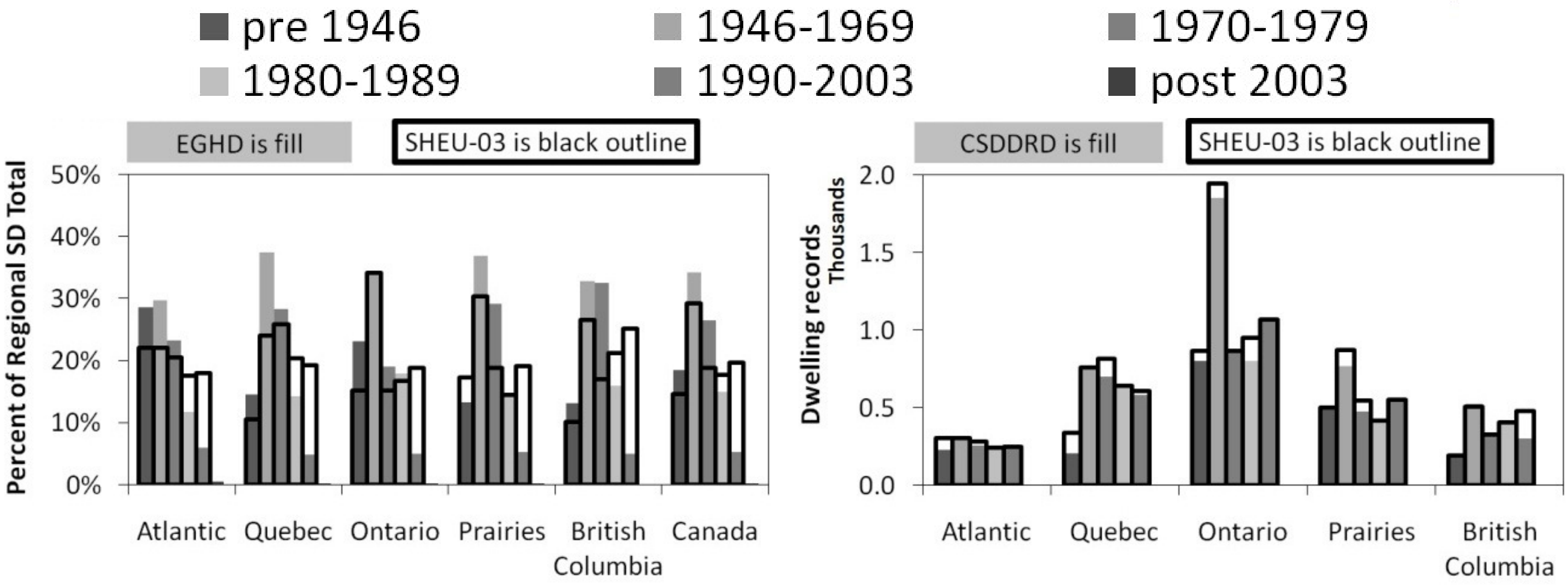
Based on the selection parameters, each record of the CSDDRD is of equal weight and represents 525 houses of the CHS. This constant weighting scheme differs from other housing databases such as the Survey of Household Energy Use 1993 database (Statistics Canada 1993) and the USA 2001 Residential Energy Consumption Survey (EIA 2001). The primary reason that representation weights changed for each house in these databases was due to non-responses within the original random sample. Equal weighting among the CSDDRD records eases comparison of energy simulation results and increases resolution for the study of the applicability of technologies that will achieve a low penetration rate.

The CSDDRD maintains the original information fields and structure of the EGHD dataset in a delimited format for use with building energy simulation. The fields of the database correspond to the detailed house generation wizard inputs of the HOT2XP® residential energy analysis software (CANMET 2008b).

3.5 Verification and Results of the CSDDRD

The CSDDRD is regionally compared to the selection parameters distributions defined by SHEU-03 to identify similarity, indicating good representation of the CHS house types.

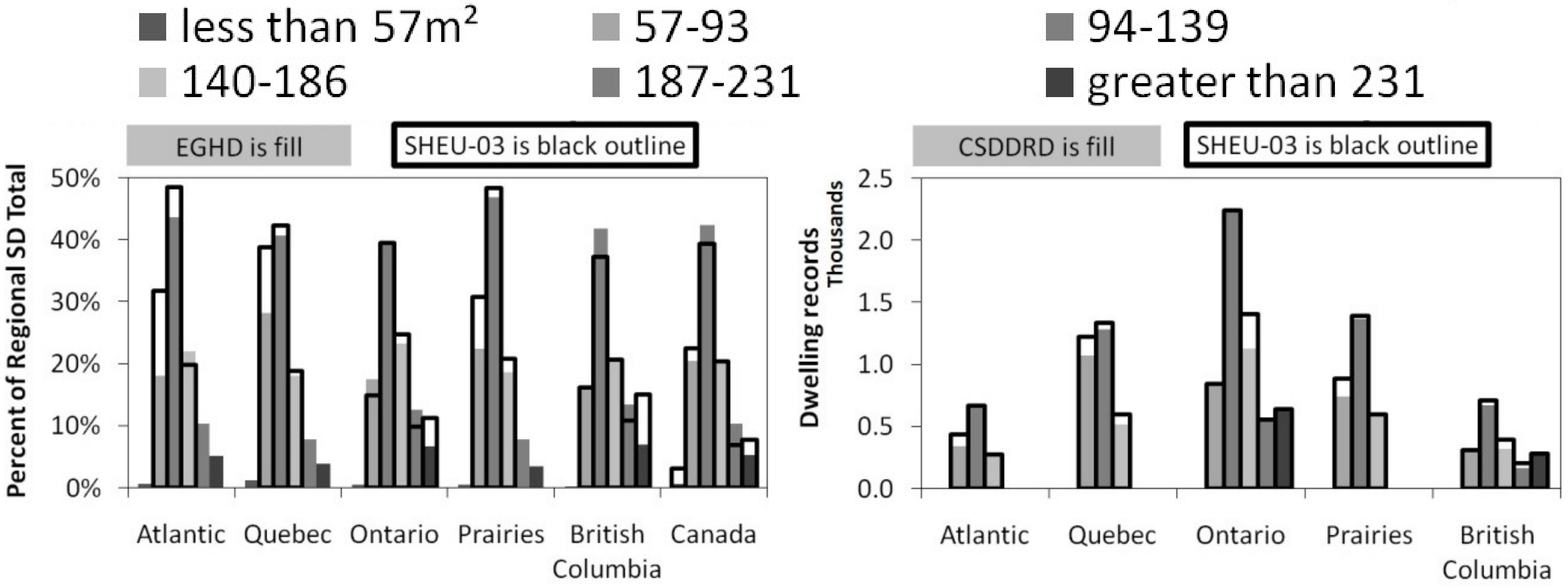
The effectiveness of the procedure used to select the houses from the EGHD to populate the CSDDRD is shown in Figures 3.5 and 3.6. While the distributions of houses in the EGHD dataset with respect to vintage and living space floor area are substantially different than those of SHEU-03 (Figures 3.5a and 3.6a), the distributions of houses in the CSDDRD match closely with those of SHEU-03 (Figures 3.5b and 3.6b). These results indicate that the selection process was successful at improving the representation of newer houses (1990 and later) as well as houses with very small and very large floor areas.



(a)

(b)

Figure 3.5 Comparison of SD vintage distributions for (a) EGHD and SHEU-03, and (b) selected CSDDRD and SHEU-03



(a) (b)

Figure 3.6 **Comparison of SD living space floor area distributions for (a) EGHD and SHEU-03, and (b) selected CSDDRD and SHEU-03**

Further investigation shows that the distributions of other selection parameters of the CSDDRD, for both SD and DR types, also closely match SHEU-03.

The only selection parameter which did not closely match between the CSDDRD and SHEU-03 was the number of storeys, as shown in Figure 3.7. This is likely a result of two issues: auditor misunderstanding of the half storey definition, and no available option for the imputation of split level houses. This resulted in placement of certain half storey houses into the two storey category. As full storeys are the dominant type this representation issue has limited impact. Figure 3.7 shows that although houses greater than two storeys existed in the EGHD dataset, none of these houses exist in the CSDDRD because SHEU-03 considers them insignificant.

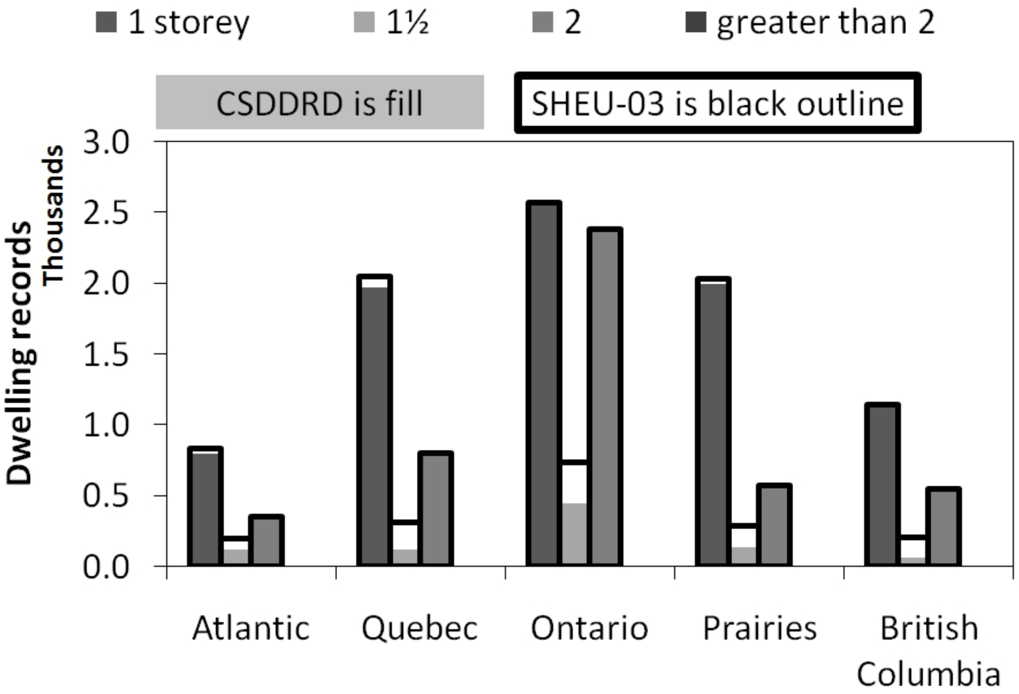


Figure 3.7 Comparison of SD storey distribution the selected CSDDRD and SHEU-03

Key characteristics of the CSDDRD are:

- Nationally and regionally representative of both the SD and DR house types of the CHS based on the selection parameters.
- Detailed information on house geometry, construction fabric, infiltration/ventilation, and heating systems.
- Inclusion of the wide variety of housing characteristics found in the CHS.
- Individual records which allow for assessment of interrelated characteristics (e.g. insulation levels as a function of region or vintage).
- High resolution level for the assessment of the applicability of alternative technologies.

3.6 CSDDRD Investigation

The characteristics of the CSDDRD allow it to be used as the dataset for energy simulation or interrelation/uptake investigation. A simple investigation of housing trends as a function of vintage and region was conducted for demonstration, and the results are displayed in Table 3.4 on page 79. Values of particular parameters of the SD houses were averaged to determine trends within this house type of the CHS.

Beginning from the foundation of the house, it is apparent that slab and crawl space foundations are a minority compared to basements. Construction rate of slab and crawl space foundations remain stable and are predominant in British Columbia (BC) which experiences a milder climate than most Canadian regions. Although this was not a selection parameter for the CSDDRD, SHEU-03 shows similar results (OEE 2006).

Living space floor area (excluding basement) of the SD house type has been increasing over the latter half of the twentieth century. It is presently averaging 144 m^2, a value similar to that estimated by SHEU-03 (OEE 2006). Ontario and BC have the largest average areas, which is likely due to increased levels of new construction (see Figure 3.6b).

Window area and count also increased, although to a lesser extent than floor size. Window size has remained nearly constant. Because of this window characteristic, and the floor area to perimeter relationship, the window to wall area (effective aperture) is decreasing. Windows currently account for 15% of the wall area. The southern facing window area averages 5% of the living space floor area. Parekh and Platts (1990) recommend 8% for passive solar heating in northern climates, based on the thermal storage capacity of typical flooring and the avoidance of overheating. Therefore, it appears that the CHS has significant potential for increased passive solar gain by the addition of southern facing windows, a parameter listed in the CSDDRD.

Thermal resistance has continuously increased, owing to better construction materials/methods and changes in building requirements. Ceiling insulation levels remain approximately twice that of walls. Basement insulation levels are increasing, perhaps due to understanding of ground losses and availability of force/water resistant extruded polystyrene.

Air change rates, as tested using a blower door, steadily decrease with newer construction. It can be seen that on average, for the same pressure difference, newly constructed houses have half the air change rate per hour (AC/h). Chan *et al.* (2005) and Sherman and Dickerhoff (1998) found similar results in US datasets. In Canada, where space heating is a dominant energy consumer of the domestic housing sector (OEE 2006b), this reduction has large impacts. The current R-2000 building standard requires a maximum value of 1.5 AC/h at 50 Pa depressurization (OEE 2005). This is about one-third of the current construction average of 4.4 AC/h at 50 Pa.

Presence of heat pumps, air conditioners, and heat recovery ventilation systems (HRV) were evaluated. The penetration rate of these appliances decreases with age, although not to the level expected by technological developments, due to their easy retrofit. Heat pumps have notably higher install rates in hydro based electrical systems. Occupants in QC and BC are accustomed to lower electricity rates as compared to the relatively inexpensive natural gas and a very cold climate which limits heat pump penetration in the Prairies. As expected, air conditioners are predominant in Ontario due to a hot summer climate; however, SHEU-03 estimates a penetration rate closer to 65% (OEE 2006). Penetration elsewhere is limited. HRV units show significant increases as they are recommended for new SD houses (NRC 1997).

Table 3.4 Average SD parameter values of the CSDDRD as a function of vintage and region

	Vintage					Region				
Parameter average	pre 1946	1946–1969	1970–1979	1980–1989	1990–2003	Atlantic	Quebec	Ontario	Prairies	British Columbia
Slab presence (%)	1.1	1.9	3.4	3.2	2.8	1.3	1.0	0.9	0.5	13.5
Crawl space presence (%)	9.0	6.2	7.9	7.3	7.5	7.3	6.2	4.1	2.8	26.0
Basement presence (%)	89.9	91.9	88.7	89.5	89.7	91.4	92.8	95.0	96.7	60.5
Living space floor area (m^2)	126.0	114.8	120.5	150.4	144.8	114.3	109.1	144.7	112.8	149.2
Gross window area (m^2)	19.4	20.3	20.2	23.7	23.5	18.9	19.7	23.1	17.8	25.6
Tot. num. windows	13.5	12.1	11.3	12.9	13.6	12.0	11.3	13.4	11.7	13.9
Avg. window size (m^2)	1.4	1.7	1.8	1.8	1.8	1.6	1.8	1.7	1.5	1.8
Window to living space wall area (%)	14.2	17.2	16.4	15.6	15.2	15.9	16.8	15.7	14.5	17.4
South facing window to living space floor area (%)	4.4	5.3	5.2	5.1	5.0	5.1	6.0	4.8	4.5	5.1
Ceiling therm. res. (RSI)	3.8	4.2	4.4	5.1	5.6	4.2	4.6	4.6	5.0	4.4
Living wall therm. res. (RSI)	1.6	1.8	2.2	2.6	2.9	2.3	2.5	2.1	2.2	2.2
Basement wall therm. res. (RSI)	1.6	1.6	1.6	1.9	1.9	1.4	2.1	1.4	1.7	2.5
AC/h at 50 Pa depressurization	10.2	6.9	5.8	5.2	4.4	6.9	6.1	6.5	5.0	8.0
Heat pump presence (%)	1.3	2.5	3.1	2.9	4.0	1.4	6.0	1.8	0.5	5.1
Air conditioner presence (%)	14.5	26.8	23.5	33.2	31.4	0.2	13.7	52.7	10.4	9.3
HRV presence (%)	1.0	3.0	5.5	7.5	20.0	18.7	14.1	5.4	2.4	1.0

3.7 Coupling to Building Performance Simulation Tools

The high level of detail of each house contained within the CSDDRD allows for its use as the data source for energy simulation. Geometry, roof type, foundation type, and orientation provide sufficient information to describe the building shell. Detailed construction codes (typically ten individual characters) list the exterior and sheathing materials, framing type and size, and the insulation layers and interior materials, which are suitable for use with transient heat transfer analysis. The type and placement of windows and doors is listed and can be used for the determination of passive solar gain potential and accounts for these constructions which typically have significantly lower thermal resistance than walls and ceilings. Foundation types and their level and placement of insulation are defined and may be used to simulate the ground and ambient air losses through the foundation. Finally, blower door test results in the form of AC/h at 50 Pa and the effective leakage area at 10 Pa may be used to simulate the air infiltration rate of the dwelling for a variety of wind and temperature conditions. The preceding information may be used to form a detailed thermal envelope description of each dwelling.

The CSDDRD also includes detailed information on the heating, cooling and ventilation systems of each house. The variety of DHW and space heating appliances cover the broad range of equipment found throughout the Canadian residential sector and includes tank-less hot water heaters, heat pumps, and condensing furnaces. Air conditioning and ventilation equipment is specified by type and ratings. HRV unit information such as flow-rate and sensible efficiency is listed. These system characteristics may be used to estimate the energy demand and energy consumption by energy source required to meet the needs of the dwelling through building simulation. As the location of the dwelling is listed, the energy simulation may be carried out using weather data from the nearest weather station.

The specific methodology used to couple the CSDDRD to a building performance simulation tool to predict the energy performance of the CHS will be the subject of future companion paper. The CSDDRD itself will be used to identify the regional potential for upgrading the building envelope or HVAC systems, and the installation of alternative or renewable energy technologies. Subsequent simulation of the CSDDRD will be used to assess the impact that such upgrades or technologies have on the energy consumption of the dwelling.

3.8 Conclusions

By comparison with the recent Survey of Household Energy Use 2003, a subset of the EnerGuide for Houses Database has been selected which statistically represents the single-detached and double/row dwelling types of the Canadian housing stock.

The selected house records, titled the *Canadian Single-Detached & Double/Row Housing Database* (CSDDRD), include nearly 17,000 individual house records with detailed information on geometry, construction fabric, air tightness, and heating, cooling and ventilation equipment. Each house record is equivalent in weight and represents approximately 525 actual Canadian houses. The high level of detail and resolution level allow for assessment of the applicability of a wide range of upgrades and new technologies.

The CSDDRD can be coupled to detailed building performance simulation tools to assess the status, trends, and applicability for upgrades of the Canadian housing stock.

Chapter 4 Occupant Related Household Energy Consumption in Canada: Estimation using a Bottom-up Neural-network Technique

This chapter has been submitted for publication to Energy and Buildings and is presently under review.

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

4.1 Abstract

A national model of residential energy consumption requires consideration of the following end-uses: space heating (SH), space cooling (SC), appliances and lighting (AL), and domestic hot water (DHW). The SH and SC end-use energy consumption is strongly affected by the climatic conditions, as well as the house thermal envelope for SH, and the occupants' subjective use of the SC system. In contrast, both AL and DHW energy consumption are primarily a function of occupant behaviour, appliance ownership, demographic conditions, and occupancy rate. Because of these characteristics, a bottom-up statistical model is a candidate for estimating AL and DHW energy consumption. This chapter presents the detailed methodology and results of the application of a previously developed set of neural network models, as the statistical method of the Canadian Hybrid Residential End-Use Energy and GHG Emissions Model (CHREM).

The CHREM estimates the national AL and DHW secondary energy consumption of Canadian single-detached and double/row houses to be 247 PJ and 201 PJ, respectively. The energy consumption values translate to per household values of 27.7 GJ and 22.5 GJ, and per capita values of 9.0 GJ and 7.3 GJ, respectively. The sum of the national AL and DHW energy consumption values is similar to top-down energy model estimates, such as the Canadian Government's Residential End-Use Model (REUM), with the CHREM estimating a value 9% greater than the REUM. However, a difference appears when examining the proportions of this energy consumption. The CHREM estimates the proportions of AL and DHW energy consumption to be 55% and 45%, respectively. The REUM estimates these proportions to be 40% and 60%, respectively. This proportion difference is likely due to the individual

bottom-up approach calculation of the AL and DHW energy consumption employed by the CHREM, in contrast to the top-down disaggregation approach of the REUM.

4.2 Introduction

In most countries, energy consumption of the residential sector accounts for 16–50% of that used by all sectors nationally, and averages approximately 30% worldwide (Saidur et al. 2007). This significant consumption level warrants a detailed understanding of the residential sector's consumption characteristics to prepare for and help guide a desired reduction in energy consumption. The residential sector uses secondary energy. Secondary energy is that received in suitable form for use by the consuming systems to support the living standards of occupants (e.g. natural gas, electricity). The major end-uses of secondary energy within a dwelling are:

- SH and SC energy consumption is that required to support heat transfer across the building envelope due to conduction and radiation, as well as air infiltration/ventilation, and internal heat gains in an effort to maintain the living space at a comfortable temperature and air quality.
- DHW energy consumption is that required to heat water to a comfortable or appropriate temperature for occupant and appliance use.
- AL energy operates common appliances (e.g. refrigerator, coffee maker) and for the provision of adequate lighting.

There are relationships between these end-uses. For example, AL energy consumption generates heat that may offset SH or increase SC energy requirements. Additionally, the relative magnitude of each end-use varies dramatically with climate, mechanical systems and technologies, building thermal characteristics, and occupant use. Each end-use presents unique opportunities for reduction of energy consumption.

An appropriate method to examine these end-uses and energy reduction opportunities is through the use of energy models. A recent review of residential sector energy consumption models by Swan et al. (2009) determined that each unique *approach* has positive and negative attributes. Top-down approach models such as the USA National Energy Modeling System (EIA 2005) heavily weigh previous years' experience and may be used to forecast residential energy supply requirements due to macro changes such as economic conditions or seasonal climatic variance. Bottom-up approach models such as the Scottish Domestic Energy Model (Clarke et al. 2008) and the Canadian Residential End-use Energy Model (Farahbakhsh et al. 1998) estimate the energy consumption of detailed representative house descriptions and scale these values up to a national context. Because bottom-up models use detailed house descriptions, they are superior in handling technological advancements such as those targeted towards reducing energy consumption.

Bottom-up models that are representative of the national housing stock may be used to assess the potential impacts of adopting renewable and alternative energy technologies within the residential sector. Such models may be used to develop strategies, such as incentive programs to promote technologies, by quantifying the potential energy and greenhouse gas (GHG) emissions savings of a technology. As with the modeling approaches discussed above (i.e. top-down or bottom-up), there are different bottom-up *methods*, each with particular strengths.

It is appropriate to select a modeling method based on the particular end-use under investigation. Steemers and Yun (2009) succinctly showed that climatic conditions and the thermal envelope dominate the magnitude of SH, enabling models based on the *engineering* method of thermodynamic and heat transfer principles to adequately represent the SH energy consumption. They also showed that climatic conditions and the occupants' use of SC dominate its energy consumption, while the thermal envelope is only weakly related. Because the subjective occupant participation in SC energy consumption has greater influence than the thermal envelope, the engineering method is not considered optimal for this end-use. However, the engineering method may still be utilized to model SC for the purpose of energy consumption investigation because of the following characteristics:

- SC and renewable energy technologies are primarily dependent upon climatic conditions
- Renewable energy technologies such as photovoltaics may be used to meet the SC end-use energy consumption
- The engineering method is capable of modeling and integrating the energy generation of variable renewable energy technologies with the energy use of SC

In contrast with the climate dominated SH and SC, both the AL and DHW energy consumption are primarily a function of occupant behaviour, appliance ownership, demographic conditions, and occupancy rate. Because of these characteristics, a model based on the *statistical* method is a candidate for estimating AL and DHW energy consumption.

For Canada, the CHREM, presently being developed by Swan et al. (2009b), takes advantage of these two bottom-up methods; hence the word *hybrid*. The CHREM employs an artificial neural network (NN) as its statistical method *technique* and uses it to estimate the AL and DHW energy consumption. The results of the CHREM statistical method are then integrated with an engineering method that estimates the SH and SC energy consumption using the numerical building simulation software ESP-r (ESRU 2002, Clarke 2001). By using this hybrid of methods (engineering and statistical), the CHREM takes advantage of the strengths of both bottom-up methods.

The CHREM relies on a set of nearly 17,000 unique house descriptions of the Canadian Single-Detached and Double/Row housing Database (CSDDRD). The CSDDRD was developed by Swan et al. (2009c) to provide a high degree of representation of the Canadian housing stock (CHS) by encompassing the variety of thermal envelope and mechanical systems as well as the regional distinctions. The data which forms the CSDDRD originates from the EnerGuide for Houses Program which conducted detailed energy audits of over 165,000 dwellings and is described by Blais et al. (2005).

The CSDDRD contains explicit descriptions of each house's thermal envelope and mechanical systems, which allows for a representative house model to be generated and simulated in the CHREM engineering method, for the estimation of SH and SC energy consumption. However, the CSDDRD information comes from home energy audits that did not assess common household appliances (e.g. refrigerator size, number of light bulbs) or demographics. Such data is required to estimate the AL and DHW energy consumption using the CHREM statistical method. The provision of such data is one of the important topics addressed in this chapter.

This chapter presents the detailed implementation methodology and the results of the application of a previously developed set of NN models, as the CHREM statistical method. The methodology of providing input data and integrating the AL and DHW energy consumption results with the CHREM engineering method for the estimation of the SH and SC energy consumption is presented in the following section. The AL and DHW energy consumption estimations and their comparison with existing models and estimations are presented in the results and discussion section.

4.3 Methodology

The hybrid modeling approach of the CHREM relies on a NN for the estimation of AL and DHW energy consumption. A NN is a large number of highly interconnected processing elements tied together with weighted connections. Because of this, a NN is capable of non-linear processing and can be used to find internal representations within raw data. A NN is calibrated much like other regression models, by providing a set of input and expected output data. A variety of iterative techniques are available to modify the weighted connection values in an attempt to reduce the prediction error. An example of a simple NN is shown in Figure 4.1. The example NN has three layers: the input layer with three scaled inputs, the hidden layer with two nodes, and an output layer. Raw inputs are scaled to provide data to each of the internal hidden layer nodes, where an array of multipliers is applied and a bias is added to the accumulated values. A similar process is evaluated to pass the hidden nodes' information to the output layer, after which it is scaled to the appropriate output units.

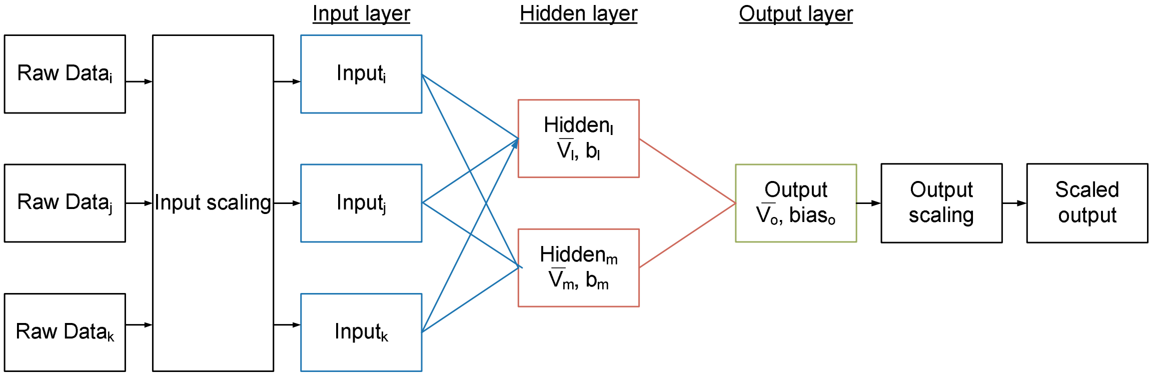


Figure 4.1 Simple NN (architecture 3:2:1) with three inputs, two internal processing elements with coefficient arrays "$\bar{V}$" and bias "b", and one output processing element

A comprehensive review of the utilization of the NN technique for modeling residential sector energy consumption has been discussed and compared to other techniques by Aydinalp et al. (2003b) and Aydinalp-Koksal and Ugursal (2008). The NN technique was found to have superior prediction capability for the AL and DHW end-uses, primarily due to the ability of discerning occupancy use trends which have no relevance to engineering analysis. Because of this superiority, the NN technique was chosen for use as the statistical method of the CHREM for the estimating of annual AL and DHW energy consumption. The following subsections describe the NN implementation within the CHREM.

4.3.1 AL and DHW Artificial Neural Network Models

Two NN models that estimate annual electrical energy consumption due to appliance and lighting and space cooling (ALC), and annual energy consumption due to DHW have been developed and demonstrated by Aydinalp et al. (2003b) and Aydinalp-Koksal and Ugursal (2008). These models were calibrated for the CHS using data from the Survey of Household Energy Use 1993 (SHEU-93), a national housing stock assessment (Statistics Canada 1993). Key to this data set is household billing information for a variety of energy sources. By exploiting the differences among houses due to energy sources, the consumption of a particular end-use was identified. For example, houses that use natural gas as the energy source for both SH and DHW purposes may be used to calibrate the ALC NN on the basis that the entire electricity consumption could be attributed to these end-uses. It should be noted that in such a case, any fans or pumps associated with the SH or DHW systems would have their electrical energy consumption accounted for by the ALC NN. A similar calibration process was used for the DHW NN with the exception that for cases where the DHW was supplied by electricity, the ALC NN is used first to determine the remaining electricity consumption that is attributable to the DHW.

The SHEU 1993 dataset identified presence and use of a wide variety of common appliances (e.g. refrigerator) as well as household demographics. The values were used as inputs to the NN models. By conducting comparative testing, Aydinalp et al. (2003b) and Aydinalp-Koksal and Ugursal (2008) selected the NN configuration that produced the most accurate estimate for each end-use. The selected configurations are shown in Table 4.1. Because the CHREM estimates the SC energy consumption using the engineering method, this aspect of the ALC NN was not utilized (henceforth it is called the AL NN).

Table 4.1 Characteristics of the ALC and DHW NN models (Aydinalp et al. 2003b, Aydinalp-Koksal and Ugursal 2008)

	Architectural		Activation function	
NN type	configuration	Scaling	Hidden nodes	Output node
ALC	55:9:9:9:1	-0.5 to +0.5	Logistic	Identity
DHW	18:29:1	+0.1 to +0.9	Logistic	Logistic

Once calibrated, a NN model is a set of mathematical functions described by the architectural configuration, scaling, vectors of weights and bias, and activation functions. Using these values as defined by Aydinalp (2002) the NNs were recreated in the CHREM, requiring only a set of input data upon which to calculate. Because there is no iteration and only a limited set of mathematical functions, the calculation time to execute both the AL and DHW NN models for the 17,000 unique houses of the CHREM requires less than one hour with a common computer.

4.3.2 NN Input Data

The NN models require suitable input data in order to perform the calculations and arrive at annual energy consumption. There is distinct input data for the AL and the DHW networks, as well as common data that affects both consumption types. For example, both a clothes washer and dishwasher use electricity and hot water. Because the AL and DHW energy consumption is heavily affected by occupant behaviour, many of the required inputs are related to the household demographics. A listing of the input data for the AL and DHW NN models is shown in Table 4.2. Aydinalp (2002) selected the NN inputs on the basis of expected effect and data availability within the SHEU 1993 dataset.

The lack of common appliance and demographic data in the CSDDRD, the source dataset for the CHREM, necessitates the provision and manipulation of suitable data to populate these NN inputs for each house. Such input data can be populated using regional distributions obtained from housing surveys or census information. A listing of the data sources for the NN models (both explicit CSDDRD data and survey/census distributions) is provided in Table 4.2, and a description of the data sources for explicit and distribution information follows.

Table 4.2 Inputs to the DHW and AL neural network models

	Input data source			
Model	CSDDRD	SHEU 1993	SHEU 2003	Census 2006
Common inputs to both the DHW and AL models	Dwelling type Population density		Dishwasher use Clothes washer use Ownership Income	No. of adults No. of children
DHW specific inputs	System energy factor Soil temperature	Storage tank age	Storage tank size Pipe insulation Insulating blanket No. of low flow shower heads No. of tap aerators	
AL specific inputs	Heated area Furnace fan Boiler pump Central air exchanger Heat recovery ventilator No. of bathroom exhaust fans Heating degree days Cooling degree days	Supplementary heat Electric blanket Water bed Humidifier Dehumidifier Fish tank Central air filter Central humidifier Central dehumidifier Central vacuum Sump pump Water softener Car block heater Car warmer Sauna Jacuzzi	Main refrigerator size Secondary refrigerator size Stove Main freezer size Secondary freezer size Microwave Color TV VCR CD player No. of halogen bulbs No. of fluorescent bulbs No. of incandescent bulbs Water cooler Ceiling fan Clothes dryer Stereo Computer	Employment ratio

4.3.2.1 Explicit Input Information

The CSDDRD includes explicit data that is utilized for certain NN inputs as shown in Table 4.2. These are primarily related to mechanical systems of the house (e.g. heat-recovery ventilation system) and the thermal envelope (e.g. heated floor area). DHW system energy factor was based upon the DHW energy source present in the house and a lookup table used to calibrate the NN, as shown in Table 4.3. These fixed annual energy factors are equal to the ratio of the DHW delivered thermal output to the higher heating value of the energy source, which accounts for the system's flue and skin losses. The values shown in Table 4.3 are representative of DHW systems found in the CHS.

Table 4.3 Mapping of DHW equipment type to system energy factor (Aydinalp 2002)

DHW energy source	DHW system energy factor
Electricity	82.4%
Natural gas or propane	55.4%
Oil	53.0%
Wood	30.0%

The CSDDRD includes postal code data and the city and province name for each house. This is used as a location identifier for census and climatic data to determine population density (e.g. rural, urban) and climatic conditions such as soil temperature and heating/cooling degree days (HDD/CDD).

The population density was found using the Canadian Postal Code Conversion File (Statistics Canada 2007) which relies on the "Population distribution of census subdivision areas" of the 2006 Canadian census (Statistics Canada 2006). This database contains a cross reference of all six-digit postal codes from which an urban/rural indicator may be determined. This variable was mapped as indicated in Table 4.4 to determine the population density at each house.

Table 4.4 Mapping of the Postal Code Conversion File to the NN input

Urban/rural indicator	Mapped NN Population Density input
Rural area	Rural
Urban core	Urban
Urban fringe	Suburban
Urban areas outside census areas	Suburban
Secondary urban core	Urban
Dissemination areas only	Rural

Climatic data is published by Environment Canada (2009). A cross reference that mapped all of the weather cities present in the CSDDRD (65 different locations) to the most representative weather station (44 different locations) based on location (latitude and longitude) and heating degree-days was developed. Using the city name associated with each house, the most representative HDD and CDD (18 °C base temperature), and annual average soil temperature at 1.5 m depth were selected.

4.3.2.2 Distribution Input Information

The majority of the NN inputs relate to appliance presence and use within a dwelling. As the CSDDRD has limited appliance and demographic information, many of these inputs must be populated using SHEU information. The most recent SHEU 2003 is available only as distributions based on house type and region (OEE 2006). The two house types under consideration in the CHREM are:

- Single-detached (SD) houses are a free-standing single-family home
- Double/row (DR) houses are single-family homes which are adjoined to other houses on either one or two sides.

These house type account for 80% of the CHS, the balance being apartments and mobile homes (OEE 2006). There are five distinct Canadian regions with populations greater than one million people:

- Atlantic (AT) consisting of provinces Newfoundland and Labrador, Nova Scotia, Prince Edward Island, and New Brunswick
- Quebec (QC)
- Ontario (OT)
- Prairies (PR) consisting of provinces Manitoba, Saskatchewan, and Alberta
- British Columbia (BC)

To illustrate this regional distinction, Figure 4.2 shows the regional distribution of DHW energy sources[2] along with the representative system energy factors listed in Table 4.3. In addition to SHEU 2003 data, distributions based on the Canadian Census 2006 and 2001 (Statistics Canada 2006, 2001)were also used to populate the NN inputs.

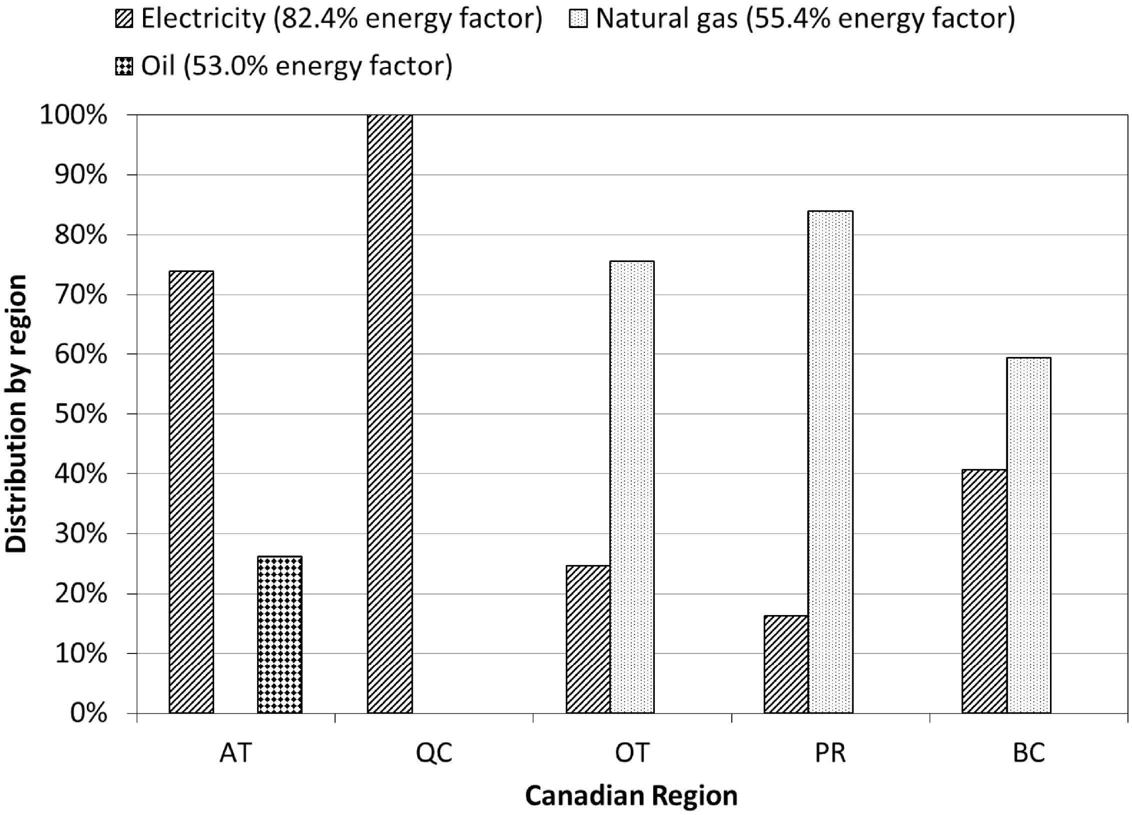


Figure 4.2 Canadian regional DHW energy source distributions for the SD and DR house types (OEE 2006)

Use of the distribution for populating the CSDDRD with appliance and demographic information relied on the finest resolution distribution available. The available distribution resolution levels in the order of descending resolution are:

1. Distribution specific to both the house type and region
2. Distribution specific to the region for all house types
3. Distribution specific to the house type on a national scale
4. Distribution of the national housing stock

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[2] Although SHEU 2003 estimates approximately 7% of QC dwellings (all types) have natural gas powered DHW, the distribution of natural gas DHW by dwelling types for QC is considered unreliable (OEE 2006).

Note that region specific distributions (#2) take precedence over house type specific distributions (#3). This is because appliance ownership and use, as well as demographics tend to be dependent upon cultural norms which are regionally distinct.

Once selected, the distribution was used to randomly populate the houses of the specific house type and region, in accordance with the distribution percentages. For example, if 50% of houses have one computer, 25% have two computers, and 25% have three computers, then the number of computers present in a household would be randomly applied to the houses in such a fashion as to maintain the distribution percentages.

The populating process was completed for each NN input which did not have an explicit value determined from the CSDDRD. There are certain NN inputs which are notably linked: number of adults, number of children, and employment ratio.

The number of adults and children was developed using a special keyed distribution of *household*. The relationship of adults to children within households is not explicitly stated by Census 2006, but can be determined for each region by a comparison of the tabulated data of “Household structure” and “Families” (Statistics Canada 2006). The fields of the household were set to a two digit integer where the first digit is number of adults and the second digit is number of children, as shown in Table 4.5. This household distribution maintains the adult to child household structure. If the number of adults and children were treated independently, this important structure would be lost. Only after shuffling of the household array are the digits separated to determine the number of adults and children.

Table 4.5 Mapping of regional household structure to number of adults, children, and employment ratio

Household structure	Adults	Children	Possible employment ratio fields
10 – 13	1	0 – 3	0.00, 1.00
20 – 23	2	0 – 3	0.00, 0.50, 1.00
30 – 33	3	0 – 3	0.00, 0.33, 0.66, 1.00
40	4	0	0.00, 0.25, 0.50, 0.75, 1.00

Employment ratio, the ratio of adults-employed to adults-in-the-household, requires the number of adults-in-the-household, because the possible employment ratio fields depend on this value, as shown in Table 4.5. Thus, employment ratio was completed as a separate populating process after the separation of the number of adults from the household field. Regional distributions of employment ratio were developed using the Computing in the

Humanities and Social Sciences database tool (UOT 2009) to examine the Census 2001 data (Statistics Canada 2001).

4.3.3 NN Model Implementation and DHW Conversion

Execution of the NN model involves a series of scaling and calculation routines that are completed using the scales, calibrated weights and biases, and activation functions developed by Aydinalp (2002). The process continues through each layer, arriving at an output value which is re-scaled to the desired units (e.g. GJ).

It is important to differentiate the clothes dryer energy consumption component as it is typically exhausted outside of the thermal zone and thus does not contribute as an internal gain within the conditioned zone. Additionally, both the clothes dryer and cook stove components may be powered by natural gas or electricity. Because of these unique attributes, the clothes dryer and cook stove must be differentiated from the other AL components which are powered solely by electricity. To accomplish this differentiation, a second round of houses was modeled that had the Clothes Dryer (loads/week) set to zero. By comparing the AL energy consumption of this variant with the original house, the impact due to the clothes dryer could be distinguished. Unfortunately, the cook stove could not be distinguished using the variant analysis technique because a cook stove is present in nearly every house. This resulted in multicollinearity and inhibited the NN from properly identifying the cook stove's contribution. The process of distinguishing the cook stove is described in section 4.3.4.

The unit of energy consumption estimated by applying the AL or DHW network is annual GJ. This is suitable for analysis and the incorporation of the AL results into the CHREM engineering model. However, it is preferable to have the DHW consumption in terms of volume draw instead of energy consumption. This is because the DHW system technology can be modeled by the engineering model, allowing for the assessment of new technologies such as solar-thermal, increased thermal storage, or instantaneous water heaters.

The DHW energy consumption E_{DHW} (J) was converted to annual water draw volume V (m³), using equation 4.1, by assuming a delivery temperature of 55 °C, and using the annual average ground temperature T_{G} (°C) and system energy factor value η (-) specified as inputs to the NN (see Table 4.3). The terms $\rho\ \left(\frac{kg}{m^3}\right)$ and $C_{\mathrm{p}}\ \left(\frac{J}{kg\ K}\right)$ are density and specific heat, respectively.

$$V = \frac{E_{\mathrm{DHW}}\eta}{\rho C_{\mathrm{p}}(55 - T_{\mathrm{G}})} \tag{4.1}$$

4.3.4 AL and DHW Load Profiles

The estimates of annual AL energy consumption and DHW volume consumption must be translated onto representative sub-hourly load profiles for integration with the CHREM engineering method. This translation allows for the consumption profile to be compared to the energy production profile of, for example, renewable energy technologies such as photovoltaics or solar-thermal systems.

AL power profiles and DHW volume draw profiles on five minute time steps have been developed for energy simulation purposes by Armstrong et al. (2009) and Jordan and Vajen (2001), respectively. An example of these profiles is shown in Figure 4.3. The profiles were developed and compiled for the International Energy Agency's (IEA) Energy Conservation in Buildings and Community Systems Program (Knight et al. 2007).

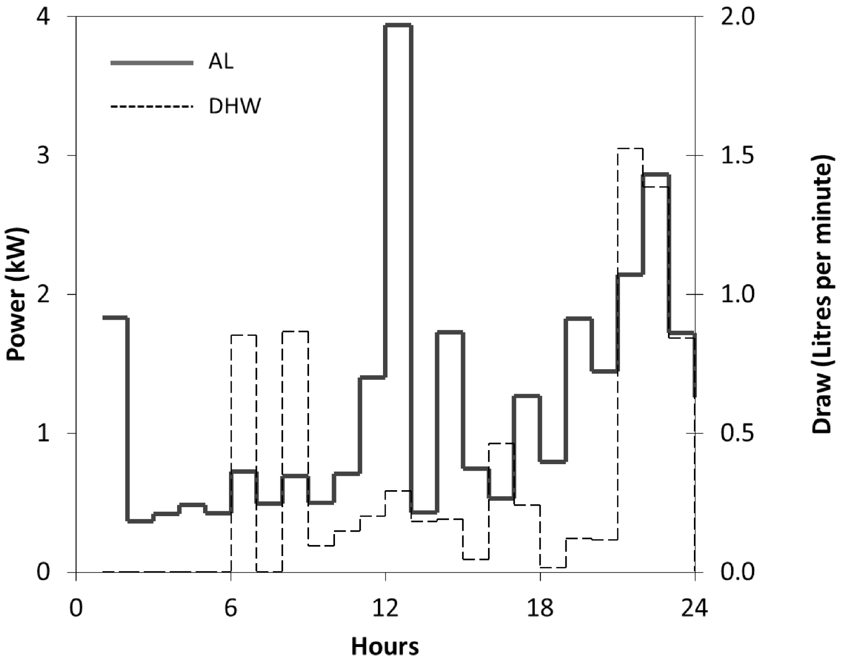


Figure 4.3 Example AL and DHW hourly profile

There are two important considerations for implementing the AL and DHW consumption within the CHREM engineering method:

- Loads must be disaggregated by energy source
    - The DHW load can be met by a variety of energy sources listed in Table 4.3.
    - The AL loads are typically met using electricity, although nearly 10% of the CSDDRD has either a natural gas cook stove or clothes dryer. Therefore the cook stove and clothes dryer AL components must have distinct profiles from the remaining AL components.
- Loads must be disaggregated according to their final destination of heat
    - The energy used in the heating of DHW does not directly result in heating of the thermally conditioned zone as water is considered to immediately drain outside the dwelling. However, the CHREM engineering method does consider the heat loss to the thermal zone due to the storage tank and the piping.
    - The energy used by the AL is considered to become a heat input to the thermal zone, with the exception of the clothes dryer which is exhausted outside.

Profiles are not only associated with a particular load, but also with the consumption level. For example, a clothes dryer may be approximated as a constant power device when running. In a high consumption household the frequency of use will be greater than in a low consumption household. Whereas, the lighting use in a high consumption household will have similar frequency of use to a low consumption household, but at a higher power level.

Three different AL and DHW usage profiles were available corresponding to *low*, *medium*, and *high* typical usage. In addition, the individual profiles for each AL component type were obtained so that the cook stove and clothes dryer could be differentiated for energy source and destination of heat purposes. Annual consumption levels are summarized in Table 4.6 and the contribution of individual AL components are shown in Figure 4.4. *AL Other* refers to the refrigerator, freezer, dishwasher, clothes washer, lights, and small appliances and plug loads.

Table 4.6 Annual consumption values of the three AL and DHW profile usage levels

Use level	DHW (average L/day)	Cook stove (GJ/year)	Clothes dryer (GJ/year)	AL Other (GJ/year)
Low	100	2.7	2.2	12.2
Medium	200	2.7	4.9	21.8
High	300	3.7	7.2	35.7

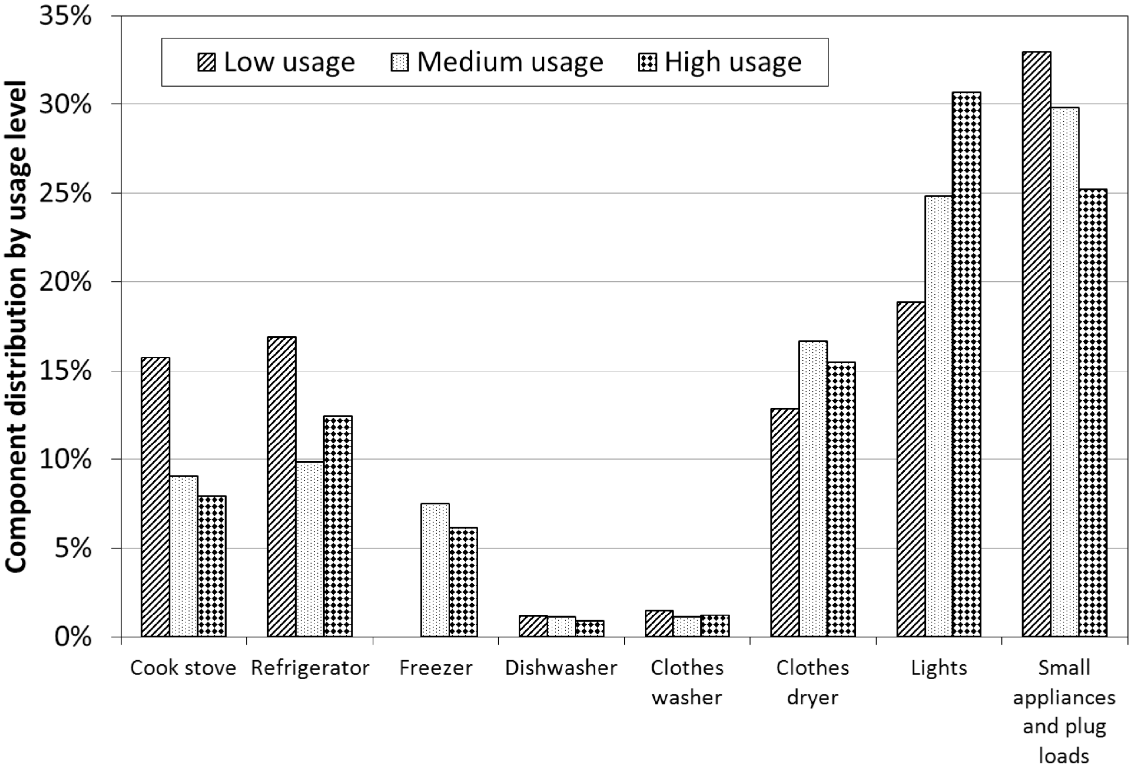


Figure 4.4 AL component energy consumption distribution for three use levels

4.3.5 Translation of NN Annual Energy and Volume Consumption Values to Time-step Profiles

A translation of the NN estimates of annual AL energy and DHW volume consumption to appropriate time-step profiles (e.g. hourly) was completed to incorporate these end-uses with the CHREM engineering method. The selection of the most appropriate time-step profile was made by comparing the annual profile consumption to that estimated for the house by the NN. The profile that minimized the absolute difference in these annual consumption values was selected.

The profiles for the DHW, clothes dryer, and the cook stove and remaining AL components, were selected individually. Because of the multicollinearity described in section 4.3.3, the cook stove and remaining AL components were lumped together for purposes of choosing the most representative profile levels. The individual profile selection allows for a house to consume large volumes of DHW, and small amounts of energy for AL, or vice versa. This was especially important as it was found that the profiles developed by Armstrong et al. (2009) estimate that the clothes dryer operates more frequently than predicted by SHEU 2003.

Although the selection of profiles minimized annual consumption differences between the profile and house, a multiplier was used to tailor the annual consumption of the profile to be identical to the house estimate. The multiplier, a ratio of the house consumption to the profile consumption, is used by the CHREM engineering method to linearly alter the time-step profile value. In the case where the clothes dryer or cook stove is powered by natural gas, the multiplier was increased by 10% to account for the appliance being less efficient.

The sets of profiles and profile multipliers for each house of the CSDDRD are then passed to the CHREM engineering method. The engineering method conducts SH and SC energy simulation taking into consideration the AL energy consumption and DHW volume draw. This integration allows the internal gains due to many of the AL component loads to offset SH requirements or contribute to SC requirements. The energy source required to meet the load is known based on the house mechanical systems, and these are appropriately aggregated by energy type in the simulation with the SH and SC energy consumption.

4.4 Results and Discussion

The results of the AL and DHW energy consumption, and DHW draw, are examined in the following subsections by house characteristics. They are then scaled up to obtain national values. A synopsis of the selected profiles and multipliers for their application into the CHREM engineering method is also provided.

4.4.1 Estimation of AL and DHW Consumption of the CSDDRD

The CHREM statistical method was used to estimate the AL and DHW energy consumption for each of the 16,952 houses of the CSDDRD. In addition, the DHW values were converted from energy units to units of volume draw as described in section 4.3.3. A description of the range of resulting values is listed in Table 4.7. These values account for natural gas powered cook stoves and clothes dryers. The range of total AL energy consumption is quite large, spanning over 75 GJ. The minimum AL clothes dryer value is zero, and represents houses that are either lacking a clothes dryer, or where the occupant does not use the clothes dryer.

DHW does not cover such a broad range and has an annual daily average of 208 L/day. This average value is 10–20% less than measured North American values summarized by Wiehagen and Sikora (2002), and Aguilar et al. (2005), and is due in part to their measurement focus on single-detached homes with dishwashers.

Table 4.7 Annual AL and DHW energy consumption and DHW volume draw estimates of the CSDDRD

	AL				DHW	
Statistic	Total (GJ)	Clothes dryer (GJ)	Cook stove (GJ)	Other (GJ)	Energy (GJ)	Volume (ann. daily avg. L/day)
Minimum	10.1	0.0	1.7	7.5	10.4	98
Maximum	85.2	9.8	8.3	75.8	40.0	359
Average	27.7	1.3	3.0	23.4	22.6	208
Standard deviation	10.0	1.4	0.7	8.8	4.2	39

The distribution of AL and DHW energy consumption, and DHW volume draw, as a function of both house type and region is shown in Figures 4.5 and 4.6. It is evident that on average single-detached (SD) households tend to consume more energy for both AL and DHW than double/row (DR) households. This is likely due to the increased floor area and appliance ownership of single-detached homes. Figure 4.5 shows that the region of British Columbia (BC), the most westerly province in Canada, uses a higher amount of AL energy per household. This may be due to a milder climate, increased floor area size, or their higher than national average income (OEE 2006).

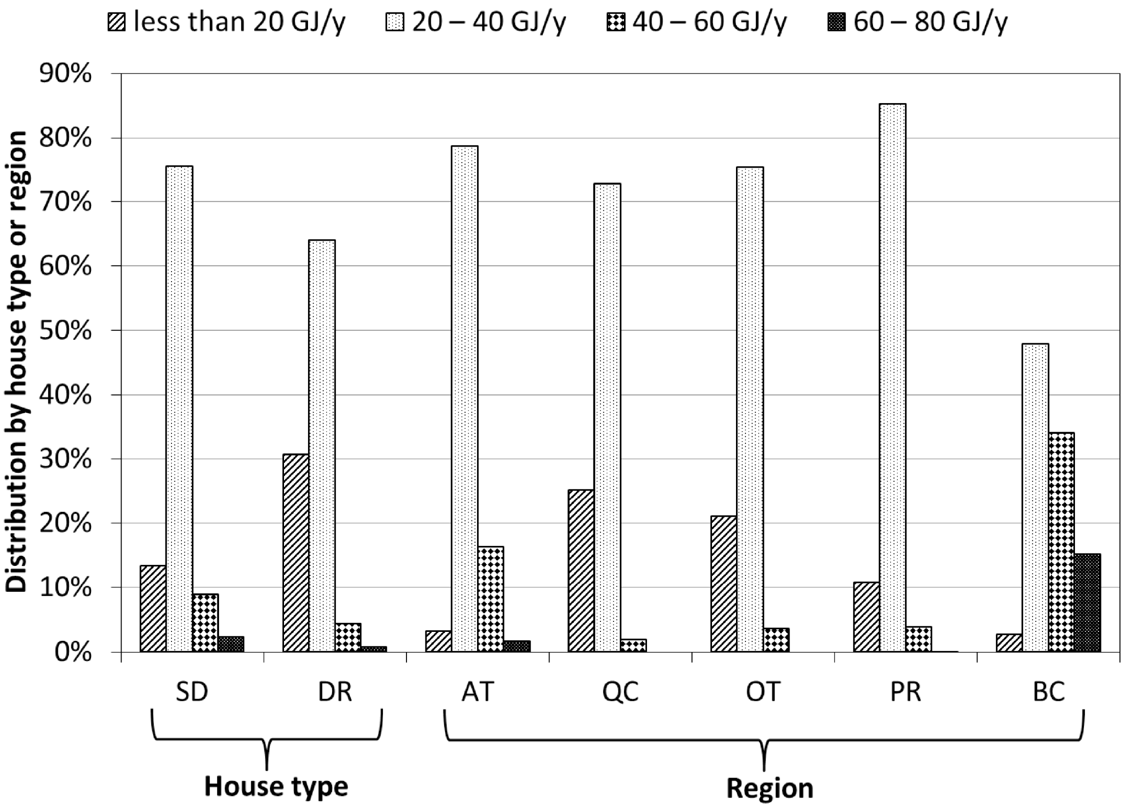
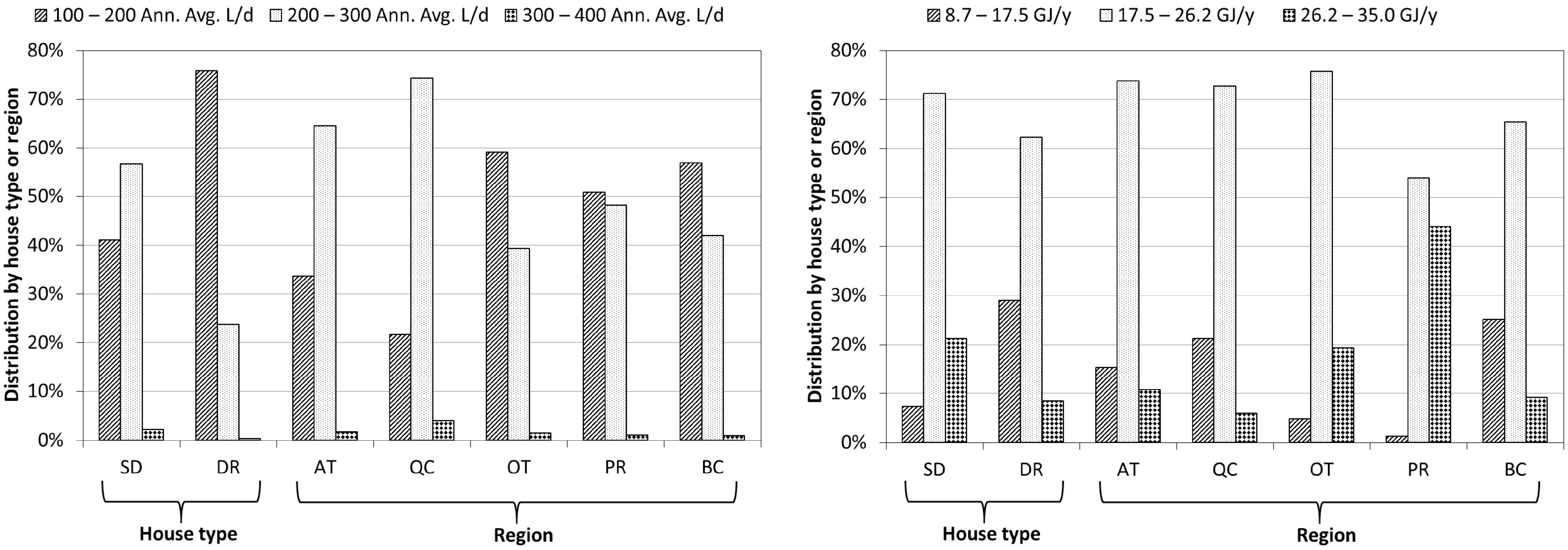


Figure 4.5 Annual AL energy consumption estimates (GJ per year) obtained using the NN model – summarized by house type and region

Figure 4.6 shows the DHW volume draw (4.6a) and energy consumption (4.6b) for comparison. The ranges of energy consumption were selected to mirror the draw ranges of a system that uses electricity and has an annual average ground temperature of 7.8 °C at 1.5 m depth. If all DHW systems in Canada were electric, the distributions would be similar between the Figures 4.6 a and b. However, it can be seen that the energy consumption distributions tend towards higher ranges than the draw, indicating that less efficient DHW systems (e.g. natural gas, oil) are in use. This is the case, as natural gas and heating oil systems make up approximately 55% of the DHW systems in the CSDDRD, as shown in Figure 4.2 where DHW system energy factor is listed in the legend.

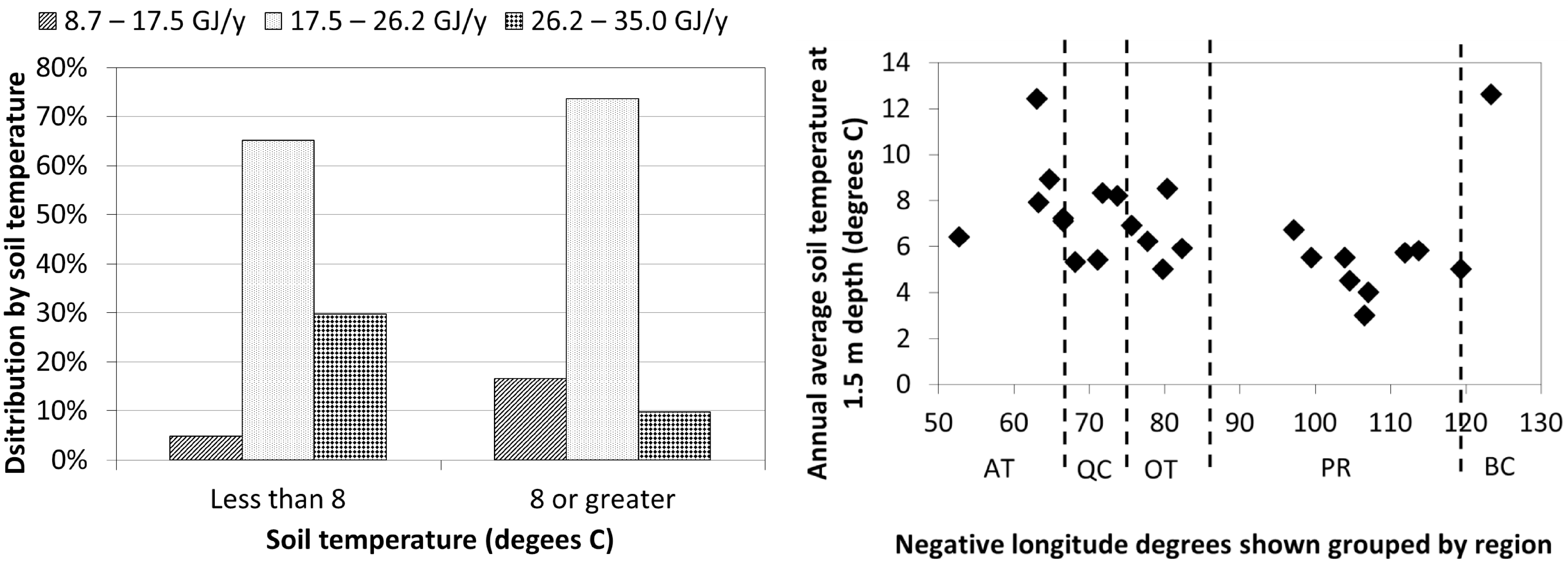
However, the high household DHW energy consumption of the prairies region (PR) shown in Figure 4.6b cannot be wholly explained by the predominance of less efficient natural gas systems, as Figure 4.2 shows they are also significant in Ontario (OT) and BC. Ground temperature may also affect DHW consumption. Figure 4.7a shows that DHW energy consumption is influenced by climatic conditions (proxied by soil temperature). DHW energy consumption tends to be greater in areas with colder ground temperature (less than 8 °C). Figure 4.7b indicates the relationship between region and soil temperature. The PR region has colder soil temperatures in comparison with the rest of Canada, averaging approximately 5 °C. This may partially explain the high DHW energy consumption of the PR region shown in Figure 4.6b.



(a)

(b)

Figure 4.6 DHW consumption estimates by house type and region, obtained using the NN model for (a) annual average daily DHW volume draw (L per day), and (b) annual energy consumption (GJ/y)



(a) (b)

Figure 4.7 Soil temperature relationships to (a) DHW energy consumption, and (b) region

4.4.2 Scaling of the CSDDRD AL and DHW Energy Consumption to National Values

An assessment of the national AL and DHW energy consumption was conducted by scaling the CSDDRD housing results to be representative of the respective house types and regions. Because of the selection algorithm used to develop the CSDDRD, each house type and region has an individual representation multiplier, although they are similar, which indicates adequate representation of each house type and region. These representation values are equal to the number of houses estimated by SHEU 2003 for the house type and region, divided by the corresponding number of houses in the CSDDRD. The representation level is shown in Table 4.8.

Table 4.8 Scaling representation from the CSDDRD houses to national values

House type	Region	House count		CSDDRD/SHEU ratio (scaling representation)
		SHEU 2003	CSDDRD	
SD	AT	662,335	1271	521.1
	QC	1,513,497	2882	525.2
	OT	2,724,438	5404	504.2
	PR	1,381,219	2703	511.0
	BC	910,051	1770	514.2
DR	AT	94,150	137	687.2
	QC	469,193	798	588.0
	OT	707,777	1231	575.0
	PR	246,848	441	559.7
	BC	203,449	315	645.9

Using the AL and DHW results from the CSDDRD, and the representation values of Table 4.8, the regional and national energy consumption of these end-use types were calculated. The results are shown in Table 4.9. The CHREM estimates that 447.5 PJ of secondary energy is required for Canadian SD and DR house types to provide for the AL and DHW end-uses. The AL energy consumption is larger than the DHW, and it accounts for 55% of the consumed energy for these end-uses. Electricity is the dominant energy source, providing for 73% of the overall AL and DHW energy consumption. Heating oil is a minor energy source and is only applicable to the DHW end-use.

Table 4.9 Regional and national AL and DHW annual energy consumption estimates by end-use and energy source for SD and DR house types

House type or region	By end-use AL (PJ)	DHW (PJ)	By energy source Electricity (PJ)	Natural gas (PJ)	Heating oil (PJ)	Combined (PJ)
SD	204.4	166.1	273.6	92.6	4.3	370.5
DR	42.4	34.7	54.3	22.1	0.6	77.0
AT	24.2	16.1	35.4	0.0	4.9	40.3
QC	47.1	40.4	87.5	0.0	0.0	87.5
OT	85.5	79.7	102.0	63.2	0.0	165.2
PR	43.4	41.9	48.8	36.5	0.0	85.3
BC	46.6	22.6	54.2	15.0	0.0	69.2
Canada	246.8	200.7	327.9	114.7	4.9	447.5
Canada percentage	55%	45%	73%	26%	1%	100%

The contributions of each energy source to each end-use are shown in Table 4.10. It is evident that natural gas plays a minor role in supplying the AL end-use. This is because only the *AL stove* and *AL dryer* can be powered by natural gas and these are relatively minor components in comparison with the *AL other* component (e.g. refrigerator, freezer, washing machine, etc.) that relies on electricity as the sole energy source. The distribution of these AL end-use components was shown in Table 4.6. In contrast, natural gas is the dominant energy source for the DHW end-use. Heating oil is used only in the Atlantic (AT) region and thus plays a minor role.

Table 4.10 National CHREM annual end-use energy consumption estimates by energy source for SD and DR house types

End-use	Energy source	CHREM Energy consumption (PJ)	Proportion by end-use (%)
AL	Electricity	244.9	99%
	Natural gas	1.9	1%
DHW	Electricity	83.0	41%
	Natural gas	112.9	56%
	Heating oil	4.9	2%
Combined	Combined	447.5	100%

4.4.3 Comparison of the CHREM Estimates to another Model

The CHREM estimates were compared to the top-down Canadian Residential End-Use Model (REUM) estimates published by the Canadian government in the Energy Use Data Handbook (OEE 2006b). The REUM relies on aggregate energy consumption data reported by Statistics Canada, and allocates this consumption to end-uses based on housing stock characteristics and estimated unit energy consumption.

As with most model comparisons, complications were encountered due to the scoping of the individual models. The CHREM estimates are based on 'average year' weather data supplied by Environment Canada. The REUM uses individual year weather data in constructing estimates to influence the end-uses year to year. Therefore, the REUM data was averaged for years 2000 to 2004 to account for annual weather variations.

A second complication in comparing the models is related to house types. The CHREM estimates energy consumption only for the SD and DR house types. The REUM estimates combined energy consumption by energy source for all house types, including apartments and mobile homes. A scaling method was developed to modify the REUM estimates to be representative of only the SD and DR house types.

In the case of DHW, the REUM also provides estimates of energy consumption by house type, and these values were used to scale the DHW energy consumption by energy source estimates. Table 4.11 shows the DHW scaling process. Of a total 339.4 PJ, REUM estimates that 237.6 PJ are due to the SD and DR house types, or 70%. The energy source components for the DHW estimates were then scaled by this 70% value, as shown in the final column of Table 4.11. This process preserves the REUM DHW estimates by house type, and assumes it is uniformly distributed across the energy sources.

Table 4.11 Annual energy consumption values used to scale the REUM DHW energy consumption estimates to be representative of only the SD and DR house types

Original REUM average 2000-2004 DHW estimates				Scaled REUM 2000-2004 DHW estimates for SD and DR house types	
House type	Energy (PJ)	Energy source	Energy (PJ)	Energy source	Energy (PJ)
SD	**199.8**	Electricity	123.0	Electricity	86.1
DR	**37.9**	Natural gas	198.8	Natural gas	139.2
Apartments	94.6	Heating oil	15.7	Heating oil	11.0
Mobile homes	7.2	Other*	1.0	Other	0.7
		Wood	0.9	Wood	0.6
Total of SD and DR only	**237.6**	Total of all energy sources	339.4	Total of all energy sources	**237.6**

* Other includes coal and propane

In the case of AL, the REUM does not provide estimates of energy consumption by house type. As an alternative, floor area was chosen as an indicator for scaling. A similar process to that shown in Table 4.11 was employed, although the basis for scaling was the floor area contributions of the SD and DR house types to the national total.

The results of the comparison of the CHREM and the REUM are shown in Table 4.12. The final column (CHREM/REUM ratio) may be used as an indicator of model agreement. The CHREM estimates a combined 6% more energy consumption than REUM for the DHW and AL end-uses. This is an acceptable level of agreement between the two models, especially considering the CHREM is a bottom-up approach and the REUM is a top-down approach. More significant variations between the model estimates appear as the end-uses are examined individually and by energy source. In particular, the CHREM estimates 34% more AL energy consumption and 26% less DHW energy consumption.

Table 4.12 National annual end-use energy consumption estimates by load type and energy source for SD and DR house types

End-use	Energy source	CHREM Energy (PJ)	CHREM Dist. (%)	REUM 2000-2004 Energy (PJ)	REUM 2000-2004 Dist. (%)	CHREM/REUM ratio
AL	Electricity	244.9	99%	181.1	98%	1.35
	Natural gas	1.9	1%	3.5	2%	0.53
	Total	*246.8*		*184.6*		*1.34*
DHW	Electricity	83.0	41%	86.1	36%	0.96
	Natural gas	112.9	56%	139.2	59%	0.81
	Heating oil	4.9	2%	11.0	5%	0.45
	Other*	0.0	0%	0.7	0%	0.00
	Wood	0.0	0%	0.6	0%	0.00
	Total	*200.7*		*237.6*		*0.84*
Combined	Combined	447.5		422.2		1.06

* Other includes coal and propane

These differences between the CHREM and REUM require explanation. There are a few obvious differences in methodology:

- The CHREM attributes the furnace fan and boiler pump components of the SH plant equipment to the AL. The REUM does not include these components. Such fans and pumps are not insignificant as a typical rating might be 250 W, and it may operate for upwards of 25% of the year (approximately 50% duty during heating season).
- The CHREM does not account for wood or “other” energy sources for the DHW energy consumption. The REUM does estimate these components although they are minor.

The most important difference in methodology between the models is related to the modeling approach and the ability of distinguishing end-use energy consumption. The top-down approach of the REUM relies on aggregate billing data, annual stock appliance assessments (primarily related to sales data), approximate usage profiles, and appliance unit energy consumption. Aggregate billing data does not include unreported energy deliveries, and the use of appliance unit energy consumption is a significant assumption in categorizing occupant behaviour. In contrast, the CHREM energy estimates are based on the bottom-up technique, and capture the interrelation of appliances and occupants via a NN technique. The ability to independently assess end-uses is a strength of the CHREM.

Because of the level of model agreement in total energy consumption of the AL and DHW end-uses, and the strengths and weaknesses of the modeling approaches, the CHREM energy consumption estimates are proposed as a new relationship between these two occupant influenced end-uses.

4.4.4 Use Profiles

The distribution of load profiles selected for incorporating the AL and DHW results into the CHREM engineering method are shown in Figure 4.8. The *AL cook stove and other* and the DHW are dominated by the medium consumption levels. This is expected because the ranges were based on Canadian data (Armstrong et al. 2009). In contrast, the clothes dryer is dominated by the low level.

Figure 4.8 Selected profile distribution levels for the CSDDRD based on annual AL energy consumption and DHW draw

As described in section 4.3.5, the CHREM engineering method linearly alters the time-step profile value using a multiplier. The multiplier may be used as a proxy for representativeness of the load profile for a particular house. A value of unity indicates that the annual consumption of the profile is exactly the same as the house. A description of the multipliers is summarized in Table 4.13. Multipliers for the *AL cook stove and other* and the DHW average close to unity. The dryer multiplier averages only 0.56. This is because the clothes dryer profiles average 3.9, 8.6, and 12.7 loads per week, for the low, medium, and high levels, respectively. The NN input for clothes dryer comes from SHEU 2003, where the levels of loads per week are 0, 1–2, 3–5, and greater than 5. Therefore, it would be advantageous to have a dryer profile at a lower level.

Table 4.13 Characteristics of the multipliers used to equate annual profile consumption with individual house consumption

Statistic	AL dryer multiplier	AL cook stove and other multiplier	DHW multiplier
Minimum	0.01	0.61	0.75
Maximum	1.74	2.23	1.50
Average	0.56	1.06	1.00
Standard deviation	0.40	0.18	0.14

4.4.5 Per Household and per Capita Consumption

SHEU 2003 estimates that there are 8.91 million single-detached and double/row households in the five evaluated regions of Canada (OEE 2006). Dividing the CHREM estimates by the number of households results in AL and DHW energy consumption of 27.7 GJ and 22.5 GJ per household, respectively, and an annual average daily DHW volume draw of 208 L/day per household.

“Population and dwelling counts” of Census 2006 estimate that there are 31.5 million people in the five regions of Canada (Statistics Canada 2006). Based on the household structure allocation defined by SHEU 2003, there are 27.5 million people living in single-detached and double/row households. The remaining population lives in apartments or mobile homes. Dividing the CHREM estimates by the number of people results in AL and DHW energy consumption of 9.0 GJ and 7.3 GJ per capita, respectively, and an annual average daily DHW volume draw of 67 L/day per capita.

The CHREM per household and per capita consumption estimates are compared to other published values in Table 4.14. Perlman and Mills (1985) measured the DHW consumption of 58 Canadian houses. Farahbakhsh et al. (1998) developed a bottom-up engineering model of the CHS based on the SHEU 1993 data. Aydinalp et al. (2002, 2004) used their NN models to assess the energy consumption of the SHEU 1993 dataset that was not used for model calibration. Their ALC estimates have been modified for Table 4.14 by removing the specified SC electricity consumption. Aguilar et al. (2005) estimated DHW consumption by applying scaling factors to total (cold and hot) water consumption.

Table 4.14 shows that the CHREM estimates AL energy consumption to be approximately 88% of previous models. This is likely due to the evolving AL ownership from 1993 to 2003, such as the increased use of energy efficient lighting (e.g. compact fluorescent bulbs). The CHREM estimate of DHW energy consumption is located within the range of other estimates. The CHREM estimate of household DHW volume consumption is 87% of the measured values by Perlman and Mills (1985). This is likely due to evolving DHW device ownership from 1985 to 2003, such as low flow showerheads and tap aerators. It appears the DHW scaling factors used by Aguilar et al. (2005) significantly overestimate DHW volume draw in comparison with other estimates.

Table 4.14 Comparison of published estimates of Canadian per household and per capita AL and DHW annual energy and volume draw consumption

Statistic	Source	AL energy consumption (GJ)	DHW energy consumption (GJ)	DHW volume draw (Ann. Avg. L/day)
Per household	Perlman and Mills (1985)	-	-	239
	Farahbakhsh et al. (1998)	31.2	21.6	-
	Aydinalp et al. (2002, 2004)	31.3	26.0	-
	Aguilar et al. (2005)	-	-	353
	CHREM	27.7	22.5	208
Per capita	Perlman and Mills (1985)	-	-	61
	Aguilar et al. (2005)	-	-	139
	CHREM	9.0	7.3	67

4.5 Conclusion

The bottom-up CHREM statistical method, which relies on a previously developed NN, has been used to estimate the national residential energy consumption for AL and DHW of single-detached and double/row houses. These house types comprise 80% of the CHS (OEE 2006). The CHREM uses unique characteristics of nearly 17,000 houses that are augmented with common appliance and demographic data as input information. The NN model is used to independently estimate the AL and DHW energy consumption, and these results are scaled to be representative of the CHS.

The annual total AL and DHW energy consumption of 447.5 PJ was found to be within 6% of a top-down model estimate, an acceptable level of agreement. However, the CHREM finds the proportion of AL energy consumption to be larger than DHW energy consumption, opposite that of the top-down model. Differentiation of the AL and DHW energy consumption is considered a key strength of the CHREM bottom-up modeling methodology as it independently estimates each end-use. Therefore, the CHREM energy consumption estimates are proposed as a new relationship between the occupancy influenced AL and DHW end-uses.

The AL and DHW estimates are used to select appropriate load profiles (e.g. five minute time-step) and calculate corresponding multipliers for use in the CHREM engineering method. Individual profiles are used for DHW, clothes dryer, cook stove, and remaining AL components. This allows for the allocation of consumed energy to either the interior or exterior of the conditioned zone (e.g. the clothes dryers vents outside) as well as consideration of the appliance energy source (e.g. the clothes dryer and cook stove can be powered by either electricity or natural gas).

The selected load profiles and corresponding multipliers for each of the 16,952 houses is incorporated into the bottom-up engineering method of the CHREM for estimation of SH and SC energy consumption, and finally the determination of greenhouse gas emissions based on emission intensity factors. The engineering method will use certain portions of the AL to offset SH or increase SC energy requirements. It also includes the AL and DHW energy consumption, with the SH and SC energy consumption, to estimate the total for each energy source of each house. These results are scaled to be representative of the CHS, and result in a comprehensive residential energy and emissions model.

Chapter 5 The CHREM Engineering Method

The Canadian Hybrid Residential End-Use Energy and GHG Emissions Model (CHREM) is a bottom-up modeling approach that employs statistical and engineering methods to estimate the end-use energy consumption and GHG emissions of the Canadian housing stock (CHS). Chapter 4 presented the detailed methodology and results of the CHREM statistical method. The statistical method was used to estimate the appliance and lighting (AL) energy consumption and the domestic hot water (DHW) volume draw. These two end-uses are primarily influenced by occupant behaviour and appliance presence.

This chapter presents the detailed methodology of the CHREM engineering method. The engineering method models the space heating (SH) and space cooling (SC) end-use energy consumption. The engineering method is also used to model the performance of the DHW system in response to the volume draw, and in doing so, estimates the DHW end-use energy consumption. The SH and SC end-uses are influenced by portions of the AL and DHW energy consumption that become a heat gain within the house. The SH, SC, and DHW end-use energy consumption are strongly influenced by the following:

- House thermal envelope
- Climatic conditions
- Equipment type and the control strategy

A representative database of 16,952 house descriptions that include this information was developed in Chapter 3, and is called the Canadian Single-Detached and Double/Row House Database (CSDDRD). The data originates from the EnerGuide Program, where professional energy auditors measured and assessed the thermal envelope and energy conversion systems of each house (Blais et al. 2005).

The CHREM engineering method uses the results of the CHREM statistical method and the CSDDRD information, and develops a set of house models for building energy performance simulation. A unique house model is generated for each house of the CSDDRD. The CHREM engineering method employs the building energy performance simulator ESP-r (Clarke 2001, ESRU 2002). The following description of the engineering method is presented in accordance with the ESP-r building model format. This chapter describes the house model development process, and the following chapter describes the energy performance simulation results.

5.1 Introduction

The estimation of the end-use energy consumption and GHG emissions of the CHS requires consideration of each end-use, as well as the interaction between end-uses. The end-uses within a dwelling may be grouped as follows:

- SH and SC maintain the thermal zone condition according to the control strategy. The SH and SC end-use energy consumption is a result of heat flux across the thermal envelope due to conduction/convection, radiation, and heat advection, as well as the performance of the SH and SC energy conversion system. Conduction/convection across the thermal envelope is due to a difference between ambient and thermal zone conditions. Solar radiation enters the thermal zones through windows. Heat advection is a consequence of different temperature air exchanging across the thermal envelope due to leakage and active ventilation.
- DHW provides hot water at a comfortable or appropriate temperature for occupant and appliance use. The DHW end-use energy consumption is a result of the hot water volume draw, as well as the performance of the DHW energy conversion system. The majority of the energy used for DHW immediately exits the dwelling, either as exhaust from the DHW system, or as hot water running down the drain. Depending upon the DHW system equipment, a small portion of the energy consumption becomes heat within the thermal zone, and may offset SH or increase SC energy consumption.
- AL end-use energy consumption supports common appliances (e.g. refrigerator, coffee maker) and provides for adequate lighting. The majority of this energy becomes heat within the thermal zone, and may offset SH or increase SC energy consumption.

Building energy performance simulation can be used to estimate the energy required by each of these end-use groups, including their interaction. However, accurate estimates of energy consumption require an adequate thermodynamic representation of the house, and a building simulator with the capabilities of handling the complex energy fluxes. As an indicator of the level of complexity required of a building performance simulator, consider the following example:

> Direct solar radiation at the house location is a vector, varying considerably in both magnitude and direction throughout the day. As different window areas may be located on each side of the house, the quantity of solar radiation admitted into the thermal envelope to offset SH is dependent upon the three dimensional house geometry. Consider further that as the solar radiation passes through the window panes, some of it is absorbed. This absorption level is dependent upon the angle of incidence and the optical characteristics of the window. The radiation absorbed at the outer pane of a double-glazed window is almost immediately lost to ambient

> conditions via convection or long-wave radiation. Early morning or late afternoon solar radiation incident on a south facing surface at Canadian latitudes is not only reduced in magnitude compared with noontime, but a lesser portion of the incident value is actually admitted within the thermal envelope.
>
> As that solar radiation continues penetrating the thermal envelope, much of it is absorbed by floors, walls, ceilings, and furnishings. However, some is reflected back out through the windows (again a portion is absorbed by the glazing as it transmits through). If thermal mass of the absorbing materials is limited, an overheating situation within the thermal zone may occur. This would lead to high rates of flux through the building envelope, either as heat flux through the building surfaces, or perhaps heat advection caused by occupants opening windows to allow airflow. Alternatively, if thermal mass is significant, the absorbed solar energy is stored as sensible heat, and may later be used to offset heat loss of the house after the sun has set.

The following subsections consider the selection of an appropriate building performance simulation engine, the simulation engine's calculation basis, and a typical scope of consideration of the heat fluxes and end-use energy consumption within the building. Section 5.2 begins the presentation of the CHREM house model development process suitable for the building energy performance simulator.

5.1.1 Selection of a Building Simulation Engine

The CHREM has the objective to be capable of assessing renewable and alternative energy technologies as applied to the CHS. These will likely involve solar energy as in the previous example. Therefore, a detailed building energy performance simulator is required. Examples of such energy simulation engines include ESP-r (Clarke 2001, ESRU 2002), EnergyPlus (Crawley et al. 2004), and TRNSYS (Klein et al. 2004). Descriptions and comparison of the capabilities of these, and more than a dozen other simulation programs, were reported by Crawley et al. (2008). Based on a review of the energy simulation requirements of the CHS and the capabilities over 30 programs, ESP-r was selected by the Government of Canada as the basis for its next generation house simulator (Haltrecht et al. 1999). Specific rationale for their selection of ESP-r included the ability to handle complicated heat flux and plant equipment, as well as availability and open-source format suitable for adding simulation capabilities and models for new technologies. As a result of Canada's selection, numerous new simulation models have been added to ESP-r to account for many characteristics and present technologies of the CHS. Based on these detailed reviews of available simulation engines, and the present technological status of the simulation engines, ESP-r was selected as the building energy performance simulator that can meet the needs and objectives of the CHREM.

5.1.2 The ESP-r Building Simulator

The following description of the ESP-r building simulator is a summary of portions of the theory presented by Clarke (2001). ESP-r was developed with the objective of modeling and integrating multiple building domains (e.g. thermal envelope, airflow, and electrical flow). Most simulation programs are based either on response function methods or numerical methods of finite difference/volume (see Clarke 2001 for a detailed discussion of the methods). The response function method is an analytical technique of handling the dynamic consideration of building energy flux. However, this method suffers from an inability to directly couple different interacting building domains, such as the thermal envelope and plant systems. This leads to the assumption of time invariant model parameters (e.g. heat transfer coefficients) and introduces inaccuracy to the energy estimates. In contrast, numerical methods are general, and allow for the application of a variety of interacting building domains in a method that emulates reality.

The ESP-r simulator is based on numerical methods that employ finite volumes to represent real matter (such as wood, concrete, drywall, and air) or a component with defined functionality (e.g. pump, lighting). Each finite volume node is assigned properties that control its thermodynamic behaviour, and is then interfaced with other nodes with which it thermodynamically communicates. A set of conservation equations are developed to represent this thermodynamic behaviour and communication with respect to energy, mass, and momentum. Boundary conditions, such as climate (e.g. temperature, solar radiation) and control strategies (e.g. heating setpoint of 21 °C) are imposed upon the equations. A timestep is considered to occur from the present nodal condition state, during which the conservation equations allow for thermodynamic exchange between nodes. The solution of the conservation equations after the timestep represents the new nodal states.

Figure 5.1 shows a simple ESP-r representation of an opaque exterior wall that encloses a room with no windows (e.g. closet). Each layer of the wall is represented by three nodes (note the shared node which interfaces layers). Conduction (CD) occurs between each interfaced node of the wall. Convection (CV) occurs between the outside wall face and the ambient air, an imposed boundary condition from climatic data. CV also occurs between the inside wall face and the house air mass (termed airpoint). The house airpoint may also have an imposed control strategy condition such as heating setpoint and heating system capacity. The outside wall face receives incident short-wave (SW) radiation from the sun, also an imposed climatic condition. Finally, both the inside and outside faces of the wall experience long-wave (LW) radiation exchange. The outside face exchanges LW radiation the ground, surroundings (such as other buildings), and sky. The inside face exchanges LW radiation with other interior surfaces. As previously mentioned, each node of the wall will have thermodynamic properties. In this case they would include thermal-conductivity, density, specific heat, LW emissivity, and SW absorptivity. Additionally, convection coefficients would be determined for the wall faces.

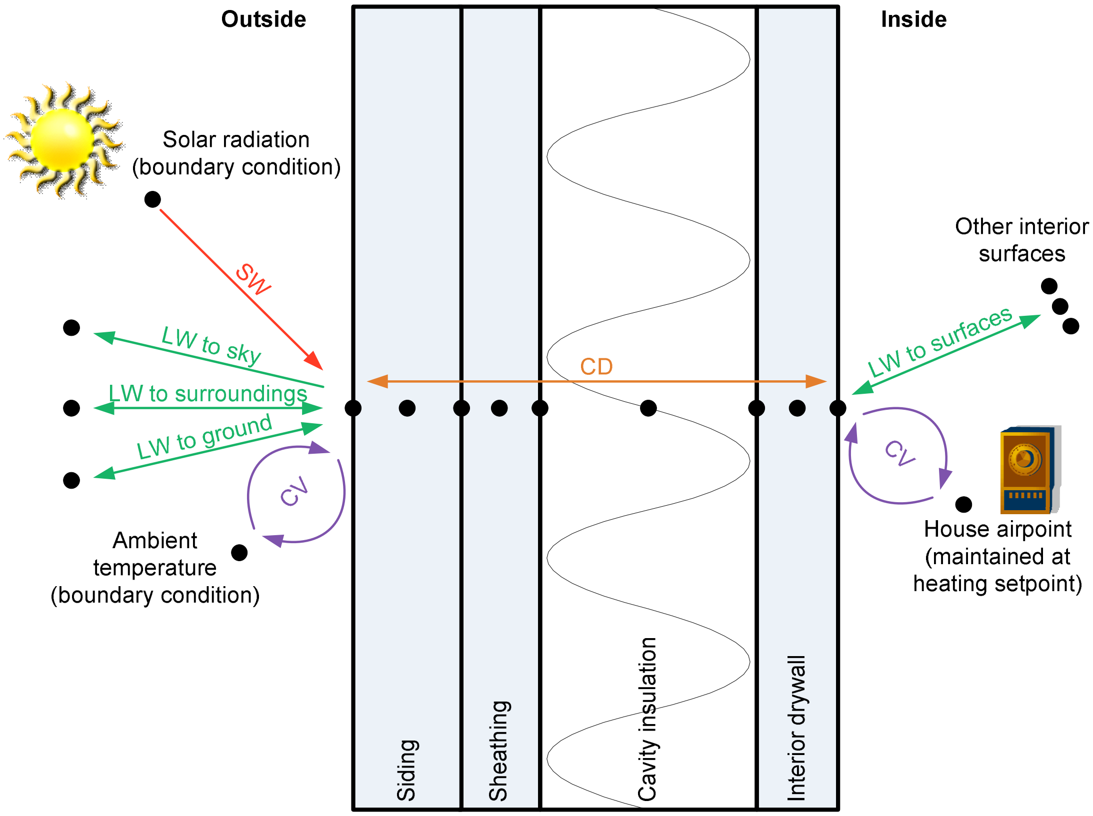


Figure 5.1 Simplified example of the ESP-r nodal structure (black dots) for an insulated opaque wall

The ESP-r simulator uses a weighted average of explicit and implicit solution schemes to the energy conservation equations. The explicit scheme relies on nodal temperatures existing prior to the timestep in determining a solution. This allows each conservation equation to be solved independently, but introduces the opportunity for instability. The implicit scheme solves the conservation equations based on the nodal temperatures at the solution state (after the timestep). This allows for unconditional stability, but requires simultaneous solution of all nodal conservation equations. By constructing a weighted average of the explicit and implicit schemes, the solution is most accurate while maintaining stability.

The main cause of inaccuracy of the ESP-r simulator is discretization errors, either by nodal structure or by timestep. Regarding nodal structure, the ESP-r default of three nodes per layer is sufficient for typical construction materials and whole building energy performance simulation (see Figure 3.1 of Clarke 2001). The timestep must be selected to adequately capture the dynamic effects of the systems. For thermal envelopes, a timestep of 60 minutes or less is suggested due to solar radiation considerations and the significance of thermal mass. For explicit plant equipment definitions (e.g. furnace and air distribution system) a timestep of 15 minutes or less is suggested to capture the cycling effects. Of course, an inappropriate or lacking representation of a house will lead to inaccurate energy estimates.

This brief introduction to ESP-r's numerical simulation technique is intended only to provide sufficient background to support the following sections and the basis for the house description methodology.

5.1.3 Scope and Consideration of Heat Fluxes and End-use Energy Consumption

The scope or consideration of heat fluxes and end-use energy consumption within a house demands a specific level of description for building performance simulation. Although Figure 5.1 illustrated the heat flux occurring across an insulated opaque wall, other fluxes must be considered. These include flux across transparent surfaces such as windows, and heat advection caused by airflow in/out of the house. Furthermore, there are heat generation terms caused by internal gains and active SH and SC systems.

A simplified example of the interaction of these fluxes inside a house is shown in Figure 5.2, where a control volume (dashed line) is drawn to encompass the interior surface nodes, air point, and the internal gains and space heating/cooling generation terms. There are three types of heat flux directly crossing the control volume boundary: CD through the transparent and opaque surfaces, SW radiation absorbed by these surfaces, and heat advection (HA) caused by air mass exchanging between the airpoint and both ambient conditions (e.g. leaking windows) and another conditioned airpoint (such as a basement). Within the control volume are heat generation terms due to internal gains from AL and occupants, as well as active SH and SC systems. It should be noted that the LW radiation between the surfaces, and the CV between the surfaces and airpoint, do not cross the control volume and are not generation terms. They are simply shown to illustrate the major heat transfer mechanisms within the dwelling, and may be used to independently show conservation of energy at any of the solution nodes.

The arrowheads shown in Figure 5.2 indicate typical directions of heat transfer. SW radiation and internal gains are uni-directional, and all other heat fluxes have the potential to be bi-directional. In addition, nodes are identified as either having an imposed condition or being solved by the building simulator. It should be noted that the solution nodes have a thermal mass, and thus any sensible heat storage (SS) must be considered.

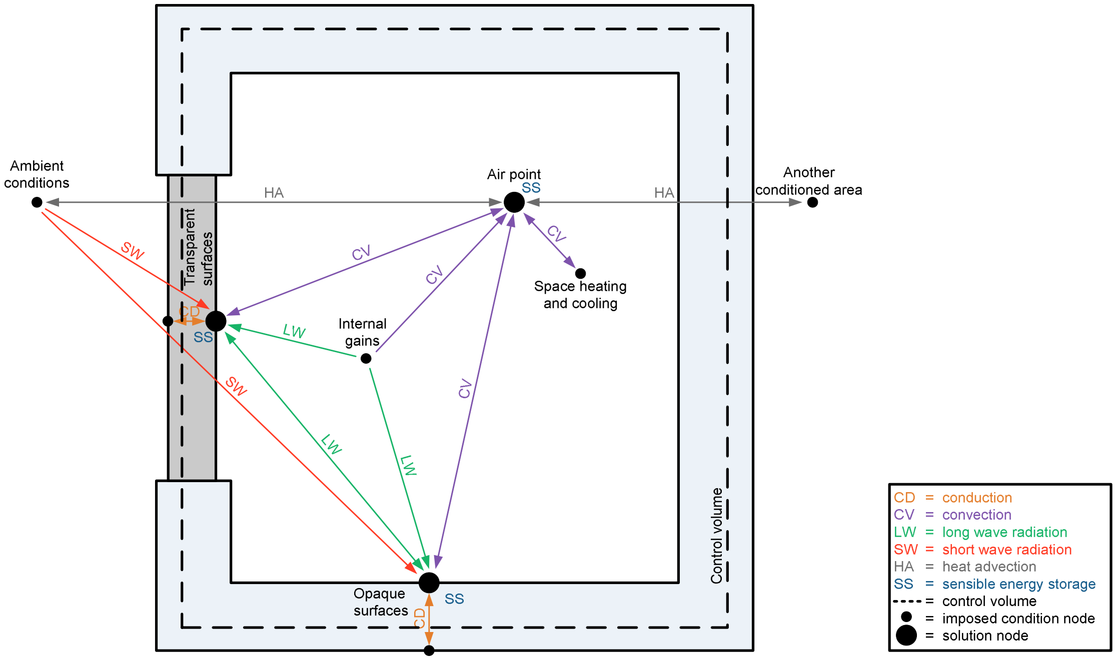


Figure 5.2 Major heat fluxes found within a house control volume that has a simple SH and SC system with delivery at airpoint

It is evident from Figures 5.1 and 5.2 that a number of detailed descriptions must be provided to adequately simulate a house for energy performance purposes. These include:

- Climatic information
- Geometry of the house
- Opaque and transparent surface characteristics
- Airflow characteristics
- Internal gains
- SH and SC functionality

Although such definition may be used to simulate the heat flux characteristics of a house, it lacks additional information of interest for a national energy model. The CHREM is primarily interested in end-use energy consumption associated with the four major end-use groups (SH, SC, DHW, and AL). A simplified relationship of these end-uses and their associated energy provision is shown in Figure 5.3, and is with reference to the internal gains and SH and SC context of Figure 5.2. As Figure 5.3 shows, the internal gains are a function of DHW, AL, and occupancy. Occupants release heat as both CV and LW radiation, as well as latent evaporation of water from the skin. Of these gains, portions of the DHW and AL are exhausted outside the dwelling. However, both the DHW and AL end-uses, as well as the SH and SC end-uses, must be considered for end-use energy consumption from the variety of energy sources. Note that electrical energy source is shown as bi-directional, as houses have the potential to act as generating facilities (not shown, e.g. photovoltaics, wind-turbine, co-generation) to export electricity to the electrical grid.

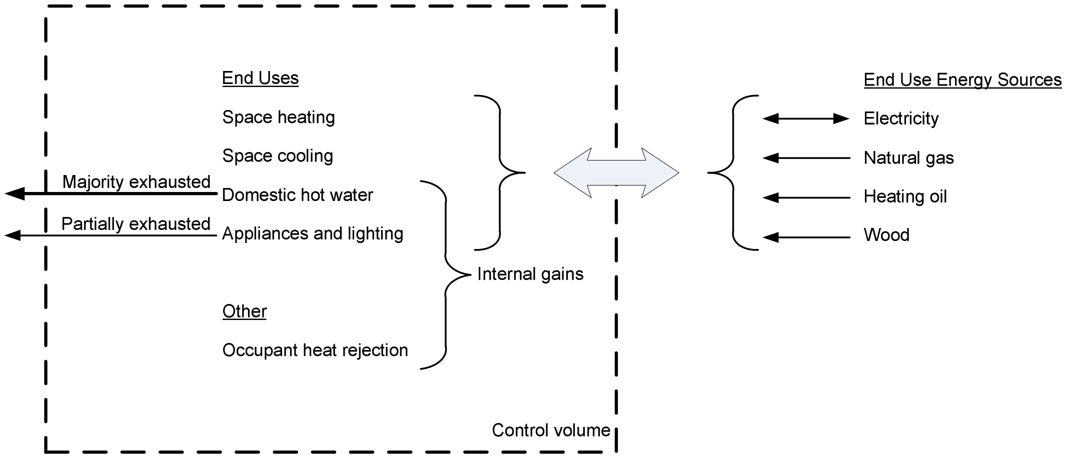


Figure 5.3 Relationship of end-uses, internal gains, and energy sources within a house energy control volume

The relationship of the end-uses and the energy consumption by energy source requires further definition of the house. Such description includes:

- SH and SC equipment
- DHW and AL equipment and consumption characteristics
- Presence of occupants

The following section discusses the description of the house with regard to both the heat flux and end-use energy consumption characteristics for the building energy performance simulator ESP-r.

5.2 Unique House Model Descriptions for Building Performance Simulation

The CHREM engineering method relies on the detailed geometric, thermal envelope, and energy conversion system information contained in the CSDDRD. The information can be used to generate a unique house model for use with the building energy performance simulator ESP-r. The definition of such a house model can be separated into distinct steps. They are:

- Climatic information
- Thermal zones
    - Separation of the house levels into thermal zones
    - Geometrical sizing of each thermal zone
- Zone surfaces
    - Definition of the basic surfaces that enclose a thermal zone
    - Insertion of windows and doors within surfaces
    - Condition to which each surface is exposed
    - Layer by layer material property description
        - Opaque surfaces including parallel elements such as framing and cavity insulation
        - Transparent surfaces including optical properties
- Airflow
    - Leakage through small cracks and gaps
    - Bulk flow through large intended openings
    - Forced mechanical ventilation

- Internal gains and occupant related use
    - AL and DHW
    - Occupant presence
- Zone thermal conditioning control strategy
- SH and SC plant
    - Equipment type and size
    - Energy source

The following sections detail these model definition aspects as employed by the CHREM engineering method.

5.3 Selection of Climatic Conditions

Building energy performance simulation requires climatic information as the imposed boundary conditions upon the exterior of the house. Simulation that considers detailed heat flux, especially those related to solar insolation, requires climatic data at timesteps of one hour or less. There are numerous meteorological measurements that can be utilized by building energy performance simulation (e.g. ground albedo), but certain data is critical for energy assessment:

- Dry bulb temperature is used to assess heat loss via conduction/convection and/or radiation from the building to the surroundings. It may further be used to assess soil temperature. This is useful for determining foundation heat loss and water supply temperatures (Moore 1986).
- Direct and diffuse solar radiation is used to assess incident solar radiation and its absorption, transmission, and reflection through transparent and opaque surfaces.
- Wind speed and direction is used to assess the pressure distribution on different building surfaces that leads to air leakage in the event that a crack or opening (e.g. window) is present.
- Relative humidity is used to assess the level of airborne water which, in detailed simulations, will influence latent heat exchange (e.g. cooling coil, window condensation), and may also be used to account for changes in air density and specific heat.

Individual year weather data is subject to annual variations (e.g. el Niño). This is undesirable for the context of national energy modeling aimed at technology assessment. Data from a certain location may only be available for a “warm” year, or may have gaps due to equipment malfunction.

Environment Canada (2009) provides 44 weather data files that were specifically developed for energy simulation purposes. These data are titled Canadian Weather for Energy Calculations (CWEC) and were developed for Environment Canada by Numerical Logistics Inc. A summary of the CWEC climatic data is provided in Appendix A. The files are described by Numerical Logistics (2010) as being:

> "… obtained by concatenating twelve Typical Meteorological Months selected from a database of, in most cases, 30 years of data. The months are chosen based on statistical criteria (representing mostly solar and dry bulb temperature)."

The CSDDRD lists both the Canadian province and the nearest city of significance for each house record. These cities of significance originated from a drop down menu selector that was linked to Environment Canada weather data (Environment Canada 2009). 65 unique city entries appear in the CSDDRD. Environment Canada has a weather station at each of these locations. However, only 35 CWEC files are direct matches by name, the remainder of the locations having only annual data and not "typical meteorological months".

As part of the CHREM, the remaining 31 cities were mapped to available weather data based on indicator parameters of heating degree days (HDD) and longitude/latitude. HDDs may be used as a proxy for SH energy intensity for a given building type. As SH is the dominant end-use energy consumer in a house it is desirable to select data with similar HDDs. However, it would be inappropriate to select a weather station located across the continent. This is because certain weather patterns such as solar radiation, clouds, and fog are regionally specific. With this in mind, the indicators of latitude and longitude were also employed for mapping of weather locations. Latitude is critical due to its influence on solar radiation levels, which will affect future CHREM estimates of new integrated solar technologies.

Table 5.1 shows the differences between these mapped cities and the CWEC weather locations. With the exception of the locations in the far north (above 53.5 degrees latitude), the latitude differences range from -1.7 to +3.4 degrees, the longitude differences range from -6.4 to +7.9 degrees, and the HDD ratio ranges from 0.98 to 1.21.

Although the latitude and longitude of the CSDDRD houses is known for each weather location, the values of the mapped CWEC weather site are utilized in generating the house model for ESP-r. This is due to the solar radiation algorithms of ESP-r which return inaccurate results if the weather station and house latitudes or longitudes differ significantly.

The appropriate climatic information is provided for each house model based on a lookup of the nearest weather location by the CHREM. The ESP-r simulator expects weather data to be "hour-centered", meaning for example, that the timestamped data at 02:00 is an average representation for the period of 01:30 through 02:30. However, the CWEC solar insolation data is "half-hour-centered", meaning it is an average of the preceding hour (e.g. solar insolation timestamped data at 02:00 is representative of the period from 01:00 to 02:00). CWEC data is structured this way because it was expected to be used to calculate the accumulated solar energy over the previous hour. A flag, as described by Mottillo (2005), was included within the CHREM model to activate an ESP-r modifier to account for these weather file differences. During simulation, it reads forward in the climatic solar insolation data to a future time and calculates an hour-centered average.

Table 5.1 Differences between the CSDDRD weather cities mapped to available CWEC weather data

CSDDRD		CWEC		Degree difference (CSDDRD – CWEC)		CSDDRD/CWEC ratio of HDD (18 °C base)
City	Prov.	City	Prov.	Latitude	Longitude	
BONAVISTA	NL	ST. JOHN'S	NL	1.1	-0.4	1.03
CARTWRIGHT	NL	GOOSE BAY	NL	0.4	3.4	0.99
GANDER	NL	ST. JOHN'S	NL	1.3	-1.9	1.06
ST JOHN'S	NL	ST. JOHN'S	NL	0.0	0.0	1.00
GREENWOOD	NS	HALIFAX	NS	0.1	-1.3	1.05
TRURO	NS	SYDNEY	NS	-0.8	-3.3	0.98
YARMOUTH	NS	HALIFAX	NS	-1.1	-2.5	1.00
SUMMERSIDE	PE	CHARLOTTETOWN	PE	0.1	-0.7	0.98
CHATHAM	NB	SAINT JOHN	NB	1.7	0.5	
MONCTON	NB	FREDERICTON	NB	0.2	1.8	1.01
BAGOTVILLE	QC	QUEBEC	QC	1.5	0.4	1.11
KUUJJUAQ	QC	SCHEFFERVILLE	QC	3.3	-1.6	1.02
SEPT ILES	QC	QUEBEC	QC	3.4	5.1	1.21
SHERBROOKE	QC	QUEBEC	QC	-1.4	-0.3	0.99
VAL D'OR	QC	QUEBEC	QC	1.3	-6.4	1.19
BIG TROUT LAKE	ON	CHURCHILL	MB	-5.0	4.2	0.84
KINGSTON	ON	TRENTON	ON	0.1	0.9	1.02
SIMCOE	ON	LONDON	ON	-0.2	0.9	
SUDBURY	ON	NORTH BAY	ON	0.3	-1.4	1.01
TIMMINS	ON	THUNDER BAY	ON	0.2	7.9	1.08
BRANDON	MB	WINNIPEG	MB	0.0	-2.8	1.03
THOMPSON	MB	LE PAS	MB	1.8	3.2	1.17
PRINCE ALBERT	SK	NORTH BATTLEFORD	SK	0.4	2.6	1.06
SASKATOON	SK	NORTH BATTLEFORD	SK	-0.6	1.6	0.99
URANIUM CITY	SK	CHURCHILL	MB	0.8	-14.5	
LETHBRIDGE	AB	MEDICINE HAT	AB	-0.4	-2.1	0.99
ROCKY MOUNTAIN HOUSE	AB	EDMONTON	AB	-0.6	-1.3	1.01
FORT NELSON	BC	FORT ST. JOHN	BC	2.6	-1.9	1.17
SMITHERS	BC	PRINCE GEORGE	BC	0.9	-4.5	1.00
WILLIAMS LAKE	BC	PRINCE GEORGE	BC	-1.7	0.6	0.99

5.4 House Zoning Description

The CHS may be described with a limited number of thermal *zones*. These thermal zones are the major conditioned or unconditioned air spaces, including the surrounding physical structure which constitutes a thermal envelope. A building is zoned for energy simulation to differentiate between conditioned zones, those that are managed in an effort to maintain occupant comfort levels, and unconditioned zones, such as an attic. Although a complete geometric description of a house requires significant amounts of information, it allows for an adequate representation of each zone thermal envelope. There are three main types of thermal zones specified in the CSDDRD:

- A *foundation* may be a heated basement, or a heated or unheated crawl space. In instances were neither of these foundation zones exist, the dwelling may be supported by either a slab-on-grade foundation structure, or simply be exposed to ambient.
- *Main levels* are those which are heated and consistently occupied. The number of levels ranges from one to three and represent discrete storeys that are located vertically above any foundation zone.
- *Attic* or *roof space* levels are unheated and located vertically above the highest main level.

An example of these zoning types and levels as employed by the CHREM is illustrated in Figure 5.4. The zoning shown in Figure 5.4a is the most simple house model, and has the minimum of two zones with equivalent floor plan layouts. This is representative of certain urban house types with no foundation zone and a flat roof. Such a house may have a slab-on-grade foundation included with the main level 1 zone, or simply have an insulated exposed floor. The roof space is provided as an insulating cavity that breathes, and in doing so provides a thermal break between the incident sunlight on the roof and the insulated ceiling of the main level 1.

Figure 5.4b shows a complicated 5 zone house model, the maximum number of zones specified by the CHREM. It is representative of a three storey house with a foundation zone, three main zone levels, and a sloped attic space. The floor plan of each zone is different, with the exception of the attic and main level 3. The attic or roof space is always sized to fit the zone located below. The exposed ceilings and floors of the main levels are insulated as specified in the CSDDRD. In all cases the foundation zone is limited to a maximum area equivalent to main level 1. In certain cases the main levels 2 or 3 have more floor area than main level 1. Each zone type is discussed individually in the following subsections.

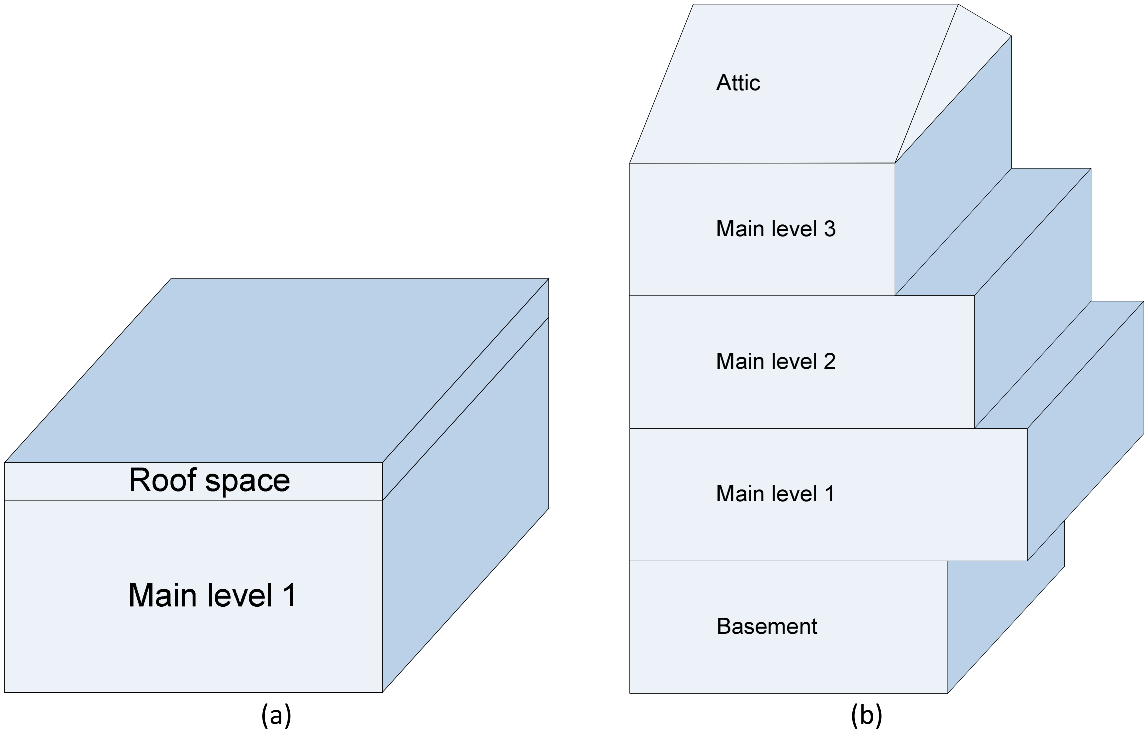


Figure 5.4 **House zoning models of the CHREM for (a) the most simple 2 zone, and (b) the most complicated 5 zone**

5.4.1 Basic Geometry Definition

The first main living area level is considered for the layout of the house. Although a layout shape indicator is present in the CSDDRD, there is insufficient geometrical data to create a detailed floor plan layout, such as an L or T shape. Based on the aspect ratio specified in the CSDDRD, the house was rectangularized. The aspect ratio is the front width divided by the side length. Because of the rectangularization process, the aspect ratio value was limited to a range of 0.66 to 1.50. The side length l was calculated based on the first main level floor area A and the aspect ratio r.

$$l = \sqrt{\frac{A}{r}} \tag{5.1}$$

The side length l was maintained for all thermal zones, in an effort to simplify geometric definition. In terms of three dimensions, each zone begins at the datum $(0,0,Z_{\text{bottom}})$ and has the opposite corner located at (X,l,Z_{top}). The width X is varied to accommodate floor areas of each particular zone, and the zone height ΔZ is specified by the CSDDRD. The CHREM rectangularization and definition of a common side length for all zones is illustrated in Figure 5.5.

After the definition of all zones corresponding to the discussed layout, the zones were rotated to orient the front of the house in the direction specified by the CSDDRD. Front facing direction is specified counter clockwise as S, SE, E, NE, N, NW, W, SW in 45 degree increments starting from zero.

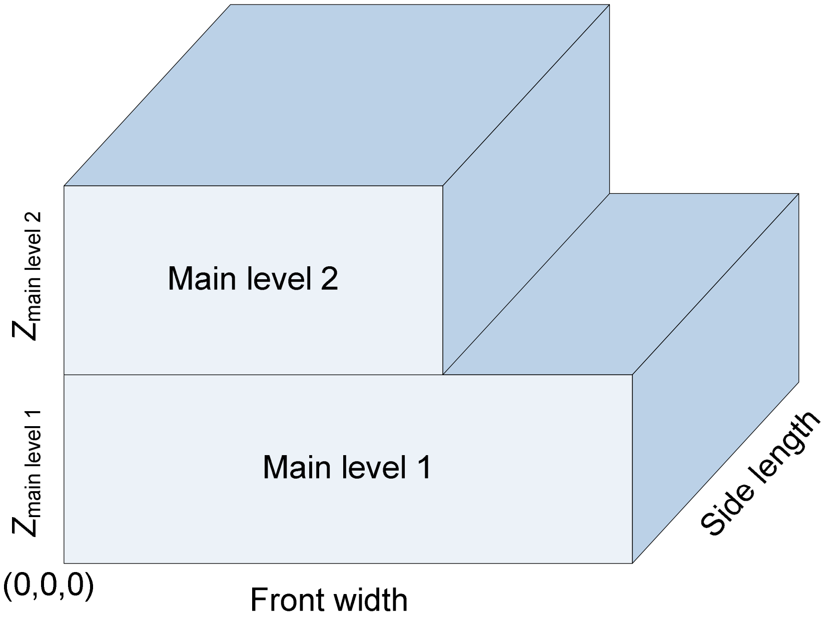


Figure 5.5 Example zone rectangularization based on the aspect ratio of main level 1 defining the side length for all zones

5.4.2 Foundation

The foundation may consist of either a zone or simply be a surface of the lowest main level. The CSDDRD lists the *interior* foundation floor area for a basement, crawl space, and slab-on-grade. In the event that the value is less than 90% of the first main level floor area (to allow for foundation wall thicknesses), it was inferred that there is an exposed floor portion of the first main level. Although the original intention of the foundation area inputs was to allow for multiple foundation types, appropriate modeling of this layout became infeasible due to lack of geometry data. Instead, the foundation type with the largest floor area was considered dominant and was selected, with the balance of the first main floor area considered to be exposed floor.

Basements are considered conditioned zone areas and are part of the overall living space. Basement types include: deep, shallow, and walkout with a selectable direction. Walkout basements were considered to have two sides above grade and two sides below grade. In general, crawl spaces are considered unheated and thermally separated from the living space of the main levels. The following crawl spaces are included:

- *Closed* crawl spaces lack intended ventilation openings and therefore permits little air exchange.
- *Ventilated* crawl spaces have intended openings which permit significant air exchange.
- *Open* crawl spaces lack closed sides.

Although closed type crawl spaces have a space heating indicator, they were rare cases and often had a lowered temperature setpoint. Therefore they were considered unheated and an appropriate floor construction (often insulated) was specified for the first main zone. Open type crawl spaces allow so much air flow that they need not be considered a thermal zone. In such cases the main level 1 was considered to have a completely exposed floor.

5.4.3 Main Levels

Information for up to three main levels is specified by the CSDDRD. Purdy and Beausoleil-Morrison (2001) discuss the amalgamation of main levels into one thermal zone and the limited impact it has on whole building performance energy simulation. Such a single-main-zone methodology was attempted. However due to the rectangularization process, it was found that the model lost accuracy with regard to either wall surface area or total building height. This is illustrated in Figure 5.4. In addition to this loss of accuracy, subsequent issues related to the insertion of windows and doors arose due to lack of available surface area. The insertion of windows and doors on each side of a zone is discussed in section 5.5.1.

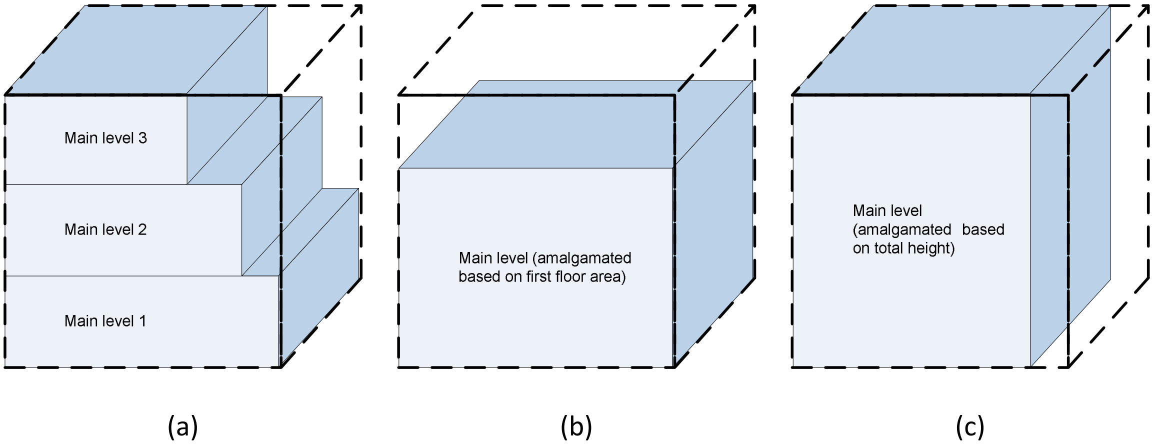


Figure 5.6 Main zone amalgamation consideration for (a) multi-level, (b) amalgamated to maintain floor area, and (c) amalgamated to maintain height

Because of the amalgamation issues, the main levels were created as distinct thermal zones (see Figure 5.4b) with lightweight connection flooring. Where floor/ceiling areas differed, an exposed floor or ceiling construction type was imposed on the affected area.

The CSDDRD includes indicators of the approximate portion of flat or sloped ceiling types. It was found that in many houses both ceiling types existed. Although a partially sloped ceiling could be created as shown in Figure 5.7, this added significant geometry complexity and was thus disregarded. This has a minor effect on ceiling area (often well insulated) and zone volume, and thus insignificant impact on whole building energy performance simulation.

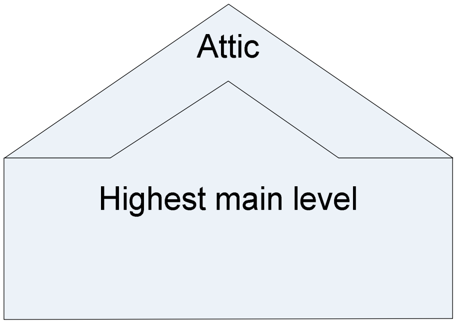


Figure 5.7 Geometry complexity for zones with sloped ceilings

5.4.4 Attic and Roof Space

Although undefined in the CSDDRD, the attic and roof space are critical elements to the housing model. This is because they create a thermal radiation break between the sky and the highest main level. During periods of sunshine, the roofing material absorbs radiation and transfers some of the heat through to the attic or roof zone airpoint. Although the attic and roof space air gets warm during this period, much of the heat is exhausted via natural air exchange through ventilation openings. In effect this provides an additional insulating barrier between the main level ceiling and ambient conditions. At night it works in much the same insulating manner, with the roofing material radiating to the open sky and natural air flow providing much of that heat.

The CSDDRD provides ceiling type information that was used to select either a roof space or attic. An attic was assumed if any sloped ceiling exists. A roof space was assumed unless a flat ceiling was defined as a gable or hip type. A roof space is considered to be a flat air space of thickness 0.3 m. An attic was considered to be either a hip or gable type with a sloped side. Unfortunately, roof slope information is not included in the CSDDRD. The roof slope was assumed to have a rise:run relationship of 5:12, at common value of CHS. The roof types are illustrated in Figure 5.8.

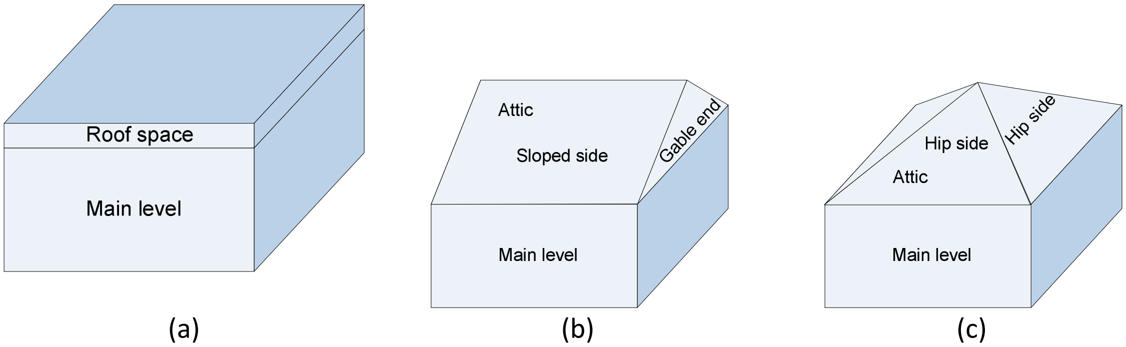


Figure 5.8 **Roof space or attic configurations (a) flat roof space, (b) gable type attic, and (c) hip type attic**

The CSDDRD contains both single-detached (SD) and double/row (DR) house types. The DR type houses present a special case for attic selection, as shown in Figure 5.9. Left and right end houses can have either a hip or gable type attic. The side facing another house must be gable type (see right end house connection to middle house of Figure 5.9). Gable ends that face another house are considered adiabatic, as is the remainder of the facing walls. Adiabatic interfaces are discussed in section 5.5.2.

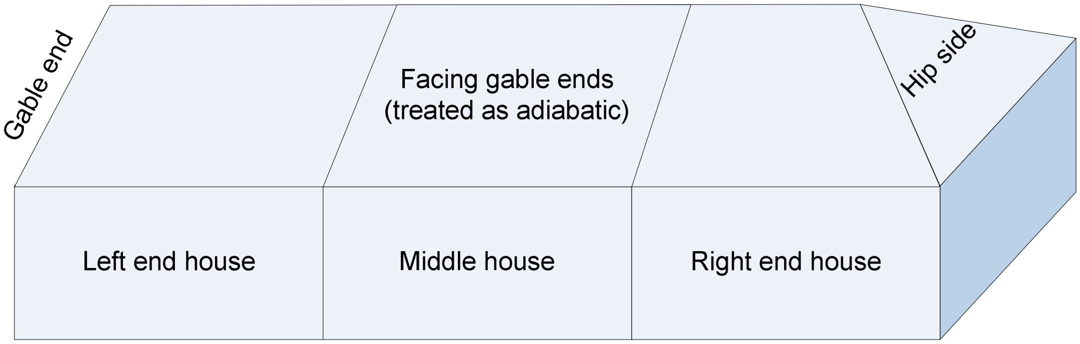


Figure 5.9 **Special treatment of DR type houses with gable and hip type attics**

Attic ridgeline direction is a key piece of information missing from the CSDDRD for gable type attics. Gable type attics are the most common type of zone located above the main levels. As it is intended for the CHREM to be used to examine solar technologies, the ridgeline direction is critical in determining the applicability of solar panels. As most of the CHS is located at approximately 45 degrees latitude in the northern hemisphere, the practical application of solar panels on an attic requires a slope facing south (preferable), southwest, or southeast. This is the case for houses with a ridgeline running east-west. Unfortunately, this information was not specified in the database. The CHREM assumes that the ridgeline runs parallel with the longer of either the house width or side length. This is determined from the aspect ratio (width for $r \geq 1$ and otherwise side length), as shown in Figure 5.10.

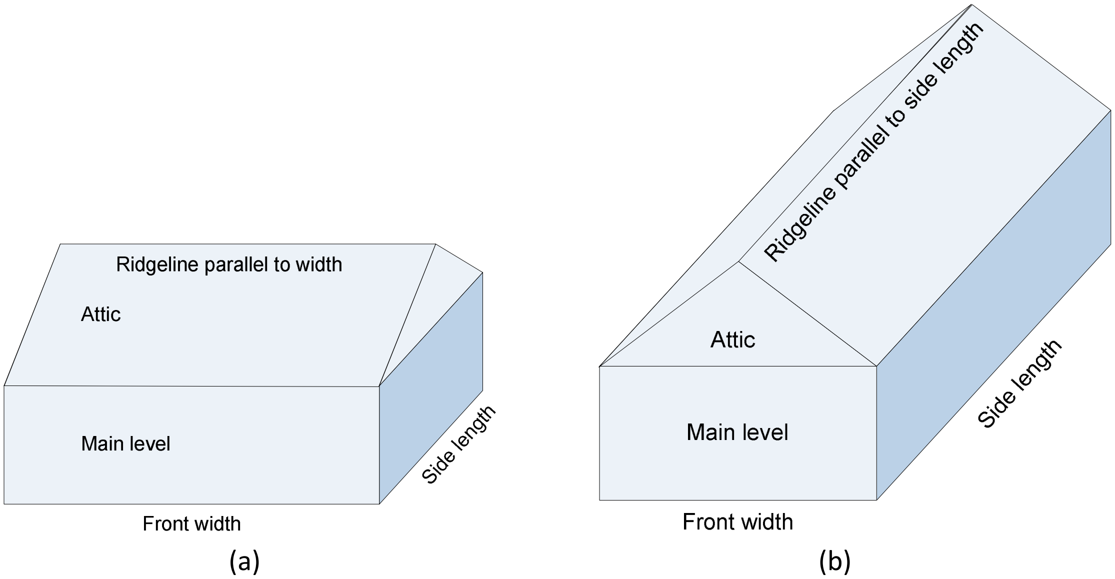


Figure 5.10 Determination of the ridgeline direction based on aspect ratio for (a) $r \geq 1$, and (b) $r < 1$

5.5 Description of Surfaces Enclosing a Zone

The zones described in section 5.4 are constructed from surfaces forming a thermal envelope. The surfaces must fully bound the zone and each surface must be defined for simulation purposes. This definition includes specifying the condition the surface faces, the surface construction of single or multiple material layers, and the optical properties of transparent surfaces. Providing such definition allows the ESP-r building simulator to calculate temperatures and the complex heat fluxes according to the energy conservation equations as discussed in sections 5.1.2 (energy conservation) and 5.1.3 (complex fluxes).

Due to rectangularization, each zone has a minimum six surfaces:

- *Floor*
- *Ceiling*. In the case of an attic this is represented by a thin (0.1 m) horizontal strip where the sloped sides meet.
- Four *sides* (front, right, back, left). In the case of an attic the sides may be vertical or sloped.

As shown in Figure 5.4b, the opportunity exists for main level zones to also have *exposed floor* and *exposed ceiling*. In addition, all houses have at least one door and one window. Windows and doors may be found on any of the main level zones, as well as the basement zone.

5.5.1 Window and Door Surfaces

Window and door information is defined in the CSDDRD. This includes widths, heights, number present, and in the case of windows, direction. An examination of the window and door information contained within the database showed that some error checking and manipulation was required to clarify erroneous data.

5.5.1.1 Window and Door Data Quality

In the case of doors it was found that certain houses had the width and height switched. This was identified by a width greater than 1.5 m and a height less than 1.5 m. In such cases the values were reversed. Door geometries were then checked for acceptable ranges of height (1.5 to 3.0 m) and width (0.5 to 2.5 m to account for French doors).

There are three separate door type listings, intended to be two types for the main levels, and a third type for a basement entry. Although most of the wall area of a basement is below grade, houses often have entry ways leading down to the basement. Alternatively, the basement may be a walkout type. The total number of doors for each type is listed in the CSDDRD. Only one door was created per surface, limiting the number of basement doors to four and the number of main level doors to four times the number of levels. If the door counts were larger than this limitation, the widths of the remaining doors were increased proportionally.

In the case of windows there is individual window information that includes: window type, total number of windows of that type, width, height, distance from eaves, and eave overhand width. A critical examination of this data indicated that the detailed height, width, and vertical/horizontal location data are largely unreliable, as determined by inappropriate values. However, data of amalgamated window areas and the facing direction, as well as window type was found to be valid.

5.5.1.2 Insertion of Doors within Surfaces

Doors were inserted into each available side of the main level and basement zones. To apply doors in the most appropriate locations, the CHREM implementation method begins at the lowest main level and proceeds upward, cycling over the ordered sides: front, right, back, and left. Most often the total number of main level doors was allocated to the first, or first and second levels. The insertion of basement doors followed a similar ordering structure as the main level, but preference was given to exposed walkout basement sides. For example, if two doors were specified for a back/left walkout basement, they would be inserted in the back and left side, as opposed to the front and right side. Although the DR house type has sides that face another dwelling, doors and windows were allowed to be inserted on these sides. This is because in reality the house is likely the have entry sections jogs due to non-rectangular floor plans.

The location of door insertion within a side was to the far right of the surface, with a margin of 0.1 m from the floor and right edge. In the event that a door came within the margin of 0.1 m from the ceiling, the door width was extended toward the surface center. An example of the door insertion is illustrated in Figure 5.11. There are two doors on main level 1 corresponding to the front and right sides. There is one door on the basement front side as this house has a walkout front/left basement.

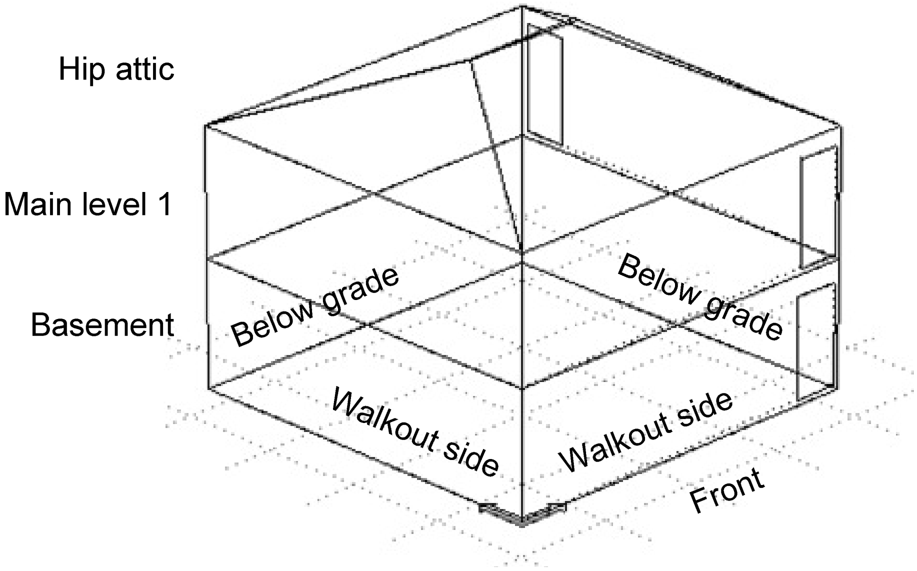


Figure 5.11 Door insertion results showing 0.1 m margin from the right, lower, and upper edge of surfaces

5.5.1.3 Insertion of Windows within Surfaces

Windows are treated differently than doors. Windows have both an aperture area (transparent) and a frame area (opaque). The window area listed in the CSDDRD corresponds to the "roughed-in" window area, inclusive of both area types. Mitchell et al. (2003) states that frame materials occupy between 10 and 30% of the roughed-in area, and that the frame creates "edge effects" that influence heat transfer in the outer area of the aperture. Purdy and Beausoleil-Morrison (2001) examined the effect of amalgamating windows and found it to have an insignificant impact on whole building energy performance simulation. The CHREM considers both of these window related aspects. As the aperture area takes on the "center-of-glass" properties, the aperture was considered to occupy 75% of the roughed-in area. Although in reality the frame surrounds the aperture area, the frame area was placed to the right-hand-side of the aperture area for modeling purposes. An illustration of window of the CHREM window representation is shown in Figure 5.12. This amalgamation of frame and aperture areas will have negligible impact on the energy simulation results as the heat transfer is one dimensional within the wall, door, and window.

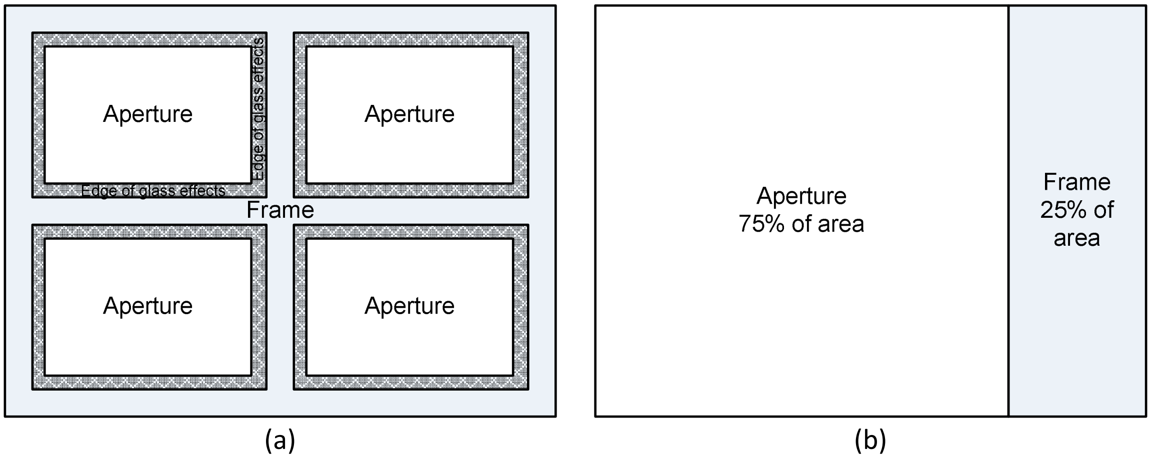


Figure 5.12 Window aperture and frame relationships for (a) the realistic layout showing the aperture, frame, and "edge of glass effects", and (b) the CHREM modeling representation

Windows may be applied to walkout basement sides, but are not applicable to below grade basement sides. Because window area information is only specified per side, the area is proportionally divided among appropriate side levels corresponding to their available area. Thus, where defined, a proportion of the amalgamated window is placed on each surface. As with doors, the CHREM method of inserting windows has a margin between surface edges (including door edges) of 0.1 m. The available window area per side is determined from the remaining side area after the doors have been inserted.

The aspect ratio of the window, including aperture and frame, was calculated to be similar to that of the wall it was being inserted within. In the case that the window would no longer fit due to a door, the window aspect ratio was adjusted within the margin limits. The window insertion results are illustrated in Figure 5.13 (this may be compared to Figure 5.11 which shows the same house prior to window insertion). It is evident that the window areas are different for each side of the house, and that they are proportioned in the case where the basement has a walkout side. Note that no windows are present on the below grade sides of the basement. The aperture area and frame area can be clearly distinguished with their 75% and 25%, area contributions, respectively.

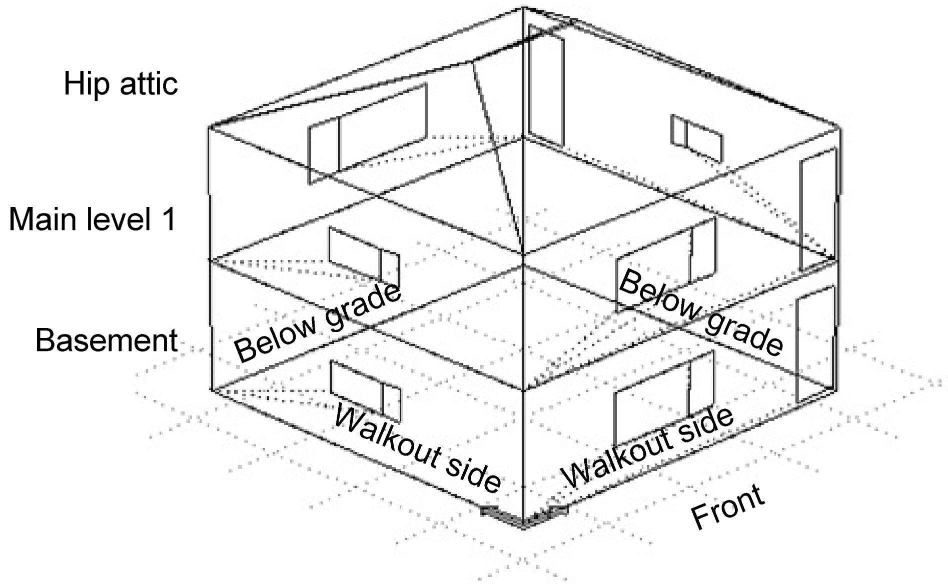


Figure 5.13 Window insertion results showing the aperture area (left-hand-side) and the frame area (right-hand-side)

5.5.2 Outward Facing Surface Conditions

Each surface of each zone of a CHREM house has two faces with a direction with respect to the zone. The inward face is exposed to the zone interior conditions, typically the zone airpoint and other surface inward faces. The outward face is exposed to the conditions exterior the zone with respect to orientation. Typical outward face conditions include ambient, adiabatic, another zone, or below-grade. Note that the terms ‘exterior’ or ‘outside’ are not used because they are ambiguous and may be misinterpreted with the term ambient. The outward facing condition dramatically influences the heat flux through surfaces.

The most common outward facing condition is that of ambient. Surfaces exposed to ambient conditions have heat transfer modes of conduction/convection, solar radiation, and LW radiation exchange with the ground, other buildings, and the sky. The following surface types are all exposed to ambient conditions: above-grade-walls (including walkout basement walls), exposed floors and exposed ceilings, windows, doors, and attic or roof-space sides and ceiling.

The second most common outward facing condition is the interface between two adjoined zones. The zones effectively share the surface and thus transmit heat from one zone to the other via conduction/convection. The adjoined zone interface condition occurs between main level floors (except slab-on-grade) and ceilings, basement and crawl space ceilings, and the attic or roof-space floor.

The CSDDRD also has a significant proportion of houses of the DR type, which are connected on one or more sides to consecutive houses, as shown in Figure 5.9. The connected sides face into other thermal zones which are assumed to be of similar materials, size, and conditioning control strategies. For example two connected houses will likely have conditioned zone airpoint temperature setpoints of 21 °C. Thus no temperature gradient exists across the connecting surface, and the outward facing condition is considered to be adiabatic. This condition eliminates heat transfer from the surface to the outward facing condition, but does not inhibit the surface from acting as a thermal mass and transferring heat at the inward face. It should be noted that the adiabatic condition does not occur at either of the faces of a surface, but at the middle. To account for this, the CHREM gives special consideration to adiabatic surfaces, modeling only those layers up to the center of the surface. This gives appropriate consideration to the thermal mass effects of shared walls.

5.5.2.1 Foundation Surface Condition

Nearly all the houses of the CSDDRD have a foundation, the vast majority being full basements. The only exceptions are houses with floors exposed entirely too ambient conditions, such as open type crawl-spaces as discussed in section 5.4.2. Note that a slab-on-grade is a type of foundation. Foundation heat transfer requires special consideration as it may have both above and below grade components, and is in contact with soil. Unlike exposure to ambient air, soil has significant thermal mass, and has a temperature gradient caused by its immobility and thermal connections to both air (fluctuating temperature) and deep ground (static temperature).

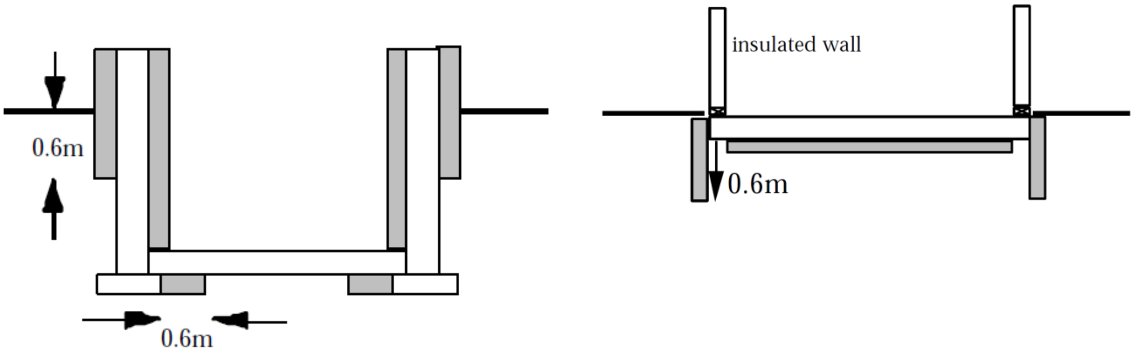
There exists an energy modeling method specifically for foundations titled BASESIMP (*simp*lified *base*ment model), which was developed by Beausoleil-Morrison and Mitalas (1997). Support for this method has been included in ESP-r. The BASESIMP model relies on a description of the foundations insulating properties, above/below grade surface areas, soil conductivity, and water table level information. Additionally, the BASESIMP model takes advantage of the Moore (1986) model to determine soil temperature based on ambient air conditions. The Moore model estimates the seasonally fluctuating (sinusoidal) soil temperature by offsetting and lagging from the seasonal ambient air temperature fluctuation.

The BASESIMP algorithm estimates total foundation heat flux, including both above and below grade components. The estimation process relies on a weighted foundation zone air temperature and a detailed set of heat transfer correlation coefficients that are specific to each foundation type and insulation placement. These coefficients were developed using finite element based simulations. The estimated heat flux calculated in ESP-r is imposed as radiation at the outward face between the surface and soil. Conduction and convection at the surface outward face are set to zero.

A specific foundation description is supplied to the BASESIMP model to allow it to estimate heat loss for different foundation types such as basements, crawl spaces, and slab-on-grade. The foundation description information includes:

- Foundation type (e.g. concrete or wood basement walls and slab, concrete slab-on-grade)
- Interior wall insulation placement (e.g. none, full, partial)
- Exterior wall insulation placement (e.g. none, full, below grade)
- Slab insulation placement (e.g. top, bottom, full, perimeter)
- Additional insulation such as thermal edge breaks and slab skirts

Figure 5.14 shows example foundation descriptions to illustrate both the variety and the terminology of BASESIMP modeling.



(a) (b)

Figure 5.14 Example BASESIMP foundation descriptions for (a) basement with full wall interior, partial wall exterior, and bottom slab perimeter insulation, and (b) slab on grade full bottom slab and skirt insulation (NRCan 1999)

Based on variations of the above information parameters, the BASESIMP model contains 145 unique foundation descriptions, complete with correlation coefficients. (Beausoleil-Morrison and Mitalas 1997, Beausoleil-Morrison 1999). The CSDDRD contains complete description information for each foundation type. This information was used to select a specific BASESIMP foundation description for each house of the CSDDRD. An examination of the database showed that 45 unique descriptions exist in the CSDDRD. A selection of these unique descriptions is listed in Table 5.2. A complete list of all BASESIMP configurations used by the CHREM is provided in Appendix B.

Table 5.2 BASESIMP foundation types used in the CHREM

			Insulation placement			
BASESIMP number	BASESIMP label	Foundation type	Wall	Slab	Edge break	Skirt
1	BCIN_1	Basement - concrete	Interior full			
2	BCIN_2	Basement - concrete	Interior partial			
8	BCEN_4	Basement - concrete	Exterior below grade			
10	BCNN_2	Basement - concrete				
12	BCCN_2	Basement - concrete	Overlapped Exterior and Interior			
14	BWIN_1	Basement - wood	Interior full			
18	BWEN_2	Basement - wood	Exterior below grade			
19	BCIB_1	Basement - concrete	Interior full	Bottom full		
64	SCA_21	Crawl space or slab on grade		Top full	Exists	Exists

The BASESIMP model estimates a total foundation heat flux. This flux must be apportioned to surfaces which face below grade conditions. In the case of crawl space and slab-on-grade foundations, 100% of the estimate was attributed to the slab. The walls of the crawl space and main level zones maintain their exposure to ambient air conditions. In the case of basements, the heat flux was apportioned to the walls and slab by surface area. The proportions were not modified based on insulation placement as this would significantly increase the level of complexity and have an insignificant impact on energy consumption results. This is because the total foundation flux to the zone is fixed to the BASESIMP estimate. In the case of walkout basements, the flux was only apportioned to below grade sides (again by surface area), resulting in a total foundation flux less than the BASESIMP estimate for all sides. The remaining walkout side outer faces are exposed to ambient air conditions.

5.5.3 Multilayer Surface Descriptions

The CSDDRD contains detailed information for each surface type including a construction code with individual digits representing each material layer, and in most cases an effective thermal resistivity value in units of RSI ($\frac{m^2K}{W}$). An example construction code (12113C1220) for a typical main wall is shown in Table 5.3 with a description of each layer.

Table 5.3 Example ten digit main wall construction code from the CSDDRD database (ten digit code 12113C1220)

Digit	Value	Field	Description
1	1	Surface	Main level wall
2	2	Construction type	Wood framing
3	1	Frame structure	38 x 140 mm (2 x 6 in.)
4	1	Frame spacing	400 mm (16 in.)
5	3	Cavity insulation	Fiberglass batt 140 mm (5.5 in.)
6	C	Sheathing insulation	Expanded polystyrene 25 mm (1 in.)
7	1	Interior	Gypsum board 12 mm (1/2 in.)
8	2	Sheathing	Oriented strand board 11.1 mm (7/16 in.)
9	2	Siding	Hollow vinyl cladding
10	0	Corner studs	0–2 studs

In most cases both information types are available. The thermal resistivity value allowed the house energy auditor to account for construction differences which they were not able to represent in the code. Furthermore, for energy audits where the construction code was entered directly into the HOT2XP, the program estimated the thermal resistivity value inclusive of the impact of thermal bridging caused by the framing materials. Therefore, in instances where a construction code and thermal resistivity value are available, the code is used to generate the multilayer surface, and the thermal resistivity value is used to adjust the insulation for best representation. If no construction code was available, a representative multilayer surface is selected and the insulation layer was again used to adjust for the best thermal resistance representation. The following subsections describe the materials and the multilayer surface definitions for opaque and transparent types.

5.5.3.1 Materials Database

A materials database system was developed in the extended markup language format (XML). The database supplies material properties for describing each layer of a multilayer surface. The database includes a variety of materials common in the CHS. Material properties were determined from texts related to building materials (Incropera et al. 2007, ASHRAE 2005, McQuiston et al. 2005). A representative group of materials is shown in Table 5.4.

Table 5.4 CHREM materials database

Class	Material	Therm. conductivity (W/mK)	Density (kg/m^3)	Spec. heat (J/kgK)	Default thickness (mm)
Masonry	Brick	0.72	1920	835	100
	Concrete	0.38	1200	653	200
	Stone	2.79	2630	775	100
Wood	Med. density fibreboard (MDF)	0.17	750	2000	15
	Oriented strand chipboard (OSB)	0.15	800	2093	15
	Plywood	0.15	800	2093	15
	Spruce pine fir (SPF)	0.13	630	2760	40
Insulation	Cellulose	0.04	60	1210	25
	Expanded polystyrene	0.03	55	1210	25
	Fiberglass batt	0.04	16	835	100
	Icynene	0.04	55	1210	25
	Mineral fibre	0.05	300	1000	100
	Newspaper	0.18	300	1000	25
	Polyurethane foam	0.03	70	1045	25
	Straw	0.07	240	180	25
	Vermiculite	0.07	60	1210	25
	Wood shavings	0.09	350	1590	25
Interior	Gypsum	0.17	800	1090	12
Roofing	Asphalt Shingles	0.06	2115	920	6
Metal	Aluminum	168.00	2790	883	1
	Steel	60.00	7854	434	1
Door/window	Fiberglass solid	0.60	1800	835	3
	Vinyl	0.16	1380	1000	3
Glass	Glass	1.05	2500	750	3

5.5.3.2 Opaque Multilayer Surface Definition

The opaque multilayer surface definitions vary considerably by zone type and surface type. A complete mapping of construction codes was developed for the CHREM to support these different surface types. When a code is encountered, it is passed to an appropriate subroutine that separates the digits and keys them to the appropriate map. From this map, the material is selected for each layer, along with a specified thickness.

The ten digit code structure shown in Table 5.3 is appropriate for surfaces such as main walls, exposed ceilings and floors, and pony walls. An example layout of a wall was shown in Figure 5.1 on page 117. A five digit code structure was used to define insulated foundation floors (see Table 5.5), and a six digit code was used for foundation walls (see Table 5.6).

Table 5.5 Example five digit foundation floor code from the CSDDRD database (five digit code 83367)

Digit	Value	Field	Description
1	8	Frame structure	Steel 40 x 92 mm (1.5 x 3.6 in.)
2	3	Frame spacing	600 mm (24 in.)
3	3	Cavity insulation	Fiberglass batt 140 mm (5.5 in.)
4	6	Interior	Wood
5	7	Sheathing	Plywood 18.5 mm (3/4 in.)

Table 5.6 Example six digit foundation wall code from the CSDDRD database (six digit code 311AD9)

Digit	Value	Field	Description
1	3	Frame structure	Wood 38 x 140 mm (2 x 6 in.)
2	1	Frame spacing	400 mm (16 in.)
3	1	Corner studs	1–3 studs
4	A	Cavity insulation	Blown cellulose
5	D	Sheathing insulation	Isocyanurate
6	9	Interior	Lath and plaster

Under certain conditions, an opaque construction code was not included in the CSDDRD. This may have been due to the code options not best representing a surface construction. In such cases the house energy auditor could simply enter the effective surface thermal resistance. To account for such cases, a database of typical surface types found in the CHS was created for the CHREM. An example of these default database entries is shown in Table 5.7. Note the “Main levels - Wall (shared)” surface which has an adiabatic condition located at the center of the shared wall, and as such has only half the insulation thickness and no drywall layer on the outside.

Table 5.7 Examples of the CHREM opaque database entries for the CHS

		Layers from outside to inside	
Zone or group	Surface type	Material	Thickness (mm)
Basement	Floor (slab)	Concrete	76
	Wall	Concrete	203
Crawl space	Floor (slab)	Concrete	76
	Wall	Vinyl	3
		OSB	15
		Fiberglass batt	140
		Drywall	12
Main levels	Floor (un-insulated to basement)	Plywood	40
	Floor (insulated to crawl space)	Fiberglass batt	140
		Plywood	40
	Floor (slab)	Concrete	76
	Floor (exposed)	Plywood	15
		Fiberglass batt	300
		Plywood	30
	Ceiling (to another main level)	Plywood	40
	Ceiling (to attic or roof space)	Fiberglass batt	300
		Drywall	16
	Ceiling (exposed)	Asphalt shingle	5
		Plywood	15
		Fiberglass batt	300
		Drywall	16
	Wall	Vinyl	3
		OSB	15
		Fiberglass batt	140
		Drywall	12
	Wall (shared)	Fiberglass batt	70
		Drywall	12
Attic or roof space	Slope	Asphalt shingle	5
		Plywood	15
	Gable	Vinyl	3
		Plywood	15
Door	Metal insulated	Steel	3
		EPS	25
		Steel	3
Window frame	Vinyl	Vinyl	3
		Gap	20
		Vinyl	3

5.5.3.2.1 Adjustment of the Insulating Properties to Account for Thermal Bridging

Certain default database entries shown in Table 5.7 have no insulation layer, and as such have no layer to modify in an effort to match the specified thermal resistance. To account for these cases, a very thin insulating layer of EPS material was inserted prior to the interior layer.

After determining the specific materials for each layer of a surface, the total thermal resistance of the surface was compared to that specified by the CSDDRD. The comparison process examined the opaque construction and flagged all insulating layers. Priority for modification was placed on the cavity insulation followed by sheathing insulation. The insulation layer thermal conductivity was modified in an attempt to achieve a surface construction thermal resistance equivalent to that specified in the CSDDRD. Most modifications resulted in a difference of less than 0.01 RSI.

5.5.3.2.2 Adjustment of the Cavity Insulation Thermal Mass to Account for Framing Materials

The structure type of the opaque surface defined in the construction code required considerable detail as it dramatically affects the options. The following are the major structure types:

- *Solid* structures primarily consist of concrete or heavy lumber foundation walls. They are also used to describe insulated concrete forms, log houses, and stone walls.
- *Panel* structures are used in curtain walls where an insulating layer is located between thin metal sheets.
- *Framed* structures constitute the majority of construction types. Framed construction has a number of alternatives which allowed for different sizing and material use. These include:
    - Wood stud framing
    - Metal stud framing
    - Truss framing primarily intended for roofing rafters or open web floor joists.
    - Composite wood floor joists which are an effective “I-beam” created using sheet OSB and wood flanges.

In the case of framed construction, the structure consists of parallel material elements within the framing/cavity layer of the construction. This parallel condition is shown in Figure 5.15a on page 147. Structure type has an impact on building energy performance as it creates “thermal bridging” and increased thermal mass. The thermal bridging impacts have already been considered by adjusting the insulation thermal conductivity.

The modeling of the framing/cavity layer in "true form”, as shown in Figure 5.15a, is impractical for whole building simulation. This is because the represented wall must be divided into many surfaces, one for each change in the framing/cavity materials. Furthermore, two dimensional heat flux conditions exist, primarily at the sheathing-framing/cavity interface area and the interior-framing/cavity interface area.

There are two feasible alternatives to modeling the parallel materials (e.g. wood and fiberglass batt) in the framing/cavity layer. Figure 5.15b shows a representation where the cavity insulation and framing studs have been grouped. This method requires two parallel surface layers to represent the wall, one created with the cavity insulation in the layer and the other with framing stud in the layer. Figure 5.15c shows a representation where a single surface may be used, and the material properties of the layer under consideration account for both the cavity insulation and the framing studs. Although these create uniformity, the temperature difference and moisture condensation considerations at the level of individual framing members are beyond the scope of the CHREM.

The representation of the hybrid layer shown in Figure 5.15c was selected for the CHREM. This representation limits the number of surfaces and avoids issues related to the insertion of doors and windows. The hybrid layer effective material properties of density $\rho_{\mathrm{h,eff}}$ and specific heat $c_{\mathrm{h,eff}}$ were solved using an area weighting as shown in equation 5.2:

$$\rho_{\mathrm{h,eff}} c_{\mathrm{h,eff}} w_{\mathrm{s}} t_{\mathrm{i}} = \rho_{\mathrm{i}} c_{\mathrm{i}} (w_{\mathrm{s}} - w_{\mathrm{f}}) t_{\mathrm{i}} + \rho_{\mathrm{f}} c_{\mathrm{f}} w_{\mathrm{f}} t_{\mathrm{f}} \tag{5.2}$$

where i, f, and s refer to insulation, framing, and framing spacing, respectively; and w and t are the width (or framing spacing) and thickness, respectively. As density is solely dependent upon the area weighting, it was solved first by neglecting the specific heat terms of equation 5.2. The equation was then reapplied with the previously determined $\rho_{\mathrm{h,eff}}$ to solve the specific heat $c_{\mathrm{h,eff}}$. The hybrid layer thickness corresponds with that of the insulation so that it does not affect the previously modified thermal conductivity.

The CHREM maps the opaque construction codes of the CSDDRD to individual house model files suitable for the building energy simulator. The mapping process describes each layer, progressing from outside to inside, as per the databases.

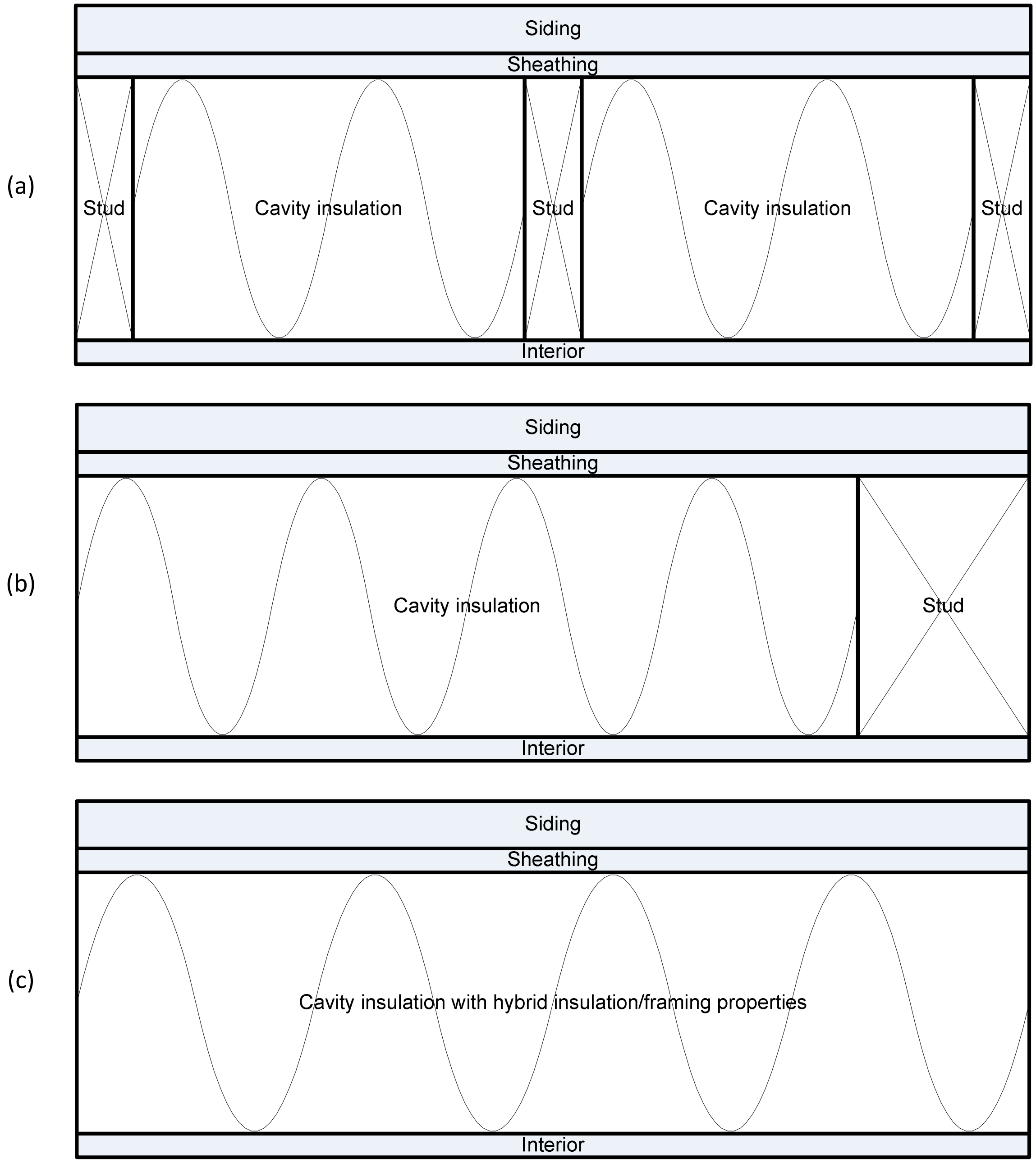


Figure 5.15 Alternative methods of accounting for parallel elements of cavity insulation and framing studs for (a) true representation, (b) grouped representations, and (c) hybrid material incorporating insulation and framing thermal properties

5.5.3.3 Window Construction Definition

Windows consist of a transparent aperture area and an opaque frame area. The description of transparent material layers is similar to opaque layers (i.e. thermal conductivity, density, and specific heat), but also requires an optical description. In addition, most recent windows installed in the CHS are either double-glazed (DG) or triple-glazed (TG), and these constructions must consider the gap between glazing layers which is often filled with dry air or an inert gas (e.g. argon).

As with other surfaces, the CSDDRD defines window multilayer surfaces using a construction code. It does not include an equivalent thermal resistance as the code is descriptive and covers the majority of variations found in the CHS. The six digit window construction code defines the type of window, the aperture properties, and the frame properties. The window construction code fields and examples of options are shown in Table 5.8.

Table 5.8 Six digit window code structure from the CSDDRD database

Digit	Value range	Field	Examples of options
1	1–A	Number of glazing layers	Single-glazed (SG), double-glazed (DG), triple-glazed (TG)
2	0–B	Coatings or tints	Clear, low-emissivity (0.04 to 0.35)
3	0–6	Gap spacing and fill gas	6, 9, or 13 mm; air, argon, krypton
4	0–2	Glazing seal	Metal, fused-glass, insulating
5	0–5	Window type	Picture, hinged, slider with sash, skylight
6	0–6	Frame material	Aluminum, wood, vinyl

The frame is an opaque construction, and as such was defined using digit 6 of the code. This definition followed as per section 5.5.3.2 (an example frame database entry was shown in Table 5.7). Six different frame constructions were defined to encompass the variety of frame materials.

Digits 1–3 of the window construction code strongly influence the thermal and optical properties of the transparent aperture area. Digits 4–6 influence the properties of the opaque window frame, but are dominated by digit 6 (frame material). Therefore, digits 1–3 and 6 were utilized by the CHREM to define the two constructions (aperture and frame) which constitute a window in the house model.

5.5.3.3.1 Window Heat Flux

The heat flux of a window aperture area is governed by CV, LW radiation, and SW radiation. Because of the high thermal conductivity of glass, CD through each glazing layer is relatively unimpeded, and as such it does not limit the overall heat flux. The major heat fluxes are shown in a simplified format in Figure 5.16 for a typical DG low-emissivity coated window of the CHS. Figure 5.16 generally represents the ESP-r method for handling transparent surfaces, with two exceptions:

- The LW radiation and CV in the gap of multi-glazed window are not modeled separately. Instead, an approximate, constant, equivalent thermal resistance is supplied.
- The low-emissivity coating is not handled as a separate layer. Instead, its absorption properties are applied to the inner glazing layer and its emissivity properties are applied to the gap equivalent thermal resistance.

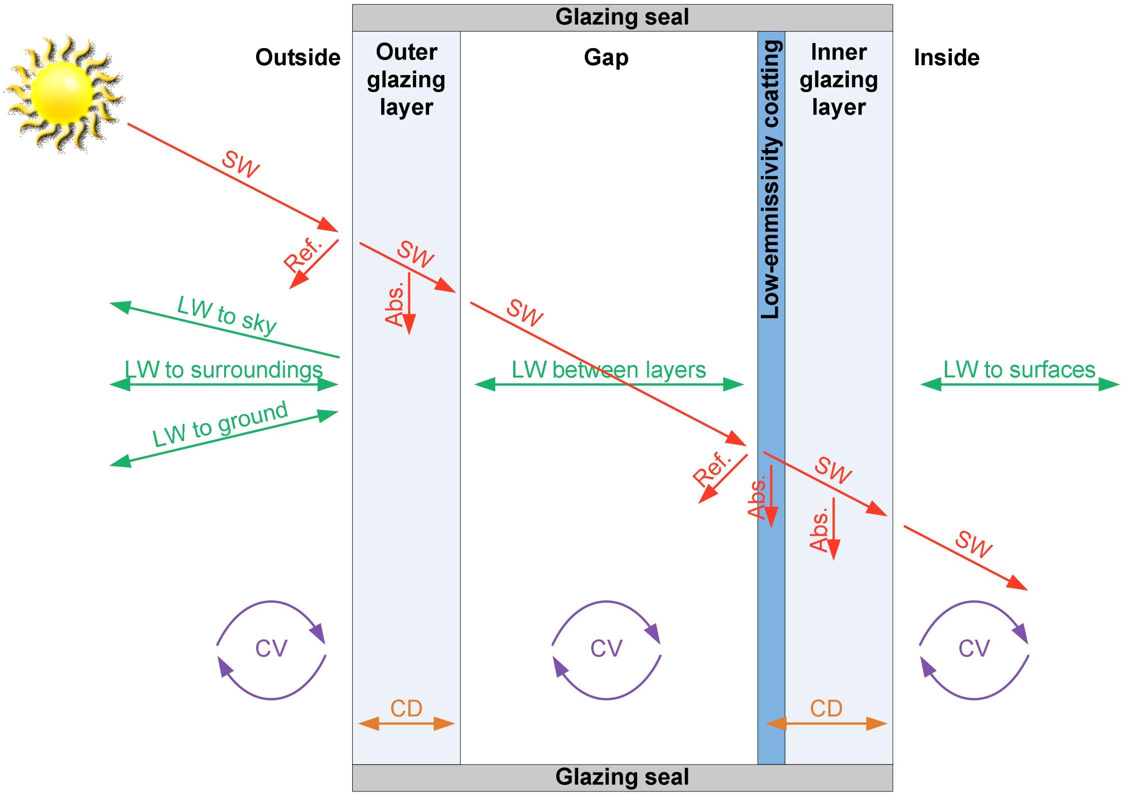


Figure 5.16 Simplified example showing the major heat fluxes across a DG low-emissivity window aperture (not shown to scale)

Although modeled as an equivalent thermal resistance, the CV which occurs in the gap is limited by width and fill gas (digit 3) as well as the number of gaps (a function of number of glazing layers, digit 1).

The glazing layers are opaque to LW radiation but each of the surface faces exchange LW radiation with their surroundings. Although modeled as an equivalent thermal resistance, LW radiation exchanges between glazing layers across the gap. A low-emissivity coating (digit 2) may be applied to the outside of the inner glazing layer to reduce this LW radiation exchange. This specific placement of the coating is for heating dominated climates such as Canada. The coating absorbs some SW radiation, and because it is located on the insulated side of the gap, the heat will tend to enter further into the thermal zone. For climates which primarily demand SC, the coating would be placed on the inside of the outer glazing layer. Coatings are placed within the glazing construct so as to avoid scratching and weathering.

SW radiation tends to pass through the aperture area and into the dwelling where it is primarily absorbed by the opaque surfaces. Some of the SW radiation may be reflected back out the window. In addition, each glazing layer and coating absorbs a small portion of the SW radiation. Thus, the amount of SW radiation that penetrates the aperture is affected by both the number of glazing layers (digit 1) and the coatings (digit 2).

5.5.3.3.2 Selection of a Window Type for each Side of a House

By considering the heat fluxes discussed above, it is apparent that digits 1–3 of the construction code affect the specific layering of the aperture construction, while only digits 1–2 affect the optical properties. This is because the gap spacing and fill gas are transparent to both LW and SW radiation.

The CSDDRD was examined to determine the variations of window construction codes present in the database. As previously described, the individual window information was unreliable with regard to geometric sizing, and window area was thus amalgamated per side. However, the number of windows and their corresponding construction codes were valid. House energy auditors had specified information for each window individually. This gave a unique characterization of the window types present on each house. Because each side of the house experiences different solar insolation, it is important to consider the dominant window type on each side of the house. For example, TG coated windows may be used on the north facing side of a house to reduce heat loss with negligible effect on admitted solar radiation. DG clear glass windows may be used on the south facing side to admit as much solar radiation as possible while maintaining a multi-glazed window.

The most prevalent window construction code, as weighted by window count (as individual window area was unreliable), was determined for each side of each house of the CSDDRD. In total, 25 unique window types are present. Because many window types are variations on the gap size and fill gas, there are only nine unique optical descriptions (digits 1–2).

5.5.3.3.3 Window Databases

Two new XML databases were created for the CHREM to describe window properties. The properties were determined using a window optical and thermal modeling program. The solar transmittance and absorptance values of each optical type were obtained from Window 5.2, a freely available computer application (LBNL 2001). Gap resistances which incorporate both the convection and LW radiation (a function of glass and coatings) were then calculated using Window 5.2 and the NFRC 100-2001 Winter environmental conditions. Window 5.2 conducts a nodal energy balance at steady-state conditions using a one-dimensional resistance network. Using iterative techniques, Window 5.2 converges to solution and uses the resultant fluxes to calculate desired quantities such as gap resistance.

The first database, shown in Table 5.9, describes the 25 unique window layouts. It should be noted that Table 5.9 follows numerical digit ordering, and as a result the most effective coating (Low-E of 0.04) comes prior to less effective coatings (e.g. Low-E of 0.2). Table 5.9 shows the gap resistance increases as a function of: increasing gap size, the replacement of air with argon gas, and the application of coatings with lower emissivity values. In TG windows, the coating is placed on the outside of the innermost layer, leading to an inner gap resistance larger than the outer gap.

Table 5.9 CHREM window database with twenty five unique window layouts

Digits 1–3	Glazing layers	Coating	Fill gas	Gap size (mm)	Inside gap resistance (RSI)	Outside gap resistance (RSI)
100	SG	Clear				
200	DG	Clear	Air	13	0.19	
201	DG	Clear	Air	9	0.17	
202	DG	Clear	Air	6	0.14	
203	DG	Clear	Argon	13	0.21	
210	DG	Low-E 0.04	Air	13	0.41	
213	DG	Low-E 0.04	Argon	13	0.54	
220	DG	Low-E 0.10	Air	13	0.38	
223	DG	Low-E 0.10	Argon	13	0.48	
224	DG	Low-E 0.10	Argon	9	0.43	
230	DG	Low-E 0.20	Air	13	0.33	
231	DG	Low-E 0.20	Air	9	0.28	
233	DG	Low-E 0.20	Argon	13	0.40	
234	DG	Low-E 0.20	Argon	9	0.37	
240	DG	Low-E 0.40	Air	13	0.26	
243	DG	Low-E 0.40	Argon	13	0.31	
244	DG	Low-E 0.40	Argon	9	0.29	
300	TG	Clear	Air	13	0.18	0.20
301	TG	Clear	Air	9	0.16	0.18
320	TG	Low-E 0.10	Air	13	0.40	0.21
323	TG	Low-E 0.10	Argon	13	0.52	0.24
330	TG	Low-E 0.20	Air	13	0.34	0.21
331	TG	Low-E 0.20	Air	9	0.27	0.18
333	TG	Low-E 0.20	Argon	13	0.42	0.24
334	TG	Low-E 0.20	Argon	9	0.36	0.21

The second database, as shown in Table 5.10, describes the eleven unique optical descriptions. It should be noted that the digits of Table 5.10 correspond to the first two digits of Table 5.9.

Table 5.10 CHREM window database with nine unique window optical descriptions

		Angle of incidence (from normal)				
Digits 1–2	Solar transmission and absorption*	0	40	55	70	80
10	Transmission	0.837	0.821	0.776	0.639	0.390
	Absorption	0.088	0.097	0.103	0.108	0.105
20	Transmission	0.705	0.678	0.612	0.436	0.204
	Outside absorption	0.094	0.103	0.113	0.127	0.133
	Inside absorption	0.074	0.080	0.081	0.074	0.055
21	Transmission	0.387	0.366	0.326	0.226	0.107
	Outside absorption	0.116	0.127	0.136	0.145	0.144
	Inside absorption	0.155	0.165	0.166	0.159	0.104
22	Transmission	0.536	0.506	0.448	0.305	0.141
	Outside absorption	0.104	0.115	0.124	0.134	0.136
	Inside absorption	0.128	0.144	0.150	0.155	0.104
23	Transmission	0.624	0.602	0.545	0.385	0.186
	Outside absorption	0.095	0.105	0.115	0.129	0.135
	Inside absorption	0.135	0.137	0.130	0.109	0.064
24	Transmission	0.632	0.606	0.545	0.388	0.178
	Outside absorption	0.095	0.105	0.115	0.128	0.133
	Inside absorption	0.126	0.134	0.134	0.118	0.083
30	Transmission	0.595	0.563	0.487	0.307	0.114
	Outside absorption	0.098	0.108	0.119	0.136	0.142
	Middle absorption	0.079	0.086	0.090	0.089	0.075
	Inside absorption	0.063	0.066	0.065	0.052	0.031
32	Transmission	0.456	0.423	0.360	0.215	0.077
	Outside absorption	0.105	0.116	0.126	0.139	0.142
	Middle absorption	0.089	0.096	0.100	0.095	0.077
	Inside absorption	0.109	0.120	0.121	0.110	0.059
33	Transmission	0.528	0.500	0.435	0.272	0.105
	Outside absorption	0.099	0.109	0.121	0.136	0.142
	Middle absorption	0.081	0.088	0.092	0.091	0.076
	Inside absorption	0.114	0.114	0.103	0.077	0.036

* Transmission is total solar transmission through the multilayer construction. Solar absorption is listed per glazing layer (outside, middle, inside)

A comparison of the solar transmission and absorption values of Table 5.10 is shown in Figure 5.17, where the optical digits were rearranged from numerical format to thermal representativeness. It can be seen that increasing the glazing layers or adding coatings reduces the overall aperture transmittance. For clear glass DG or TG windows, the outer glazing has a higher absorptance because of the reflected SW radiation of the inner glazing layers (as shown in Figure 5.16). This is not the case for coated windows as the coating absorptance is attributed to the innermost glazing layer.

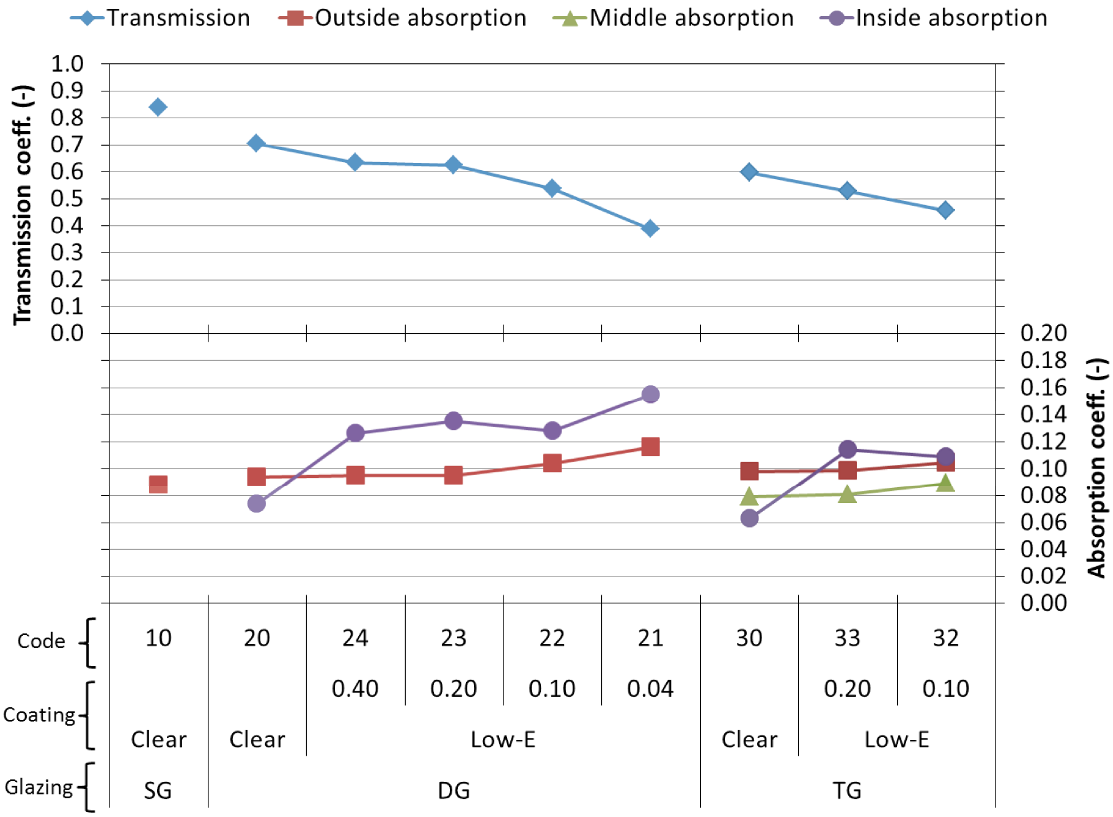


Figure 5.17 Relationship of solar transmission and glazing solar absorption for different optical database entries for zero incidence angle

5.5.3.3.4 Mapping of Window Layers using the Database

The CHREM mapped the window construction codes of the CSDDRD to house model files suitable for the building energy simulator. Both the transparent aperture and the opaque frame were described layer by layer, progressing from outside to inside, as per the databases. In addition, the transparent aperture surface description of the house model was linked to an optics house file, where the optical characteristics were independently provided for the most popular window type of each house side.

5.6 Heat Advection

Although the thermal envelope prescribed for each zone is the primary driver of space heating and cooling, the exchange of air between the zone and ambient conditions can result in significant heat advection (HA). This air mass transport is continuously occurring across the building envelope in the form of intentional exchange for air quality purposes, and unintentional exchange through gaps and cracks in the envelope.

Airflow occurs due to a pressure difference which may be caused either naturally or forcefully. Natural air exchange occurs due to pressure differentials caused by wind and the buoyancy of air at different temperatures (stack effect). Forced exchange is that due to active equipment such as fans.

An important distinction for HA is the source of the airflow. Zone-ambient HA may be caused by mechanical ventilation systems, gap and cracks, or open windows. It may be natural or forced flow. But air also flows between conditioned zones. Examples of such zone-zone HA include circulation fans on SH or SC systems, or open stairwells. Quite often, zone-zone airflow does not result in HA as the conditioned zones can be controlled to similar setpoints (e.g. temperature of 21 °C). However, under certain conditions, such as intense sun, or when the heating/cooling system is at maximum capacity, the opportunity exists for there to be zone-zone heat advection. Both types of airflow were shown as potential sources of HA in Figure 5.2 on page 119.

To account for this variety of airflows, the CHREM utilizes three unique airflow descriptions within ESP-r. They are:

- A *mechanical ventilation* description is used to account for active zone-ambient air exchange through a variety of different fan type systems. Central ventilation systems, heat recovery ventilators, and basic exhaust fans such as those in washrooms and above kitchen stoves, are all forms of mechanical ventilation.
- *AIM-2*, the Alberta Infiltration Model, is used to model natural zone-ambient air exchange through gaps, cracks, and flues. This exchange is due to pressure differentials induced by wind and stack-buoyancy effect.
- An *air flow network* modeling description is used to account for forced zone-zone airflow, and natural zone-ambient airflow through large openings such as windows or attic vents.

Each of these airflow descriptions affects the equivalent thermal conductance used by ESP-r to model heat advection. The airflow models are discussed in the following subsections.

5.6.1 Mechanical Zone-ambient Ventilation

Many of the houses of the CHS are equipped with active mechanical ventilation systems. These systems exchange air between the zones and ambient conditions for air quality purposes (e.g. the rejection of stale air or pollutants) and humidity control. A simplified model exists in ESP-r to handle these fixed flow devices. Three typical systems are available and may be used in combination:

- A central ventilation system (CVS) is an air exchanger unit intended to operate continuously. It draws ambient air directly into the dwelling and supplies it at distributed registers. The system is typically balanced such that the supply mass flow rate is equivalent to return rate (exhausted outdoors). If it is unbalanced, air leaks through the building envelope gaps and cracks. The CVS model within ESP-r produces an effective thermal conductance value, the product of the air mass flow rate and specific heat. This value is added with other zone-ambient airflow values for the heat advection calculation.
- A heat recovery ventilator (HRV) is similar to a CVS, with the addition of a heat exchanger that transfers heat from the return airflow to the supply airflow. HRV units typically have a sensible heat transfer effectiveness of 50 to 75%. This dramatically reduces the SH energy consumption required to support losses due to heat advection. The HRV model used by ESP-r is described by NRCan (2001b). The HRV model is used to calculate the heat transferred between incoming and outgoing flows, and uses this value to reduce the effective thermal conductance value that would be estimated based only on mass flow rate and specific heat. This reduced thermal conductance is then added with other zone-ambient airflow values for the heat advection calculation.
- Basic exhaust fans are often located in washrooms and kitchens, and provide direct exhaust vents. They are unbalanced and cause air inflow through cracks and gaps in the building envelope. Exhaust fans are treated like the CVS with respect to thermal conductance values.

The CSDDRD contains a description of the mechanical ventilation systems of each house. The data fields available from the CSDDRD include intake and exhaust flow rates, and HRV heat transfer effectiveness. Although the original EnerGuide for Houses Database included information on a CVS temperature controlled operation range, this data was not included in the CSDDRD. This would have only a minor effect on national results as CVS systems are present in only 427 of the 16,952 houses.

In the case of a CVS system, the larger of the intake and exhaust flow rates was used. This is because the makeup air always comes directly from ambient conditions. During input of HRV flow rates, the house auditor was forced to use balanced values. Exhaust fans only have exhaust flow rates because the makeup air comes directly from ambient conditions through gaps, cracks, and flues.

The mechanical ventilation system description for the building energy simulator has inputs for system electrical consumption to represent the fan energy use. This energy is considered to enter the airstream. As energy consumption of fans and pumps was already considered in the CHREM statistical method (described in section 4.3.2.1 on page 90), these values were set to zero.

The HRV system inputs for the building energy simulator require information on the ductwork and heat transfer effectiveness. As ductwork data was not included in the CSDDRD, representative information was provided based on NRCan (2001). Heat transfer effectiveness values for the heating season represent the transfer of sensible energy in the heat recovery core from the building side exhaust to the ambient side intake. These values range from 20% to 90% and are a function of temperature. HRV systems are present in 966 of the 16,952 houses of the CSDDRD. The relationship of HRV systems to region and vintage was given in Table 3.4 on page 79.

Data taken during winter of 2010 from the author's HRV unit is shown in Figure 5.18 to illustrate this heat transfer effectiveness. The exiting airstream at the building return (approx. 20 °C) is cooled to the ambient exhaust temperature (approx. 6 °C), providing heat to the incoming airstream at the ambient intake (approx. 2 °C) and raising it for the building supply (approx. 17 °C). The change in temperature of the supply flow is greater than the exhaust. This may be due multiple reasons (e.g. imbalanced flow, heat gain from fans), but is likely because of the latent heat transfer in the exhaust flow where moist warm air leaving the zone has water condense on and drain away from the heat exchanger. Regardless, it is apparent that the HRV is highly effective at transferring heat from the outgoing airstream to the incoming airstream. Figure 5.18 also shows heating system operational peaks where cross flow is occurring from the SH air distribution system to the mechanical ventilation system.

In all cases of mechanical ventilation systems the airflow is considered to be continuous throughout the year. This required a CHREM specific source code change to the ESP-r building energy simulator. The calculated total ventilation flow rate for the dwelling was distributed among the thermally conditioned zones (basement and main levels) in proportion to their volumes.

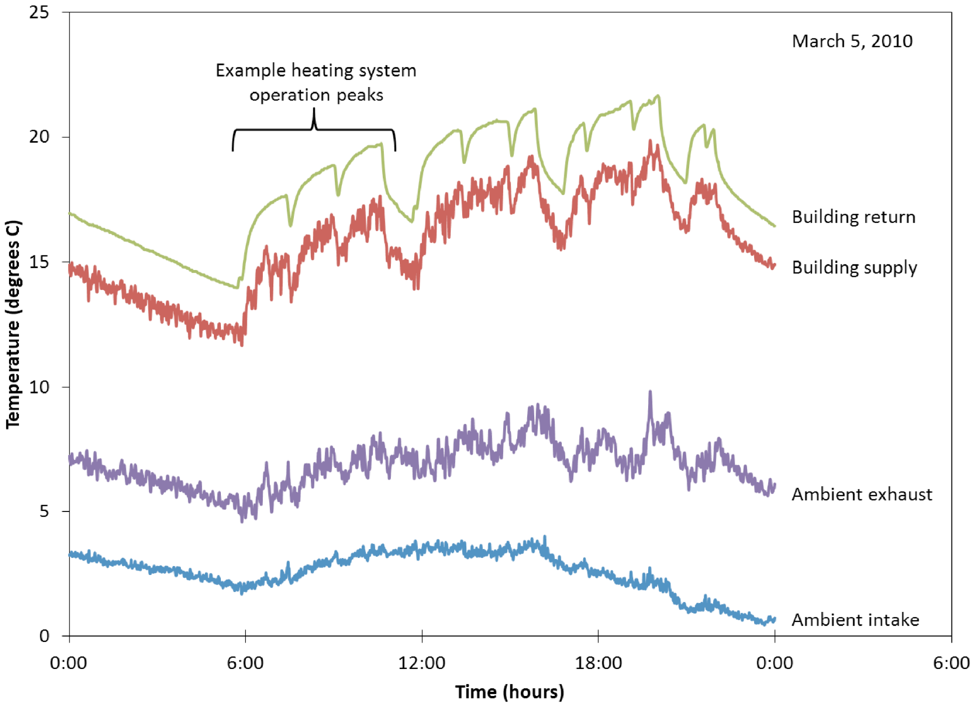


Figure 5.18 HRV temperature measurements across the heat exchanger core

5.6.2 Zone-ambient Airflow due to Gaps, Cracks, and Flues

Zone-ambient airflow occurs due to a pressure distribution across the zone surfaces that forces air through small openings such as gaps, cracks, and flues. Gaps and cracks are well distributed among zone surfaces, often near window and door edges. It would be unfeasible to identify each one and characterize its particular airflow characteristics. As an alternative, the house may be (de)pressurized using a fan, and a pressure-difference/flow-rate relationship established which is representative of the combined small gaps and cracks. Using such blower door information and a number of other easily obtained measurements, Walker and Wilson (1990, 1998) developed a model of zone-ambient airflow through small openings of the conditioned zones due to wind-induced and stack effect pressure differences. The name of this modeling method is the Alberta Air Infiltration Model, AIM-2. The AIM-2 method estimates the total zone-ambient airflow due to gaps, cracks, and flues located in all conditioned zones. Implementations of the AIM-2 functionality are described by Bradley (1993), Beausoleil-Morrison (2000), and Wang et al. (2009), and have been included with ESP-r.

The AIM-2 functionality within ESP-r relies on a house description that defines both the environmental and envelope characteristics. The major input requirements are shown in Table 5.11. As discussed in the next subsection, the CSDDRD includes this information and was used to generate appropriate building simulation files for each house.

Table 5.11 AIM-2 input information

Input	Description
Blower door test results	AC/h_{50}, ELA_4, and discharge coefficient
Leakage distribution	Ceiling, wall, and floor distribution
Locality description	Terrain and shielding characteristics
Eave height	Ceiling leakage height for stack effect
Flue diameters	Heating and DHW system
Zone indices	Zones for calculation and distribution of airflow
Window control	Setpoints for opening/closing windows

5.6.2.1 Provision and use of AIM-2 Input Data

The blower door test results available from the CSDDRD include air-changes per hour at 50 pascal pressure difference (AC/h_{50}), and effective leakage area (ELA) at either four or ten pascal pressure difference. These values are industry standardized indicators of house airtightness based upon the blower door test. These indicators provide a practical representation of the house airtightness (e.g. “changes air completely this many times per hour at full wind", or "essentially a hole this big in the house"). However, the pressure difference across the building envelope is continuously varying, and as such the relationship of flow rate to pressure difference is required for building simulation. The indicator values come from the blower door test data that measures the flow rate over a broad range of pressures. An example of blower door test data from the author's house is shown in Figure 5.19. Such data has shown good fit over an extended range with a power law profile. It is the power law leakage coefficient (C_F) and exponent (n) which are of interest for building simulation as they may be used to estimate the airflow at any pressure differential. Beausoleil-Morrison (2000b) describes the method used by ESP-r to convert the indicator values of AC/h_{50} and ELA to the power law coefficient and exponent. A discharge coefficient of 0.611 was used for this process.

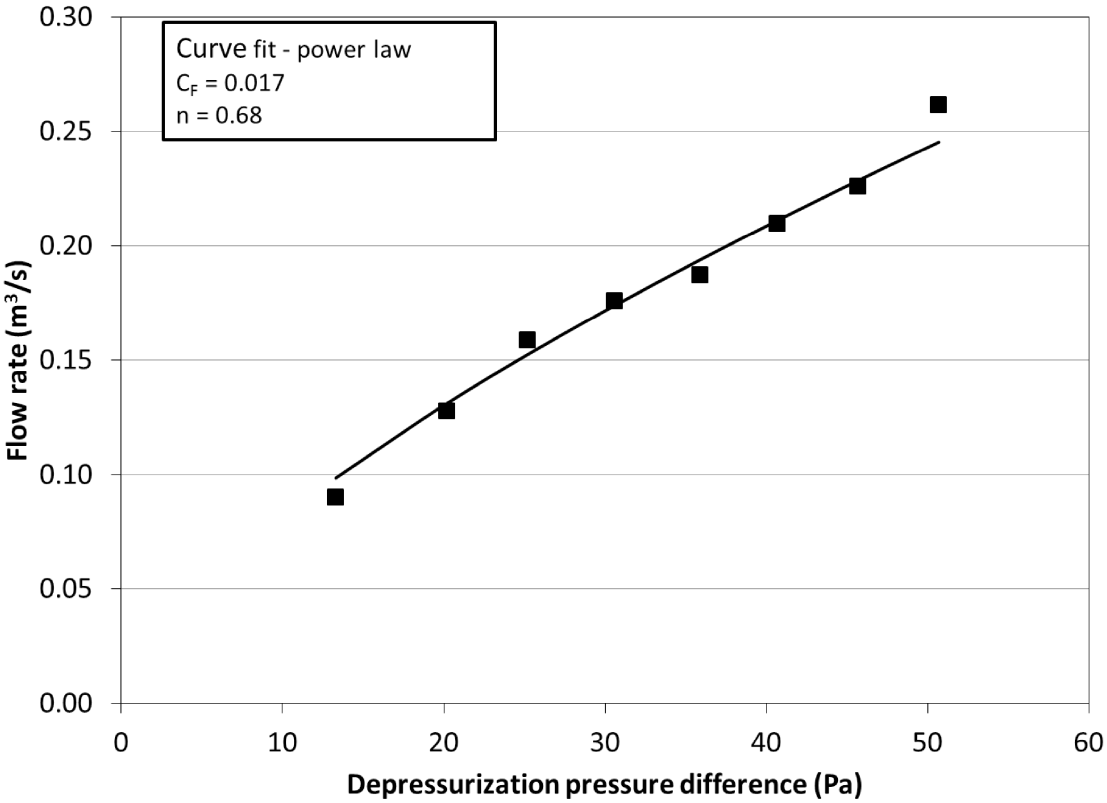


Figure 5.19 Blower door test results

The leakage distribution of the ceiling, walls, and floor are not defined in the CSDDRD. Values of 0.3, 0.5, and 0.2, respectively, were utilized as they are representative of detached dwellings.

The locality description contains both weather station and dwelling values. Environment Canada weather stations are typically located in open terrain with wind measurement occurring at a 10 m height (e.g. airport). The terrain at each house site was determined using the rural/urban indicator discussed in section 4.3.2.1 on page 90. The rural/urban indicator was mapped to terrain as shown in Table 5.12. In all cases, light local shielding was imposed upon building walls and flues. The values of terrain and shielding are used by ESP-r to modify the wind induced pressure distributions upon the building envelope. Terrain values modify the wind speed measurement to be representative of that near the house. Shielding values then inhibit a portion of the wind-induced pressure as calculated using the modified wind speed.

Table 5.12 Mapping of rural/urban indicators to terrain type

Rural/urban indicator	Terrain type	Roughness indicator
Rural	Parkland (combination of open and forested areas)	0.5
Suburban	Suburban (detached buildings with trees)	1.0
Urban	City center (high buildings and trees)	2.0

The house eave height is required for the calculation of airflow due to the stack buoyancy effect. The eave height of each house of the CSDDRD was determined by summing each main level wall height, along with any foundation height located above grade. Flue diameters of both the SH and DHW systems were determined based on the energy source. With the exception of electrically supplied systems, a SH flue of 127 mm and a DHW flue of 76 mm were prescribed for each house. The flue sizes were used for all systems, including furnaces, boilers, and stoves. ESP-r assumes that the flue is located 1.5 m above the eave. It is also cognizant of the flue restrictions for certain types of SH appliances (e.g. spark ignition furnace with a vent damper).

The AIM-2 model in the building simulator is provided a link to each of the conditioned zones of the house. It uses this information to determine the volume, and for distribution of calculated airflow proportionally by volume. Although the AIM-2 model has support for crawl-spaces and attic/roof-spaces, this functionality was not employed. Instead, an air flow network was used for these zones, as discussed in the subsequent section. Modifications specific to the CHREM were made to the ESP-r simulator to support the application of AIM-2 airflow to prescribed zones only.

5.6.2.2 AIM-2 Calculation of Zone-ambient Airflow

The AIM-2 method, as implemented in ESP-r, calculates the zone-ambient airflow due wind-induced and stack effect pressure variations at each timestep. The representative flow coefficient is calculated for the house, including the effect of any open (or partially closed) flues, and this is distributed across the envelope (floor, walls, ceiling). Both the wind and stack effect are considered from a flow coefficient perspective, and the pressure difference and airflow is calculated for each cause. These two values of total house-ambient airflow are then interacted as specified by Walker and Wilson (1990), to result in a single representative total house-ambient airflow. Finally, this total house-ambient airflow is apportioned to conditioned zones in relation to their volume.

5.6.2.3 Impact of Opening Windows on Crack and Gap Leakage

Support also exists in the AIM-2 model of the ESP-r building simulator to account for window openings. Used as a natural method of SC, the majority of windows in the CHS are operable. It is critical that windows be operable for houses that do not include a SC system. Otherwise, the thermal zones may overheat, achieving temperatures greater than 40 °C. Window opening functionality presently exists in the building simulator by ignoring the AIM-2 calculated airflow, and replacing it with values calculated by an air flow network. These values account for the large window openings instead of the small gaps and cracks.

Window functionality is highly dependent upon occupant behaviour. Because windows create large openings, the entire air mass of thermal zone can be replaced within the timestep period of the simulation. This can cause instability of the solution, and odd interactive behaviour between window openings and active SH and SC systems. For example, on a sunny day with an ambient temperature of 16 °C, the zone temperature can easily reach over 25 °C and the windows may be opened. If it is windy, the entire air mass may be replaced during the timestep, causing the zone temperature to decrease dramatically. This may activate the SH heating system. The zone may then close the window, return to the original temperature, and the process would be then be reinitiated. To avoid such a scenario, a conservative window opening regime was implemented.

If no SC system exists, the windows may be opened when the zone temperature is greater than the ambient temperature, and both temperatures are above the heating setpoint. If a SC system does exist, the preceding remains true, and the windows will close if the zone temperature rises above the cooling setpoint. A number of changes specific for the CHREM window control strategy were made to the ESP-r building simulator. All houses were allowed to use window control. Each thermally conditioned zone that has windows is allowed to evaluate the criteria independently. However, a check was used to verify that the zone was not undergoing active SH or SC as directed by another master zone.

5.6.3 Zone-ambient and Zone-coupled Airflow due to Large Openings

The preceding section considered the airflow through small openings such as gaps, cracks, and equipment flues. Due to their small size, these openings were amalgamated and considered as a total conditioned zones leakage description using the AIM-2 method. However, larger openings exist in the thermal envelope and due to directional dependence cannot be modeled by AIM-2 (e.g. windows in Figure 5.13 on page 136). Examples of these openings include open windows, stairwells and doorways between levels, and large vents in crawl-spaces, attics, and roof-spaces. Modeling of large openings requires individual consideration of the characteristics of each opening, such as size and direction, as well as linkages it provides (e.g. zone-ambient or zone-zone). The ESP-r simulator includes support for such air flow modeling, termed air flow networks (AFN). Hensen (1991) provides a comprehensive overview of the AFN method used by ESP-r.

The AFN is a mass-balance technique primarily concerned with the bulk airflows to and from thermal zones. It is not concerned with the detailed flow regime within a thermal zone, as might be modeled using computational fluid dynamics (Beausoleil-Morrison 2000c). As the AFN is focused on bulk airflows its description is relatively simple. An AFN is composed of the following:

- Air mass *nodes* have distinct pressures and temperatures. Examples are the external wind induced pressure nodes facing a wall and internal pressure nodes representing the zone airpoints.
- *Components* have a pressure/flow-rate relationship (likely non-linear) that permits airflow. Examples are an open window which restricts air flow and a fan which induces airflow.
- *Connections* exist between the nodes and a component, including consideration of height differences. Examples of connections include that from ambient to a window to a thermal zone, and a stairwell vertically connected to two main zone levels.

The ESP-r simulator functions by imposing conditions upon the AFN, such as wind induced pressure on external nodes, or fan flow rates. These conditions, and an estimate of remaining node pressures, result in a mass flow network, with flows travelling between nodes through components (pressure/flow-rate relationship) via connections. The simulator iteratively evaluates the flow rates and pressures in an effort to balance mass flow rate. It treats air as an incompressible fluid for the purposes of a house.

Figure 5.20 shows a simple AFN constructed with four nodes (wind induced and main levels), three components (windows and stairwells), and three linking connections. The simulator would iteratively solve the network such that the mass flow rates entering and leaving each main level node are equal, while accounting for the pressure difference across each component. The pressure drop across each component is different due to sizing (perhaps one window is not as far open) and pressure/flow relationship. Should the wind be removed from the example in Figure 5.20, and the conditioned zone temperatures greater than ambient, flow would continue in the direction shown due to stack effect caused by buoyancy.

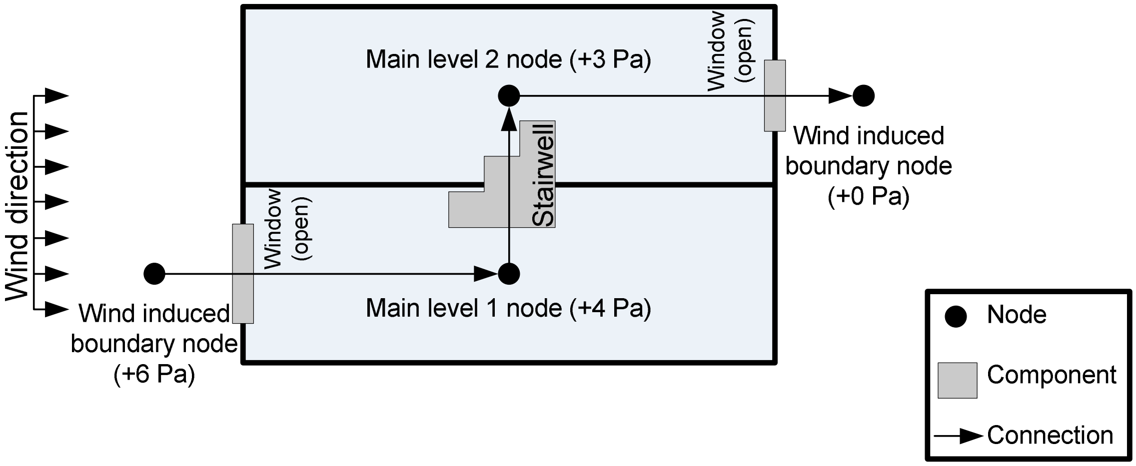


Figure 5.20 Simple AFN showing boundary nodes of increased (+) and decreased (-) pressure, internal main level nodes of unknown pressure, window and stairwell components, and connections (arrows) linking nodes through components for air flow

5.6.3.1 Attic, Roof-space, and Crawl-space Vents

The CHREM uses an AFN to describe both zone-ambient and zone-zone airflows. Crawl-spaces, attics, and roof-spaces are zones which are not intended to have airflow exchange with other zones, and are intentionally vented using large openings. The AFN is used throughout the entire course of the simulation to estimate the airflow through these vents.

Figure 5.21 illustrates the AFN as defined in the CHREM for the attic, roof-space, and crawl-space zones. It is apparent that none of these zones have an airflow connection to another zone. All three zone types have side vents of some type ("end", "gable", or "roof" vents). These vents are vertical and allow for wind induced airflow. The side vents of the attic and roof-space were uniformly set to 0.25 m^2, a typical value for prefabricated vents. The discharge coefficient of the opening is equal to 0.65. The side vent area of the crawl-space was set proportionally to the side area. "Ventilated" crawl-spaces were set to 5% of the side area, and "closed" crawl-spaces were set to 1% of the side area. The wind-induced nodes that form the boundary conditions outside the side vents use wind-speed/pressure coefficient relationships representative of a 2:1 aspect ratio (width:height) semi-exposed wall.

As attics and roof-spaces achieve high temperatures in the summertime, a natural venting structure was implemented to use stack effect. This system relies on horizontal eave vents which are located below the zone airpoint. Due to this height difference, air would flow in through the eave vents and out the side vents in a low-wind hot attic/roof-space situation. Eave venting area varies considerably with house vintage. Older houses typically have multiple 75 mm diameter openings, whereas newer housing may have a 0.25 m wide vent running the length of the attic. Because other factors such as roof type also influence the eave vents, they were uniformly set to 0.25 m^2 each. The crawl-space does not have such eave vents due to both the realities of foundation design and its naturally cool state (heat loss to the ground and lack of incident SW radiation). The wind-induced nodes that form the boundary conditions outside the eave vents, and the eave opening area, use the same coefficients as side vents. Although the eave vent is horizontal, the wind induced node that connects to it was based on a wall and specified at a vertical position below the vent (note the node locations below the eave vents in Figures 5.21 a and b). This is representative of the wall condition of the zone below the attic or roof-space which will dominate the eave pressure distribution.

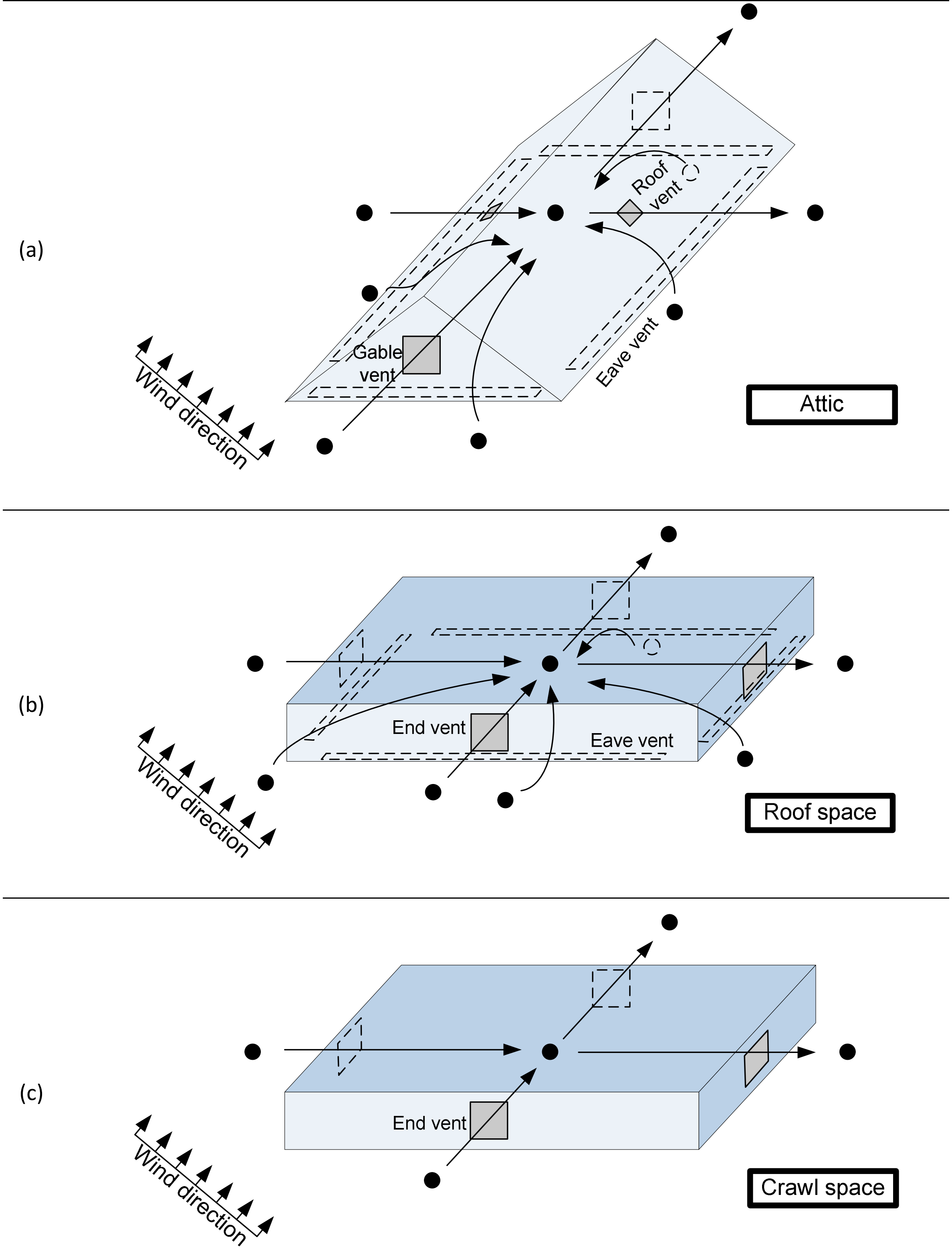


Figure 5.21 Air flow network designs for CHREM zones (a) attic, (b) roof-space, and (c) crawl-space

5.6.3.2 Window Openings and Zone-zone Airflow

The AFN is also used for modeling basement and main level zone airflow. This airflow may be divided into two categories: zone-ambient due to open windows, and zone-zone openings (e.g. stairwells). Figure 5.22 illustrates these two airflow categories.

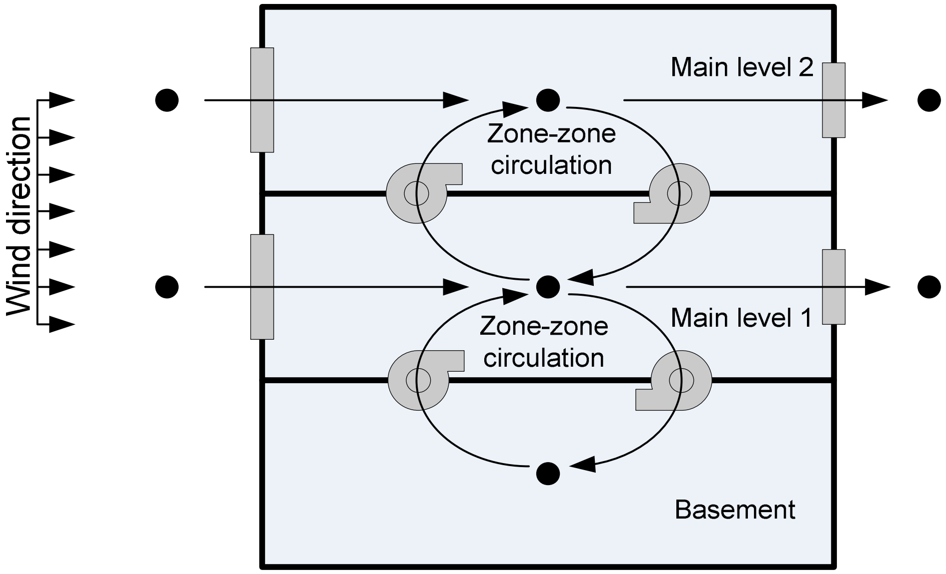


Figure 5.22 Air flow network designs for CHREM basement and main level zones including zone-ambient airflow and zone-zone circulation airflow

The use of the AFN for zone-ambient window airflow is only invoked in the model when the windows are opened. During other periods the airflow description defaults to the AIM-2 method. Support for this transition between controlling air flow models was implemented in ESP-r as part of the CHREM. The opened window area for each side of each zone was set equal to 25% of the window aperture area. Aperture area was used instead of total window area as much of the window frame is fixed. The value of 25% opening was selected based on half of the present windows being opened halfway. Although casement type windows can open entirely, the remaining types (awning, hopper, slider, single-hung, double-hung) only open halfway at most. The wind-induced nodes that form the boundary conditions outside the windows used the same coefficients as previously described for the attic and crawl-space.

The use of the AFN for zone-zone airflow between the basement and main level zones is continuous throughout the year-long simulation. Zone-zone airflow rates are difficult to estimate because many such openings have operable doors and are strongly influenced by internal structure partitions and level interface constructions. However, if no provision is made for zone-zone airflow, then zones which are highly glazed will tend to overheat (greater than 40 °C) in the summertime. This has ramifications as it does not represent reasonable zone temperatures and will influence energy storage in the thermal mass layers of the opaque surfaces. Another important consideration for zone-zone airflow is the SH and SC control strategy employed in the house. If a central SH or SC controller is located in a zone which is distinctly different than others (e.g. large or small, many or few windows, slab-on-grade or wood floor), the remaining zones could be severely over/under heated or over/under cooled, impacting the energy consumption of the corresponding end-use.

To avoid such circumstance, a fixed, balanced air mass flow rate was implemented in the CHREM to exchange air between facing conditioned zones. This fixed, balanced exchange is illustrated as two circulation fans located between each zone interface in Figure 5.22. Two fixed mass flow rate fans were selected so as to maintain the mass balance of the AFN and not allow the zone-zone exchange to influence zone-ambient airflow. The mass flow rate of the fans was calculated based on an assumed volumetric air exchange rate of 0.35 AC/h. Because central SH and SC controllers were located in the first main level, the other zone volumes were used as the basis of the mass flow rate calculation.

5.7 Internal gains and Occupant Related End-uses

Referring to Figures 5.2 and 5.3 (pages 119 and 120) it is clear that AL and DHW end-uses directly affect energy consumption. Only a portion of these end-uses become internal heat gain. Occupants themselves release heat that becomes an internal gain. Data for each of these gains or end-uses is acquired from the CHREM statistical method. Specifically, the CHREM statistical method provides the most representative use profiles for DHW, AL-dryer, AL-stove, and AL-other, along with a set of profile multipliers (see section 4.3.5). Additionally, the statistical method provides occupancy information in the form of number of adults, children, and employment ratio.

The CHREM engineering method utilizes the DHW, AL, and occupant information, and imposes these as internal gains within the ESP-r building simulation. These internal gains can then affect the SH and SC end-use energy consumption. The following subsections describe the process for imposing the internal gains, as well as the treatment of the internal gains themselves.

5.7.1 Use Profiles

The profiles of AL and DHW originate from Armstrong et al. (2009) and Jordan and Vajen (2001), respectively. The AL profiles are only available in five minute timesteps. The DHW profiles are available in 1, 5, 6, 15, and 60 minute timesteps. A method of reading such profiles and applying multipliers exists in ESP-r in the form of user specified boundary conditions (Ferguson 2005). However, the timestep read-in functionality is unable to average this data and requires identical timesteps for all provided profiles.

As an example of this limitation, consider a 5 minute DHW profile which varies dramatically over a 60 minute period, averages 3 L/min flow rate, and has a peak value of 15 L/min on the hour. For simulation conducted with a timestep of 60 minutes, the 15 L/min value on the hour would be selected and considered constant for 60 minutes, resulting in grossly exaggerated 900 L of DHW flow.

Furthermore the read-in of high resolution boundary condition data for simulation purposes takes time. To avoid such timestep and read-in-time issues, a set of boundary condition files was created specifically for CHREM. Functionality was added to take the original AL and DHW profiles and develop a boundary condition file with the timestep information averaged according to the simulation timestep. For example, if 5 minute timestep profiles were used for a 60 minute timestep simulation, 12 values of the source profiles would be averaged to create one value for the CHREM boundary condition file. Furthermore, to avoid long read-in times, a set of 27 boundary condition files were created to allow for combinations of all end-use level variations (low, medium, high) of the profiles DHW, AL-Dryer, and combined AL-Stove-Other. The use level variations were discussed in section 4.3.4.

5.7.2 Domestic Hot Water

The CHREM statistical method provides the most representative DHW flow rate profile and a profile multiplier to the engineering method. DHW is modeled in ESP-r on the basis of the water volume consumption, and accounts for system heat losses that result in internal gains. Examples of such system heat losses include the distribution piping system and the standby tank losses (skin losses). It is assumed that all heat carried with the DHW flow stream is immediately drained from the building and does not constitute an internal gain. It is recognized that in reality some stagnant DHW will occur (e.g. full bathtub), but such gains are usually offset by increased exhaust fan use, and the use of cold water which tends to remove heat from the dwelling.

The DHW support in ESP-r is detailed by Lopez (2001) and relies on data inputs as shown in Table 5.13. In all cases a supply temperature of 55 °C was assumed. The DHW system was assumed to be located in the basement if one exists, otherwise in the main level 1 zone. The CSDDRD contains information on the energy source and tank type. If a tank exists, it was assumed to be 180 L capacity, a typical value for Canadian DHW heaters. Energy factors were specified by energy source as shown in Table 4.3 on page 90. A map was created to populate the remaining items based on the energy source and tank type as shown in Table 5.14.

Table 5.13 DHW model inputs

Input field	Description or example
Supply temperature	55 °C
Zone	Zone in which the DHW system is located
Energy source	Electricity, natural gas, heating oil
Energy factor	Nominal ratio of delivered thermal output to the higher heating value of the energy source
Tank type	Conventional, tankless, induced-draft
Heating capacity	Value in watts
Pilot rating	Value in watts
Tank size	Value in liters

Table 5.14 Example of DHW tank type characteristics

Energy source	Tank type	Heating capacity (W)	Pilot rating (W)
Electric	Conventional	3000	0
	Instantaneous	15000	0
	Heat pump	3000	0
Natural gas and Heating oil	Conventional spark	5000	0
	Conventional pilot	5000	5
	Instantaneous pilot	15000	5
	Condensing	5000	0
Wood	Stove with coil	5000	0

During each timestep ESP-r assesses the DHW volume draw, end-use energy consumption, and internal gain released to the zone due to tank and piping losses. Support was added to ESP-r to use the CHREM specific boundary condition data.

5.7.3 Appliances and Lighting

The CHREM statistical method provides the most representative AL power profile and a profile multiplier to the engineering method. It also provides indicators if the clothes dryer or cook stove are powered by electricity or natural gas. The provision of this data to the ESP-r building energy performance simulator is to support both the inclusion of AL as internal gains, and the end-use energy consumption of electricity and natural gas.

There exist three AL categories: clothes dryer, cook stove, and AL-other (e.g. plug loads, lighting, and other common appliances). All energy used by the clothes dryer was assumed to exhaust from the house. All energy used by the cook stove and AL-other uses was assumed to become sensible heat in the thermal zone (assumed to be a mixed 50% convective, 50% radiative). The cook-stove was located in the main level 1 zone, while the AL-other use was proportionally distributed among conditioned zones by volume. In reality, some clothes dryer heat does remain in the zone, and some lighting is used on the exterior of the building. These are small portions and will tend to offset one another.

Changes specific to the CHREM were made to the ESP-r building simulator to support these internal gains. For example, a natural gas clothes dryer and cook stove would both affect natural gas consumption, but only the cook stove energy consumption would result as heat within the thermal zone. Functionality was also added to place the electric AL end-uses onto the ESP-r electrical network. Although not presently used, this functionality will support future CHREM development aimed at examining the impacts of solar photovoltaic and electrical energy storage technologies, and their ability to meet the house electrical loads.

5.7.4 Occupant Presence

The CHREM statistical method provides information on the adult and children occupant count, and the employment ratio. This information is used to populate the dwelling, resulting in the occupants rejecting heat that becomes an internal gain within the zone.

ASHRAE (2005) provides values of occupant heat rejection for a variety of conditions, gender, and adults and children. The selected daytime value corresponds with “seated, very light work”, and the night time value corresponds with “seated in a dark theater”. A male is considered to reject 130 W during the day and 115 W during the night. Females and children correspond to 85% and 75% or the male values, respectively. As gender information was not provided by the CHREM statistical method, the average of adult male and female values was used to represent adult occupants.

A typical Canadian four period occupancy profile consisting of night time, daytime, and work day schedules was imposed, as shown in Table 5.15. During the morning and evening periods the occupants are assumed to be home and active (daytime heat rejection values). During the workday the adult value is adjusted to account for employed individuals and the child value is one half to account for attendance of school and afternoon activities. The same profile is used for both weekdays and weekends.

Table 5.15 Occupancy profile

Period	Time range (hours)	Heat rejection value type	Adult adjustment	Child adjustment
Night	21:01–05:00	Night time	-	-
Morning	05:01–08:00	Daytime	-	-
Day	08:01–17:00	Daytime	1 – employment ratio	0.5
Evening	17:01–21:00	Daytime	-	-

The sensible (approximately 63%) and latent (approximately 37%) components were specified separately for both day and night as per ASHRAE (2005). The convective and radiant portion of the sensible heat was set to 60% and 40%, respectively.

5.8 Zone Thermal Conditioning Control Strategy

As previously mentioned, zones may be considered either conditioned or unconditioned. Thermal zones such as crawl-spaces, attics, and roof-spaces are unconditioned, and as such have no thermal conditioning control strategy. This is termed “free-floating” in ESP-r. As defined in the preceding sections, these unconditioned zones are primarily exposed to ambient conditions through uninsulated opaque surfaces and large vents. In general, heat is added to these unconditioned zones from surfaces connected to conditioned zones, or from surfaces exposed to SW radiation. Nearly all of this heat is then carried away by the large air flow rate passing through the vent openings.

In contrast, thermally conditioned zones, such as basements and main levels, have active SH, and possibly active SC systems. Such systems are typically controlled by either a master thermostat located in the first main level, or by distributed thermostats located in each room of each conditioned level. These systems typically deliver or extract thermal energy from the conditioned zones via convection to the airpoint. Certain systems involve a significant amount of LW radiation (e.g. wood stove).

Each house of the CSDDRD has a summary description of the SH system that includes energy source and equipment type. Less information is available for SC systems as they are expected to use electricity. The thermal conditioning setpoints of the SH and SC system are defined in the CSDDRD. However, house energy auditors typically left these as the HOT2XP default values of 21 and 25 °C, respectively. This was due to the standardized assessment protocols related to the EnerGuide for Houses program.

5.8.1 Ideal SH and SC Representation in ESP-r

The ESP-r building energy performance simulator allows for SH and SC systems to be defined in two ways: an ideal system which emulates the measurement and energy injection/extraction functionality, and a detailed explicit system which requires definition of each connected component and its functionality (e.g. pump, boiler, supply piping, radiator, and return piping). As such explicit information is unavailable in the CSDDRD, the ideal system representation was employed. Section 5.9 discusses how the ideal representation was interpreted to account for end-use energy consumption caused by system characteristics such as plant equipment type and energy source.

The ideal SH and SC systems were implemented into the house model by considering the available CSDDRD data, and augmenting it with specified setpoints and delivery methods. The principal selection of control strategy was based on the equipment type. All SH and SC equipment types were considered to be "centrally" controlled, with the exception of electric baseboard systems. However, if central SC and an electric baseboard SH system were present, central control was specified due to limitations in the ESP-r ideal control strategies. The sensor for SC and SH activation measures the dry bulb temperature of the zone in which it is placed. For central systems, the sensor was located in the main level 1 zone. In all cases, the SH and SC heat injection/extraction point was considered to be the zone airpoint.

The capacity of the SH and SC system was apportioned to each conditioned zone based on volume. SHEU-2003 found that the majority of Canadian households use heating setpoints between 20 and 22 °C (OEE 2006). Therefore, the SH and SC temperature setpoints were specified as 21 and 25 °C, respectively. A "basic" or "slave" controller was selected in ESP-r to model the heat injection/extraction corresponding to the setpoints and capacity. Such controllers represent ideal systems that can vary the heat injection/extraction as required to maintain the zone according to the control strategy, within the capacity limits of the system. This does not appropriately model the fixed output and cyclic nature of actual energy conversion systems, as will be considered in section 5.9. The capacity of SH is specified in the CSDDRD. This capacity value was calculated by the HOT2XP program using standard F280 (CSA 2009) to match the heating design load for a 22 °C setpoint. The SC capacity was not defined in the CSDDRD. To avoid the circumstance of undercooling houses, the SC capacity was assumed to be equal to the SH capacity.

5.8.2 Control Strategy Periods

A year-long control strategy was employed to account for the heating and cooling seasons found in the Canadian climate. Typical Canadian thermostats have three modes: heat, cool, and off. In practice the occupant generally leaves the thermostat in heat mode during the heating season (e.g. November through March) and cool mode during the cooling season (e.g. June through September). During the remaining months the thermostat may be set to any of the three modes. To account for thermostat use by an occupant, and the varied climates found throughout Canada, a five period control strategy similar to that specified by the HOT3000 Canadian building simulation program (CANMET 2010) was employed. The strategy, as shown in Table 5.16, differs from HOT3000 which specifies no SH or SC during periods 2 and 4. The CHREM allows SH and SC during these periods because it was found that colder climates required SH throughout April and May, and warmer climates requires SH into October. A time-of-day temperature setback strategy was not used.

Table 5.16 Five period SH and SC control strategy

Period	Dates	Space heating available	Space cooling available
1	Jan 1 – Apr 1	√	
2	Apr 2 – Jun 3	√	√
3	Jun 4 – Sep 16		√
4	Sep 17 – Oct 7	√	√
5	Oct 8 – Dec 31	√	

5.8.3 Application of the Control Strategies during Simulation

The ideal SH and SC conditioning control strategies are used by the ESP-r simulator to calculate the required heat injection/extraction from the conditioned zones of the house. This is simply the energy required to maintain the conditioning setpoints within the specified capacity limits.

Referring to Figure 5.2 on page 119, ESP-r uses the previously discussed house definition (geometry, zoning, surface attributes, and airflow), and imposes the conditions (climatic and internal gains). It then applies the ideal SH and SC conditioning control strategies (temperature setpoint and capacity limits) and calculates the heat injection/extraction from the zones of the house, and the resultant temperatures. The heat injection/extraction due to the ideal SH and SC must be supplied by a representative energy conversion system that accounts for the equipment characteristics. Using such information, the SH and SC end-use energy consumption can be estimated.

5.9 SH and SC Energy Conversion System Characteristics

The ideal SH and SC conditioning control strategies discussed in section 5.8 calculate a heat flux injected/extracted from the thermal zones over the timestep. However, this does not account for the fixed output and cyclic nature of SH and SC energy conversion systems. Nor does it account for the efficiency of such systems. As an example, consider a one hour timestep on a cold day where 36 MJ (10 kWh) is required to maintain the heating temperature setpoint. A 75% efficient (higher heating value steady-state) natural gas furnace with a 20 kW capacity exists. Due to the thermostat dead band, the furnace will cycle every 30 minutes at 50% duty. Because of the steady state efficiency, the furnace will require 48 MJ of natural gas. But due to the cycling, which results in start-up/shutdown inefficiency, the furnace will likely require 50 MJ of natural gas.

To account for the SH and SC system efficiency and characteristics, a post processing module of ESP-r was employed. Following each timestep calculation of the required heat flux injection/extraction, the values are compared to the separately specified operational characteristics of the SH and SC system. These are used to calculate the end-use energy consumption of the SH and SC systems. This “HVAC” functionality is detailed by Purdy and Haddad (2002), and Haddad (2000, 2000b, 2001, 2001b).

The HVAC functionality determines the total SH and SC heat flux required by the serviced zones. It then calculates the part load ratio of the system by dividing the required flux by the system capacity. If the part load ratio is greater than one, a backup system may be employed. The part load ratio is used to calculate a degradation of the higher heating value steady-state efficiency of the equipment based on correlations by Henderson et al. (1999). Both the steady-state efficiency and degradation due to the part load ratio are applied to the required timestep flux to calculate the end-use energy consumed during the timestep. If the system is a heat-pump, the source temperature (air, water, or soil) is used to calculate the coefficient-of-performance (COP). In addition, the method considers energy consumed to support fans and pumps, and passes flue open/closed information to AIM-2. The method may be applied to the following SH and SC systems: furnace, boiler, stove, electric-baseboard, air-source heat pump (ASHP, heating and cooling), and ground-source heat pump (GSHP, heating and cooling). As the ASHP capacity is dramatically affected by ambient temperature, its capacity is varied accordingly and used to modify the subsequent timestep capacity limitations for the ESP-r building heat flux solution. GSHPs experience similar effects (but of less variance) although it is based on ground temperature as discussed by Purdy (2002). In both cases, the heat pump is assumed to continue operation when auxiliary heating is required.

A mapping process was developed to use the SH and SC data provided in the CSDDRD to develop the house model files for ESP-r, suitable for using the HVAC functionality. A summary of required input information is shown in Table 5.17. Certain equipment was present in the CSDDRD which was not available in HVAC method. In particular, electric radiant floor/ceiling panels were treated as baseboard heaters and a variety of wood stove types (pellet, masonry, fireplace, insert) were treated as conventional wood furnaces.

Table 5.17 SH and SC end-use energy consumption model inputs

Input field	Examples
Energy source	Electricity, Natural gas, heating oil, wood
Equipment type	Furnace, boiler, stove, baseboard, ASHP, GSHP
Capacity	Value in watts
Efficiency	Higher heating value percentage or COP
Fan or pump power	Value in watts
Zone information	Zones receiving heat flux and proportion

The HVAC functionality allows for multiple system descriptions. The minimum number used by the CHREM was one, and accounted for a conventional (e.g. furnace) SH system. Two systems were used when a SC system was present, or for GSHPs which have backup, but are not used for SC (they are assumed to be water-water and would suffer from condensation issues). For ASHPs, three systems were used: the primary heating mode heat pump, a secondary backup heating source such as electric baseboard or natural gas furnace, and a primary cooling mode heat pump. It was assumed that the presence of an ASHP within the CSDDRD would allow for the occupant to also use it as an air conditioner.

Because furnace fans and boiler pumps had already been identified in the AL end-use (see sections 4.3.1 and 4.3.2), they were not included within the SH energy consumption model. However, circulation fans used for SC systems, and exterior fans for heating mode ASHP systems, are included and are set to 250 W each. The sensible heat ratio of SC equipment is set to 0.75 in accordance with examples included with ESP-r.

The HOT2XP program limited the capacity of heat-pumps in heating mode to a value of 7.5 kW. All remaining capacity of the heating capacity value was therefore attributed to the secondary system. When an ASHP was specified, the cooling COP was set to the heating COP plus one, because the temperature differential for rating purposes is less.

Although a GSHP system may be specified in HOT2XP, and such systems exist in the CSDDRD, no information is present on their characteristics. In contrast, ESP-r requires detailed information on the GSHP for use in the simulation. A number of GSHP system specifications from example models were examined and representative residential values were prescribed. These consist of a horizontal 2 pipe system with side-by-side arrangement and 750 m length.

The definition of these values allows for ESP-r to calculate end-use energy consumption of the SH and SC system with consideration to the energy conversion system operation. The SH value constitutes the major end-use energy consumption in a Canadian house.

5.10 Conclusion

This chapter discussed the detailed methodology of the CHREM engineering method. The CHREM is a hybrid model which integrates the results of the statistical method within the engineering method, allowing interaction between the end-uses. The engineering method relies on both the CSDDRD (Chapter 3) and the CHREM statistical method results (Chapter 4) to create detailed representations of the houses that are suitable for the building energy simulator ESP-r. The description includes information regarding the house thermal envelope, airflow characteristics, internal gains, zone conditioning strategies, and plant system characteristics. The following chapter describes the simulation and results of the CHREM engineering method.

Chapter 6 Simulation and Results

The Canadian Hybrid Residential End-Use Energy and GHG Emissions Model (CHREM) methods were described in the preceding chapters. This chapter describes the simulation of the houses and resultant estimations of end-use energy and GHG emissions. The first section discusses the method and issues encountered in generating house models. The second section discusses the simulation of these house models using ESP-r, as well as the accumulation and reporting of results. The final section considers the CHREM results, and scales these values to a national context. The CHREM estimates are then compared to other models and survey estimations and billing data.

6.1 House Model Generation

Chapter 5 discussed the method by which the house descriptions of the Canadian Single-Detached and Double/Row House Database (CSDDRD) and the CHREM statistical method results were integrated, reorganized, and developed into a form for use with the building energy performance simulator ESP-r. The actual process was conducted using a computer code written in the language of Perl (CPAN 2009). The CSDDRD data is contained in delimited text file format, with rows of house records and columns of field information. The CHREM statistical method results (AL energy and DHW volumetric draw) and use profiles were also incorporated in delimited files. The XML databases (materials, multilayer constructions, and plant equipment) were also introduced in Chapter 5.

A script was written in Perl to read these data inputs and then cycle over each house of the CSDDRD to create the house model files for ESP-r. The files required by ESP-r vary according to model complexity and definition technique. The number of files used to describe an individual house ranges from 18 to 31, depending upon house characteristics. The presence of a foundation zone and additional main level zones increase complexity and the number of description files. An example of these files is shown in Table 6.1.

As implemented, the CHREM generates 16,962 folders. These consist of two house type organizational folders, each with five region subfolders, plus the 16,952 unique house model folders. A house model folder is created for each house of the CSDDRD. A set of house description files for each house of the CSDDRD was successfully generated using the described technique. In total, 402,506 files, totalling 1865 megabyte size were created. On average, each house has 24 files and 113 kilobytes of data.

Table 6.1 Example files of a typical house model description for simulation in ESP-r

File	Description
House.cfg	Model configuration data and links
House.log	Log file containing summary information
House.main_1.geo	Vertex and surface information of the main level 1 zone
House.main_1.con	Multilayer construction properties of the main level 1 zone
House.main_1.tmc	Transparent optical properties of the main level 1 zone
House.main_1.opr	Occupancy and AL information of the main level 1 zone
House.bsmt.geo	Vertex and surface information of the basement zone
House.bsmt.con	Multilayer construction properties of the basement zone
House.bsmt.opr	Occupancy and AL information of the basement zone
House.attic.geo	Vertex and surface information of the attic zone
House.attic.con	Multilayer construction properties of the attic zone
House.cnn	Outward facing surface conditions
House.mvnt	Mechanical ventilation equipment
House.aim	AIM-2 description: air leakage, conditions, window control
House.afn	AFN description: nodes, components, connections
House.dhw	Domestic hot water equipment
House.elec	Electrical network for AL electricity consumption
House.ctl	Zone control descriptions: master and slave
House.hvac	Heating and cooling system descriptions
House.xml	Definition of results storage

The CSDDRD is housed in ten separate organizational folders corresponding to house type and region as shown in Figure 6.1. Using an unbalanced multithreading method on a two-processor four-core computer, the file generation process takes less than ten minutes for all houses of the CSDDRD. Multithreading is a process of separating the information into groups to make use of multiple computer processors and cores. Functionality was added such that regeneration of house files (e.g. for upgrade analysis) is only required for houses of interest, or those that are compatible with the particular upgrade scenario.

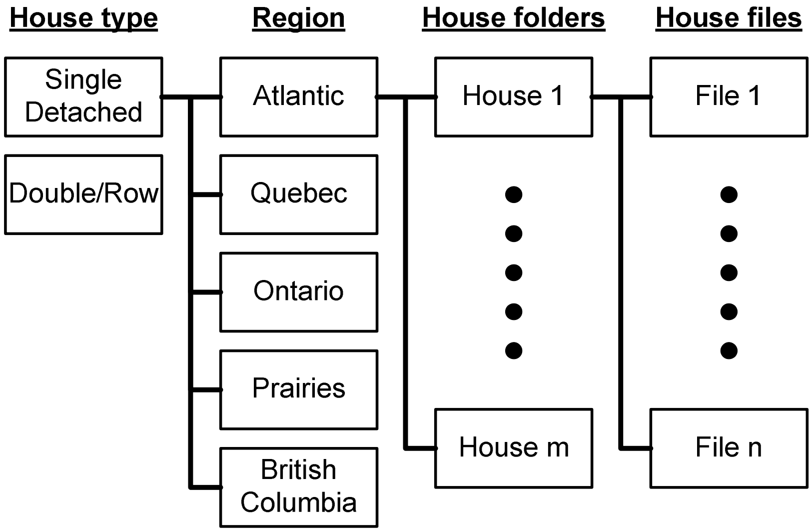


Figure 6.1 CSDDRD folder organization

Numerous data verification tests were programmed into the code to ensure data integrity and appropriate use. Data irregularities (i.e. houses which have values outside the expected range) identified during the house file generation procedure were noted, and the value was adjusted to be within range. The encountered data integrity issues were grouped and their characteristics are shown in Table 6.2.

Aspect ratio is an issue that affects more than 1000 houses. Aspect ratios were often outside the allowable range because of the variety of complex house shapes found within the CHS. It was difficult for house energy auditors to interpret the width and length of a house with more than four corners, or those having L or T shapes.

Another issue which affects more than 1000 houses is surface maximum residual thermal resistance difference. The adjustment of the effective thermal resistance was attempted for each surface as described in section 5.5.3.2 on page 142. However, certain construction codes specified uninsulated walls, floors, and ceilings. In such cases, a residual difference often remained between effective thermal resistance of the surface and the value specified by the CSDDRD that was intended to account for thermal bridging. Although the aspect ratio and surface description issues affect many houses, the "typical offending value" column of Table 6.2 indicates that the "errors" were often not substantial, and the required "adjustments" were small.

Table 6.2 Summary of issues encountered during the house generation procedure

Group	Issue	Occurrences	Limit	Typical offending value
Aspect ratio	Maximum	1936	1.5	1.68
	Minimum	2784	0.66	0.55
Foundation	Max. of Foundation floor area minus main level 1 floor area	507	0 m^2	10 m^2
Door	Width/height reversed	123	-	-
	Maximum height	44	3.0 m	3.5 m
	Minimum height	791	1.5 m	1.4 m
	Maximum width	208	2.5 m	2.7 m
	Minimum width	381	0.5 m	0.4 m
Window	Max. of window area minus available window area	144	0 m^2	3 m^2
	Not specified in database	4	-	-
Surface	Min. thermal conductance	26	0.02 $\frac{W}{mK}$	0.01 $\frac{W}{mK}$
	Max. residual thermal resistance difference	1190	0.1 RSI	0.2 RSI
BASESIMP	Max. insulation	162	9 RSI	15 RSI
	Max. wall height	937	2.5 m	2.7 m
	Min. wall height	809	1.00 m	0.91 m
	Max. height above grade	444	0.65 m	0.80 m
	Min. height above grade	284	0.11 m	0.09 m
Heating system	Minimum heat pump perf.	5	1.5 COP	1.4 COP
	Maximum capacity	23	70.0 kW	81.0 kW
	Minimum capacity	4	5.0 kW	4.5 kW
Cooling system	Minimum performance	2	2.0 COP	1.5 COP

6.2 Simulation of the Houses

The building performance simulator ESP-r was used to simulate each house of the CHREM. A Perl script was written to control the simulation of the 16,952 houses. Using a balanced multithreading method on two computers, each with two four-core processors running at 1.86 GHz, the simulation process takes approximately 20 hours. This is for an annual period with a 60 minute simulation timestep. The average house simulation time was 68 seconds.

The primary component of the ESP-r building performance simulator package, *bps*, was used to conduct the energy simulation. The simulation was specified over an annual period from January 1 to December 31, with a total of 365 days. The *bps* simulator reads in and verifies the model files for acceptable format and value ranges. Errors are reported, and in most cases the existence of such errors would result in termination of the simulation. The number of houses with errors and their treatment is discussed in section 6.2.5. The *bps* simulator initializes zone air temperatures to 0°C, surface layer temperatures to 15°C, and heat fluxes to zero. Building energy simulation begins prior to the period of interest, so as to "climatize" the airpoint and surface layers from their initial settings to values corresponding to the conditioning control strategy and climatic conditions. A start-up period of four days was selected for the CHREM as the construction materials do not have enough thermal mass for weekly or seasonal impacts.

The *bps* simulator itself lacks certain capability with regard to the treatment of SW solar radiation. To account for this, a secondary component of the ESP-r building performance simulator package, *ish*, was employed. *Ish* has the capability of modeling external obstructions that block SW solar radiation from reaching the house, and the capability of distributing the direct solar radiation admitted through windows onto the appropriate inward facing surfaces of a zone. These solar radiation processes are important as it is expected that the CHREM will be used for analysis of shading (e.g. trees or overhangs) and thermal energy storage surfaces (e.g. Michel-Trombe wall). *Ish* in invoked prior to use of the *bps* simulator. Using climatic data and ray tracing techniques, *ish* provides *bps* with a time-series of SW solar radiation shading multiplier data for each external and internal surface.

6.2.1 Modifications to the ESP-r Source Code

As discussed in Chapter 5, a number of modifications were made to the building simulator to affect the handling of heat flows. In particular, heat advection due to simultaneous airflow mechanisms was allowed (mechanical ventilation, AIM-2, and AFN), and logic was added for the separation of internal gains (e.g. heat exhausting outside the zone). These additions extend the capability of ESP-r for more adequate treatment of heat flows in the CHS. They do not affect the verified conservation of energy balance method and calculation technique of ESP-r.

A series of automated tests are supplied with the ESP-r source code. These are intended to verify that new code additions do not negatively affect existing functionality or prediction.

The test suite simulates 149 cases and reports on any differences between a reference simulator and a modified simulator. The automated tests were applied to the CHREM specific ESP-r code changes and no substantial differences were reported. This indicates that the CHREM specific changes did not impact the verified energy balance method and calculation techniques of ESP-r, for the technologies present in the test suite. There are no test cases included in the suite that would specifically exercise the heat advection and internal gain changes specific to the CHREM. House files that were able to exercise these changes were developed using the CHREM and were independently evaluated. The differences were examined and found to be as expected based on the code functionality alterations.

6.2.2 Storage of Simulation Results

The results of the annual energy simulations were stored in XML format for post-processing related to both GHG emissions and results accumulation/scaling to a national context. The format, described by Ferguson (2007), provides an extensible utility for selecting and accumulating variables of interest.

In detailed building energy performance simulation, it is of critical importance to understand each heat flux, and in effect, each term of the conservation of energy equations. This is because the building energy performance simulator is capable of modeling a wide variety of fluxes, including those imposed by boundary conditions, as well as the addition of energy efficiency, solar, or other renewable energy technologies. With such capability comes the necessity of assessing each flux for validity and verifying the conservation of energy. This is because inappropriately applied heat fluxes will cause the building energy simulator to become corrupt and/or report erroneous results.

For the purposes of the CHREM, two sets of energy results were accumulated. The first set is zone energy balance results corresponding to the control volume illustrated in Figure 5.2 on page 119. The second set are energy consumption results corresponding to the four end-use groups (SH, SC, DHW, and AL) and energy sources shown in Figure 5.3 on page 120.

6.2.2.1 Energy Balance Results for the Thermal Zones

An energy balance was constructed for each of the large nodes shown in the Figure 5.2: the inward facing surface nodes of the opaque and transparent constructions, and the zone airpoint. An example of these nodal energy balances from one of the CHREM simulations is shown in Table 6.3 on page 185. There following points should be noted:

- Specific to the main zones
    - The predominant heat losses of the main zones are opaque and transparent surface conduction (CD), and airpoint heat advection (HA) caused by airflow crossing the control volume. These are supported by airpoint space heating (SH), and short-wave (SW) radiation that is primarily absorbed by opaque surfaces.
    - The long-wave (LW) radiation that exchanges between the opaque and transparent inward facing surfaces is equal and opposite. This is because transparent surfaces are opaque to LW radiation. This is a significant exchange from the opaque surface to the transparent surface.
- Specific to the basement zone
    - There is no absorbed SW radiation as there are no transparent surfaces located in the basements.
    - The airpoint CV caused by internal gains is significant because of the DHW system losses. The DHW system is located in the basement zone.
- Specific to the attic zone
    - The attic heat transfer is dominated by the exterior roofing surface which is not shown in Table 6.3. The roofing surface absorbs SW radiation and emits LW radiation to the sky. These roofing heat fluxes present themselves in Table 6.3 by affecting the opaque surface CD. This heat is then transferred from the opaque surfaces to the airpoint via CV. The heat is then carried away by HA caused by airflow through the attic vents.
- The opaque and transparent LW radiation from internal gains, and the airpoint CV, vary between the main level and basement zones due to the location of equipment and appliances. As described in sections 5.7.2 and 5.7.3, the DHW system was placed in the basement and the cook-stove was placed in the main level 1 zone.
- The airpoint HA due to mechanical ventilation differs between the main levels and the basement zone. This is because the basement zone airpoint temperature is less than that of the main level zones. This is a consequence of the master thermostat location in the main zone, and the effect of SW radiation.
- Although the airpoint HA estimated by AIM-2 is proportionally applied by volume to all conditioned zones, the values differ between the main levels and the basement zones due to the use of windows for natural SC. Windows are only present in the main levels.
- The airpoint zone-zone HA can be seen to move heat from the main level 2 to the main level 1, and then the main level 1 to the basement zone. The reason that heat is transferred from main level 2 to main level 1 is that main level 2 has a highly insulated ceiling. Main level 1 has an uninsulated floor which faces a cooler basement zone.

- The airpoint SH and SC values of all conditioned zones are similar due to a master/slave control algorithm with capacities proportioned to each zone by volume. The basement and main level zones have similar volume.
- In all zones, the change in sensible heat storage with time is approximately zero. This is because the conditioned zones are maintained at a setpoint temperature, and all zones start and end at the same ambient conditions (for an annual simulation).

Table 6.3 Example of CHREM conservation of energy results for an annual simulation of a single-detached two storey dwelling in the province of Ontario

		Thermal zones			
Node	Heat flux or storage (GJ)	Main 1	Main 2	Basement	Attic
Opaque	CD	-30.3	-30.1	-27.7	19.6
	CV	8.5	9.5	24.8	-19.6
	SW	21.1	21.4	0.0	0.0
	LW from internal gains	5.9	4.9	2.9	0.0
	LW between inward facing surfaces	-5.2	-5.7	0.0	0.0
	Sum of preceding fluxes	*0.0*	*0.0*	*0.0*	*0.0*
	Sensible heat storage	0.0	0.0	0.0	0.0
Transparent	CD	-9.4	-10.2	0.0	0.0
	CV	2.6	2.9	0.0	0.0
	SW	1.3	1.4	0.0	0.0
	LW from internal gains	0.3	0.2	0.0	0.0
	LW between inward facing surfaces	5.2	5.7	0.0	0.0
	Sum of preceding fluxes	*0.0*	*0.0*	*0.0*	*0.0*
	Sensible heat storage	0.0	0.0	0.0	0.0
Airpoint	CV to inward facing surfaces	-11.0	-12.4	-24.8	19.6
	CV from internal gains	5.5	4.4	9.3	0.0
	HA (mechanical ventilation)	-2.7	-2.0	-0.7	0.0
	HA (AIM-2, windows)	-16.3	-17.0	-13.8	-19.6
	HA (zone-zone)	-2.4	-0.7	3.1	0.0
	SC	-5.3	-5.4	-5.3	0.0
	SH	32.2	33.1	32.2	0.0
	Sum of preceding fluxes	*0.0*	*0.0*	*0.0*	*0.0*
	Sensible heat storage	0.0	0.0	0.0	0.0

6.2.2.2 End-use Energy Consumption and Energy Source Results

A summary of the energy consumption by end-use and energy source is shown in Table 6.4 for the same example CHREM house that was used in Table 6.3. The house relies on electricity and natural gas to serve the four end-uses. The following points related to Table 6.4 should be noted:

- SH is the dominant energy consuming end-use and is powered by natural gas. By dividing the sum of the zone SH requirements in Table 6.3 (97.5 GJ) by the end-use SH energy consumption in Table 6.4 (106.5 GJ), a higher-heating-value efficiency of 91% is calculated. This high energy efficiency corresponds to the condensing natural gas furnace present in this particular example house. This advanced furnace technology does not suffer significant efficiency loss due to part load operation.
- SC is solely provided by electricity.
- AL end-uses consume both electricity and natural gas. The natural gas consumption is due to the clothes dryer and cook stove.
- Natural gas constitutes the largest energy source as it is used to supply SH.
- The total house consumption is 156.8 GJ. This is only marginally greater than the average Ontario single detached dwelling energy consumption of 150 GJ, as determined from the Survey of Household Energy Use 2003 (OEE 2006).

Table 6.4 Example of CHREM end-use energy consumption by energy source for an annual simulation of a single-detached two storey dwelling in the province of Ontario

End-use	Energy source	Energy (GJ)	Quantity
SH	Natural gas	106.5	2863 m^3
SC	Electricity	7.7	2116 kWh
AL	*Electricity*	*18.1*	*5026 kWh*
AL	*Natural gas*	*2.4*	*65 m^3*
AL	All	20.5	
DHW	Natural gas	22.2	598 m^3
All	Electricity	25.7	7142 kWh
All	Natural gas	131.1	3526 m^3
All	All	156.8	

6.2.3 Identification of Simulation Issues using the Energy Results Accumulations

An analysis of the CHREM energy balance and end-use energy consumption results, similar to those shown in Tables 6.3 and 6.4, revealed two pre-existing errors in the ESP-r simulation package. The first of these errors was the representation of zone-zone HA. The flux was treated correctly in the simulation, but misreported in the XML results. This error was discovered by comparing the zone energy balance, and discovering that zone-zone heat advection was unexpectedly large and that energy was not conserved. This error had not previously been identified because it is of limited interest for whole building simulation, as it is often contained within the conditioned thermal envelope of the house. The second error is of the DHW system standby losses to the surroundings. These heat losses were not properly considered as an internal gain, resulting in increased SH and decreased SC requirements. This issue was identified by comparing the SH and SC energy consumption, as shown in Table 6.4, with and without a DHW system.

The identification of these errors illustrates the importance of considering all heat fluxes and the conservation of energy. These errors were fixed in the ESP-r building energy simulator and were subjected to test suite verification as described in section 6.2.1.

6.2.4 Determination of GHG Emissions

One of the objectives of the CHREM is the assessment of GHG emissions associated with the end-use energy consumption. The primary GHGs emitted during the combustion of non-renewable fossil fuels are carbon dioxide (CO_2), water (H_2O), methane (CH_4), and nitrous oxide (N_2O). Water is not considered to contribute to human induced global warming as its atmospheric levels are controlled by precipitation. GHGs are characterised by a global warming potential (GWP). The GWP is referenced to the strength of CO_2 as it is the dominant gas of interest emitted during combustion. Considering the GWP of CO_2 to be unity, CH_4 and N_2O have 100 year GWPs of 25 and 298 by mass, respectively (Forster et al. 2007). As combustion of fossil fuels results in all three important GHGs, the cumulative effect is quantified in terms of equivalent carbon dioxide (CO_2e). This is equal to the sum of the product of each GHG emission mass and its GWP, as shown in Equation 6.1.

$$\mathrm{CO_2e} = \mathrm{CO_2} + 25\,\mathrm{CH_4} + 298\,\mathrm{N_2O} \qquad (6.1)$$

As the CHREM only predicts *end-use* energy consumption, it does not consider the GHG emissions associated with upstream activities such as mining, refining, or transportation. Only GHG emissions directly attributable to energy use by the end-use groups of each dwelling are accounted for by the GHG reporting. These emissions include those due to on-site fuel combustion and the emissions directly attributable to electricity production, inclusive of transmission.

6.2.4.1 GHG Emissions due to On-site Fuel Use

The GHG emissions caused by the combustion of home heating fuels using residential equipment is published by Environment Canada (2007), and the energy content (higher heating value) of these fuels is published by the Canadian National Energy Board (2008). These values are shown in Table 6.5. They may be used to calculate the GHG emission intensity factor (EIF), the level of CO_2e emitted per unit input energy of common home heating fuels in Canada.

Table 6.5 GHG emissions due to the conversion of fuels using residential equipment

Residentially consumed fuel	CO_2 (g)	CH_4 (g)	N_2O (g)	CO_2e (g)	Energy content ($MJ_{thermal}$)	EIF (g of CO_2e per $MJ_{thermal}$)
Natural gas (m^3)	1891	0.037	0.035	1902	37.1	51.3
Light fuel oil (L)	2830	0.026	0.006	2832	38.5	73.6

6.2.4.2 GHG Emissions Due to Electricity Generation

As shown in Figure 6.2, Canadian electricity generation is supported by a wide variety of energy sources: hydro, coal, nuclear, natural gas, and heavy fuel oil. Of these, only coal, natural gas, and heavy fuel oil contribute to non-cyclic GHG emissions.

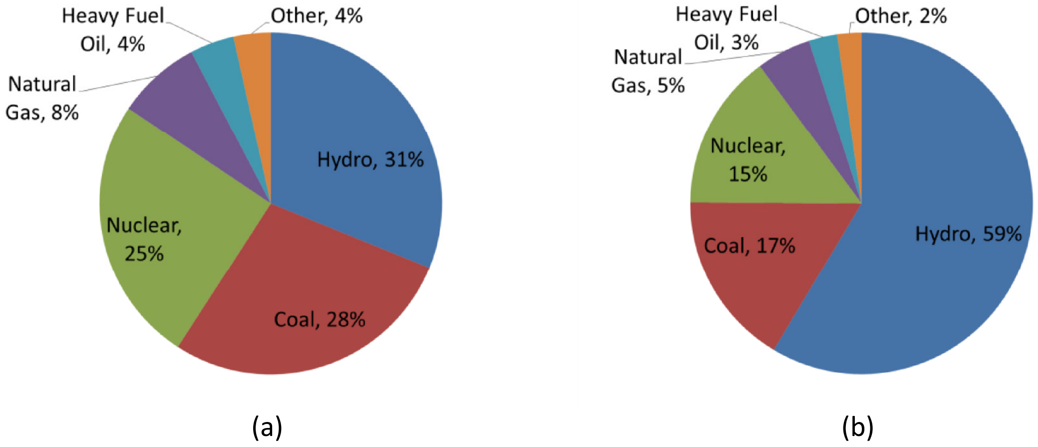


Figure 6.2 Canadian electricity generation sector by energy source (a) energy use, and (b) electricity generated (OEE 2006b)

The GHG EIFs for electricity generation range further than home heating fuels, due to the efficiency of conversion from thermal to electrical energy, and the addition of coal fuel which has many varieties. Estimates of combustion products and combustion efficiencies of common electricity generation techniques are published by Environment Canada (2007b). As shown in Table 6.6, these values may be used to calculate typical GHG EIFs for electricity generation. Note that the GHG EIFs are reported as a function of kW·h energy units as this is the typical metering unit of electricity.

Table 6.6 Examples of GHG emissions due to the conversion of fuels to generate electricity

Electricity generation fuel	CO_2 (g)	CH_4 (g)	N_2O (g)	CO_2e (g)	Energy content ($kW{\cdot}h_{thermal}$)	Avg. plant efficiency (%)	GHG EIF (g of CO_2e per $kW{\cdot}h_{electrical}$)
Natural gas (m^3)	1891	0.49	0.049	1918	10.3	34.8%	536
Heavy fuel oil (L)	3080	0.034	0.064	3100	10.7	34.6%	838
Bituminous coal (kg)*	1852	0.022	0.032	1862	7.7	31.6%	766

*The emitted CO_2 content for coals varies widely with source and type. Values for common coals used in Canada range from 1427 to 2254 g/kg (Environment Canada 2007b)

Electricity generation may be described as base and marginal, the combination of which supports the total load on the grid. Base and marginal generation are differentiated by dispatch order. Base generation provides continuous electricity, with levels rising and falling over the course of weeks and seasons. Base generation is commonly provided by equipment with high operating inertia, and is serviced by low cost energy sources. Examples of base generation energy sources include coal, hydro, and nuclear. Marginal generation follows the highly variable load and changes over seconds and minutes. The marginal generation responds to incremental load which is added or removed from the electricity grid. Examples of marginal generation energy sources include hydro and natural gas. In many cases a particular energy source will be used for both base and marginal generation.

The GHG emissions due to the present electricity consumption of the CHS are calculated using the average GHG EIF of the regional electricity generation. This includes both fossil and renewable energy sources, and both base and marginal generation. The addition of new technologies to the CHS can cause an incremental change in the electricity consumption. The marginal generation will respond to this incremental change. Consequently, the change in GHG emissions due to the incremental change in electricity consumption is calculated using the marginal GHG EIF of the regional electricity generation.

Farhat and Ugursal (2010) provide a comprehensive review of the electrical generation aspects of Canada. They discuss the base and marginal generation, and show the wide variation among Canadian provinces. Using annual and monthly generation data they calculate the EIF for both average (combination of base and marginal) and marginal electricity generation. These values, shown in Table 6.7, are available for most provinces on an annual basis, and on a monthly basis for the provinces of Quebec, Ontario, and Alberta.

Table 6.7 Average and marginal GHG EIFs and transmission/distribution losses for Canadian provinces (Farhat and Ugursal 2010)

Electrical generation characteristic		Canadian provincial GHG EIF (g of CO_2e per kW·h)									
		NF	NS	PE	NB	QC	OT	MB	SK	AB	BC
Annual $EIF_{Average}$		26	689	191	433	6	199	13	789	921	22
Annual $EIF_{Marginal}$		22	360	6	800			1	225		18
Monthly $EIF_{Marginal}$	Jan					23	395			591	
	Feb					0	352			591	
	Mar					0	329			785	
	Apr					0	463			785	
	May					0	501			785	
	Jun					0	514			769	
	Jul					0	489			769	
	Aug					0	491			769	
	Sep					0	455			769	
	Oct					0	458			785	
	Nov					0	379			591	
	Dec					4	371			591	
Transmission and distribution losses		9%	4%	6%	6%	4%	6%	12%	6%	4%	3%

It is evident from Table 6.7 that the electricity generation energy sources vary dramatically among Canadian provinces. Figure 6.3 illustrates this variation in provincial GHG EIFs for electricity generation, and compares it to the on-site fuel GHG EIFs of natural gas and heating oil. Note that the GHG EIF in Figure 6.3 is displayed in units per MJ and includes the transmission/distribution losses. The electrical generation of NS, SK, and AB are primarily coal powered, leading to average GHG EIFs greater than 180 g of CO_2e per MJ (650 g of CO_2e per kW·h). The electrical generation of NF, QC, MB, and BC are primarily hydro powered, resulting in a GHG EIF close to zero. The relationship between average and marginal GHG EIF also varies by province. For example, the marginal GHG EIF of NS is approximately half that of the average GHG EIF, owing to the base coal generation and the marginal natural gas and hydro generation. The province of OT is opposite; it has a marginal GHG EIF nearly double that of the average GHG EIF. This is due to the Ontario base nuclear generation and the marginal coal generation. This summary illustrates the complexity of examining GHG emissions due to electricity energy consumption in the CHS, and the change in GHG emissions due to the application of new technologies to the CHS.

A technological upgrade that reduces electricity consumption may have no impact on GHG emissions in one province, weakly affect GHG emissions in another province, or strongly affect GHG emissions in a third province. Additional complexity may be added by energy source switching (e.g. from a natural gas furnace to an electric heat pump) at a house site. Such a change may result in significant energy savings, but the impact upon GHG emissions will be provincially specific.

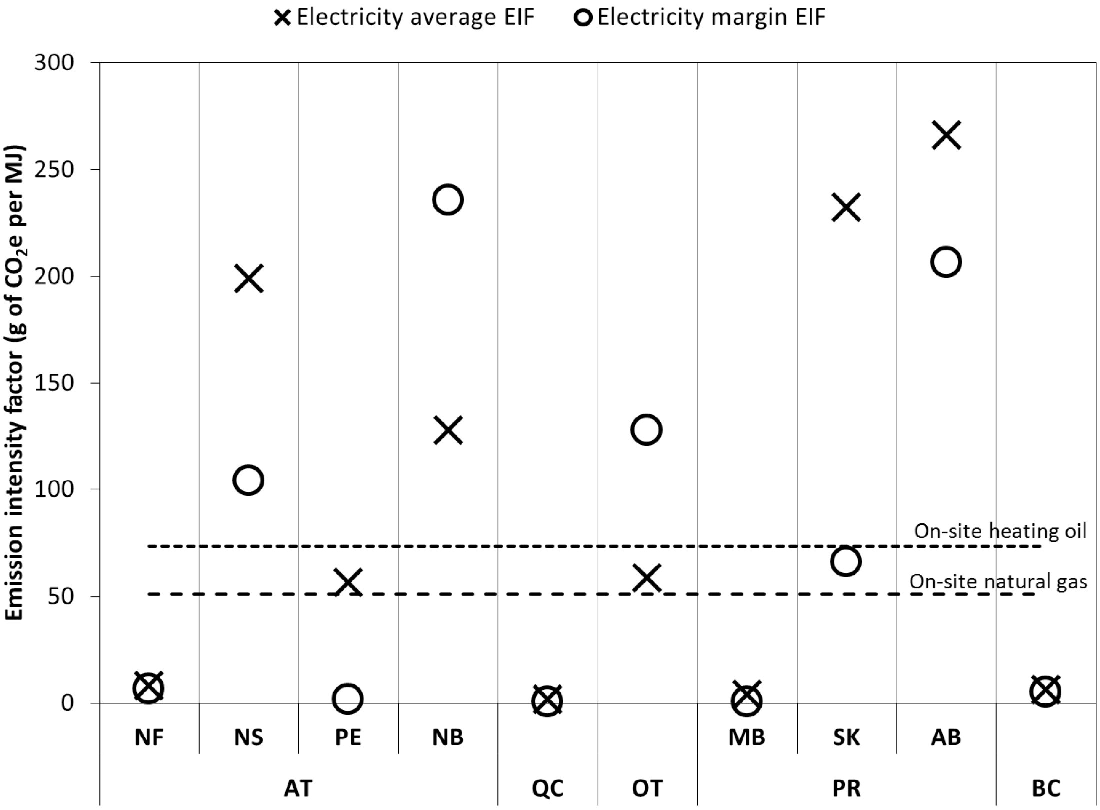


Figure 6.3 Provincial GHG emission intensity factors for electricity generation including transmission/distribution losses and shown with on-site heating oil and natural gas values

It is important to note that the electricity generation GHG EIFs are subject to changes in the generation energy sources. At present, there are numerous ongoing projects within the Canadian electricity generating sector to reduce the use of coal and increase the use of renewable energy and nuclear energy. These changes will result in a reduction of the electricity generation GHG EIFs in the near future, and thus influence the GHG emissions results of the CHREM.

6.2.4.3 Application of GHG EIFs to the CHREM Energy Results

The GHG EIFs listed in Tables 6.5 and 6.7 form the basis of the CHREM GHG emissions calculations. In practice, the GHG EIF of fuel use at a house site varies insignificantly throughout the year. Thus, the GHG EIFs presented in Table 6.5 are used as direct multipliers to the end-use energy consumption of natural gas and heating oil. In contrast, the GHG emissions caused by the use of electricity vary greatly by province, include a loss for transmission/distribution, and may vary by month. It is important to note that the provinces within a region have dramatically different GHG EIFs. For example, the provinces NF (hydro powered electricity, 26 g of CO_2e per kW·h) and NS (coal powered electricity, 689 g of CO_2e per kW·h) are both in the Atlantic region. Because of these variations, all houses of the CHREM were subsequently examined on a provincial level as opposed to a regional level. The determination of the provincial representation is discussed in section 6.2.6.

A baseline GHG emission value due to electricity consumption of the CHREM was calculated by increasing the energy consumption to account for provincially specific transmission/distribution *losses,* and then multiplying by the annual average GHG EIF. When technology upgrades or retrofits are applied to a CHREM house, the electricity energy savings (difference between the base/upgraded cases) are increased to account for transmission/distribution *savings*, and are then multiplied by the marginal GHG EIF corresponding to the appropriate month.

As an example of these GHG emissions calculations, the example Ontario house of Tables 6.3 and 6.4 is shown again in Table 6.8 with GHG emissions estimates for both natural gas and electricity.

Table 6.8 Example of CHREM end-use energy consumption by energy source for an annual simulation of single-detached two storey dwelling in the province of Ontario

End-use	Energy source	Energy (GJ)	Quantity	GHG emissions (kg of CO_2e)
SH	Natural gas	106.5	2863 m^3	5400
SC	Electricity	7.7	2116 kWh	448
AL	Combined	20.5		1187
AL	*Electricity*	*18.1*	*5026 kWh*	*1064*
AL	*Natural gas*	*2.4*	*65 m^3*	*123*
DHW	Natural gas	22.2	598 m^3	1127
Combined	Electricity	25.7	7142 kWh	1512
Combined	Natural gas	131.1	3526 m^3	6650
Combined	Combined	156.8		8162

6.2.5 Issues Encountered during Simulation

Although numerous range checks and considerable attention was placed on generating valid house models for the building simulation engine ESP-r, there were certain issues that became apparent during simulation. Although undesirable, this was expected as the variation among houses is great.

Of the 16,952 houses models generated for ESP-r, only 33 simulations failed; a failure rate less than 0.2%. The failures were typically caused by a LW radiation correlation that resulted in simulator instability, producing out of bounds errors or causing a permanent hang. A number of the unstable simulations were examined and no distinct trend for failure appeared. To avoid having to troubleshoot each of these hanging simulations individually, a timer was used to terminate simulations lasting longer than 500 seconds. This value is considerably larger than the average 112 second simulation, so as to account for complicated houses. The time limit may be changed for future simulations which involve complicated technology additions.

In rare cases (9 total), the post-timestep HVAC method described in section 5.9 would produce erroneous results on start-up. These were an order of magnitude larger than expected. A ratio of the zone energy requirements and the end-use energy consumption for SH and SC was used to identify this issue. The annual heating coefficient of performance was allowed to vary from 0.15 to 7.00, representative of a wood fireplace and high performance GSHP, respectively. The annual cooling coefficient of performance was limited from 1.5 to 8.0, representative of a variety of air-conditioning systems. In the event that a house had a coefficient of performance outside these ranges, its results were discarded. Note that if the CHREM did not examine energy consumption from both the zone and end-use perspectives (see section 6.2.2), this issue would not have been identified.

6.2.6 Scaling of Results to a National Context

Because of the 33 failed simulations, the scaling factors vary among regions. In addition, the GHG EIFs are specific to provinces. To account for this, a scaling factor based on successful simulations and provincial representation was used. The Survey of Household Energy Use 2003 (SHEU-03, OEE 2006) formed the regional basis of the CSDDRD and those values were used to represent regions. In order to determine multipliers specific to provinces, the provincial distribution of houses from Census 2006 (Statistics Canada 2006) was applied to the SHEU-03 regional values. This process is shown in Table 6.9, where the Atlantic and Prairies regions are separated by province with consideration given to house type.

Table 6.9 Scaling targets by province and house type based on SHEU-03 and Census 2006 distributions

	SHEU-03		Census 2006		CHREM targets	
Region or province	SD	DR	SD	DR	SD	DR
Atlantic	662335	94150				
Newfoundland			22.5%	27.7%	148879	26098
Nova Scotia			39.2%	41.2%	259392	38778
Prince Edward Island			5.9%	6.4%	38980	6014
New Brunswick			32.5%	24.7%	215084	23260
Quebec	1513497	469193			1513497	469193
Ontario	2724438	707777			2724438	707777
Prairies	1381219	246848				
Manitoba			22.1%	14.0%	305111	34609
Saskatchewan			20.7%	11.9%	285601	29494
Alberta			57.2%	74.0%	790508	182745
British Columbia	910051	203449			910051	203449
Sum	7191540	1721417			7191540	1721417

The scaling factors were calculated by dividing the CHREM targets shown in Table 6.9 by the number of successfully simulated houses for the province and house type. The scaling factors are shown in Table 6.10. The original intention of the CSDDRD was to have similar scaling factors for each region, thereby having equal representation. It successfully achieved that goal with scaling factors of approximately 500, as shown for most provinces in Figure 6.4. Because the CSDDRD was not selected on a provincial basis, the scaling factors for the Atlantic and Prairies regions vary more significantly. Newfoundland, New Brunswick, and Saskatchewan are notably underrepresented in Figure 6.4 (especially in the case of DR houses), indicated by their higher scaling factors. The variance is not expected to have a significant impact on energy estimations because each province continues to have more than a dozen houses of each type that were successfully simulated (see Table 6.10). The DR house type in Saskatchewan is the least represented, with 13 simulations corresponding to unique houses within the province.

Table 6.10 CHREM scaling factors calculated as the ratio of targets and successful simulations

	Successful simulations		Targets		Scaling factors	
Region or province	SD	DR	SD	DR	SD	DR
Newfoundland	179	22	148879	26098	831.7	1186.3
Nova Scotia	629	84	259392	38778	412.4	461.6
Prince Edward Island	65	14	38980	6014	599.7	429.6
New Brunswick	396	17	215084	23260	543.1	1368.2
Quebec	2874	796	1513497	469193	526.6	589.4
Ontario	5389	1231	2724438	707777	505.6	575.0
Manitoba	858	78	305111	34609	355.6	443.7
Saskatchewan	188	13	285601	29494	1519.2	2268.8
Alberta	1655	347	790508	182745	477.6	526.6
British Columbia	1770	314	910051	203449	514.2	647.9
Canada	14003	2916				

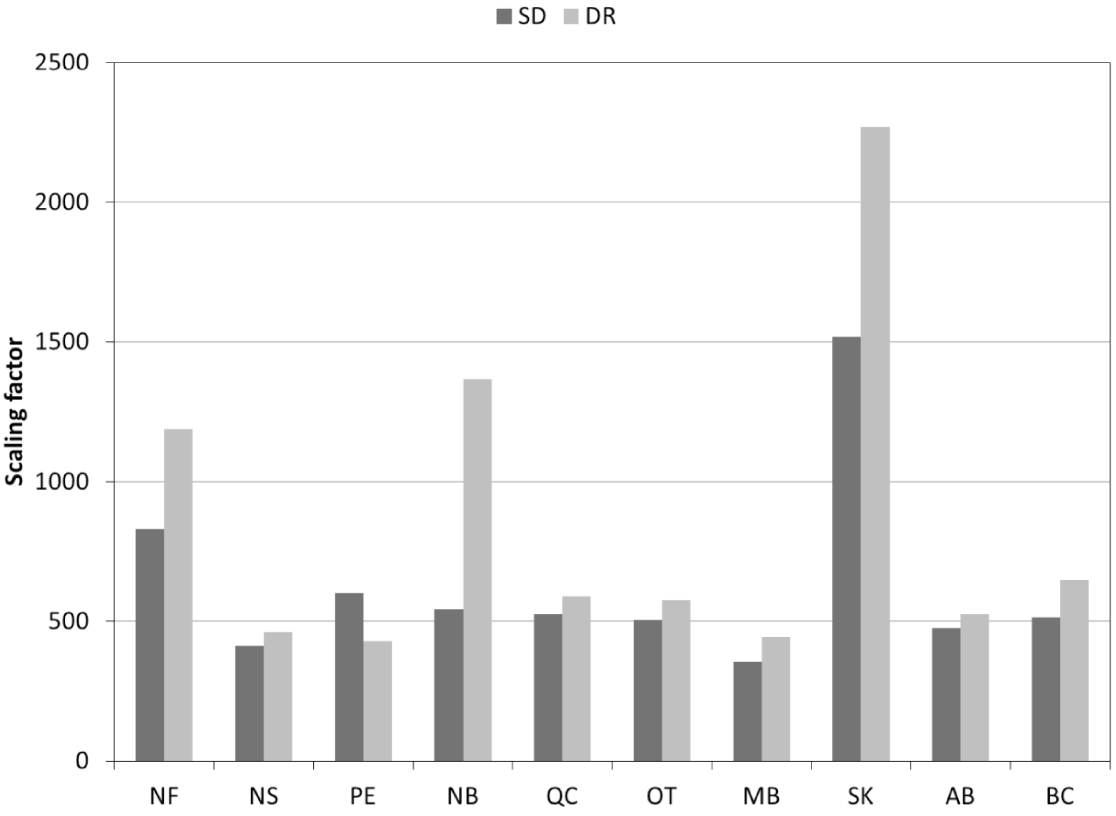


Figure 6.4 CHREM scaling factors by province and house type

6.3 Results

The simulation of the CHREM houses produced results files which were used to calculate GHG emissions and were then scaled to be representative of the CHS. The results were summarised in a variety of fashions and examined, with the most detailed version being categorized as follows:

- House types (SD or DR)
    - Provinces (10 locations)
        - End-uses (SH, SC, DHW, AL)
            - Energy sources (electricity, natural gas, oil, wood)

It was found that the results of both house types were similarly distributed among the subcategories. As well, the effects of different energy sources on each particular end-use could be discerned by examining summarized end-use and energy source information together. Thus, the results are summarized below either by house type, province, or at a national level, and either by end-use or energy source according to the following categories:

- House types
    - End-uses
    - Energy sources
- Provinces
    - End-uses
    - Energy sources
- National level
    - End-uses
    - Energy sources

The following sections present the CHREM estimates on a per house and national scale. These are then compared with national estimates of other models or surveys, and then verified against billing data. All of the following results were obtained using a simulation timestep of 60 minutes. A second run of simulations was conducted with a 30 minute timestep and no appreciable differences were obtained. This agreement is due to the use of the idealized SH and SC systems described in section 5.9. It is expected that in future use the CHREM will model discrete system technologies (such as building integrated photovoltaic-thermal panels) and a shorter timestep will be employed.

6.3.1 CHREM per House Estimates of Energy Consumption and GHG Emissions

The CHREM estimates were examined from the perspective of the *energy requirements* of the thermal zones as well as the end-use *energy consumption*. The energy requirement of the thermal zones is used as an indicator of the thermal performance of the housing envelope. Because it is only a function of heat losses and gains, it is not associated with the performance of SH or SC energy conversion equipment. On the other hand, the end-use energy consumption reflects the performance of the active SH, SC, and DHW system equipment, in addition to the energy requirement of the thermal zone. Representative statistics of the CHREM energy estimates are shown in Table 6.11. Note that statistics of each field are exclusive (i.e. the maximum SH performance is not the ratio of the maximum zone energy requirement and end-use energy consumption). Each of these statistics is considered individually below.

Table 6.11 Representative statistics of the CHREM annual energy estimates

	Space heating		
Statistic	Thermal zones energy requirement (GJ)	End-use energy consumption (GJ)	Performance (COP)
Minimum	1.2	1.2	0.3
Maximum	376.2	685.8	3.3
Average	77.1	96.9	0.8
Standard deviation	37.6	52.0	0.2

	Space cooling		
Statistic	Thermal zones energy requirement (GJ)	End-use energy consumption (GJ)	Sensible performance (COP)
Minimum	1.2	0.7	1.5
Maximum	59.4	21.7	3.4
Average	11.6	5.7	2.0
Standard deviation	4.5	1.9	0.2

Statistic	DHW (GJ)	AL (GJ)
Minimum	5.8	10.1
Maximum	48.2	85.1
Average	21.8	27.7
Standard deviation	3.7	10.0

The minimum SH energy estimates shown in Table 6.11 are both 1.2 GJ. These correspond to a small, single main level house with no foundation zone (as shown in Figure 5.4a on page 127), that has well insulated walls and small windows. It is located in Halifax, NS (see HDD field in Appendix A), is a DR house type with a shared (adiabatic) end-wall, and employs electric heating. Although these characteristics result in low SH energy values, the actual heat loss through the thermal envelope is much larger than 1.2 GJ. The reason for this difference is that the house has an exceptionally large AL energy consumption of 64 GJ, primarily due to its occupancy characteristics. This AL energy consumption provides heat to the dwelling via convection and LW radiation. Effectively, the occupants are heating with AL.

The maximum SH energy estimates differ from one another in Table 6.11. The maximum zone SH energy requirement corresponds to a large multi-level house with poor insulation. The maximum SH end-use energy consumption corresponds to a different house, one that heats with a grossly inefficient wood fireplace. The average and standard deviation of the SH energy estimates in Table 6.11 are representative of the CHS.

The SH performance ranges from 0.3 to 3.3 COP. The minimum value corresponds to a fireplace, and the maximum value to a ground source heat pump. The average is 0.8, or 80% efficiency, and is representative of the combination of electrical, natural gas, and oil fired furnaces and boilers found throughout the CHS.

The range of values seen in the SC statistics of Table 6.11 is primarily a function of climate, house size, and window area. The statistical data is based only on the simulation of houses that have active SC systems. The sensible cooling performance of the SC system averages 2.0 COP. A sensible heat ratio of the cooling coil was specified as 0.75 to account for latent heat transfer, as discussed in section 5.9. Therefore, the average total performance of the SC systems is actually 2.66 COP.

The AL energy consumption shown in Table 6.11 is exactly the same as Table 4.7. This is expected as it was imposed directly into the simulation as boundary condition information.

The DHW average and standard deviation are similar for Tables 4.7 and 6.11, but the minimum and maximum statistics are different. This is because the DHW information from the CHREM statistical method was imposed upon the CHREM engineering method as volumetric flow rate, not energy consumption. This allows the CHREM engineering method to simulate the specific equipment functionality. The minimum DHW value of Table 6.11 is half that of Table 4.7, and is associated with the use of a heat pump. The maximum DHW value of Table 6.11 is 20% more than that of Table 4.7, and is associated with an oil fired tankless heating coil (40% energy factor).

6.3.2 CHREM Estimates of Annual Energy Consumption and GHG Emissions by House Type and Region

The CHREM estimates of house energy consumption and GHG emissions were scaled to be representative of the CHS. A complete list of CHREM annual energy consumption and GHG emissions estimates by house type, province, end-use, and energy source is provided in Appendix C. As previously described, the results are presented here by end-use and by energy source, and are shown by house type and province. As will be shown, it is important to consider the end-use and energy source estimates together for interpretation purposes.

The annual summaries of energy consumption and GHG emissions as a function of end-use and energy source are shown in Tables 6.12 and 6.13. The CHREM estimates annual total end-use energy consumption for the SD and DR house types of the CHS at 1312.4 PJ, which results in GHG emissions of 65.98 Mt of CO_2e. The SD house type contributes to over 80% of this energy consumption. GHG emissions are not shown by house type as they are strongly influenced by province.

By examining the estimations for all of Canada in Tables 6.12 and 6.13, it is evident that SH is the dominant end-use in the CHS with regard to both energy consumption and GHG emissions. The total energy consumption is primarily supported by electricity and natural gas, each contributing significantly to GHG emissions.

Table 6.12 CHREM estimates of annual energy consumption and GHG emissions as a function of end-use

House type or province		Energy (PJ)					GHG emissions (Mt of CO_2e)				
		SH	SC	DHW	AL	Total	SH	SC	DHW	AL	Total
House type	SD	724.8	10.9	158.9	203.5	1098.1					
	DR	135.8	2.1	33.5	42.9	214.3					
Province	NF	18.7	0.0	2.7	6.0	27.4	0.67	0.00	0.00	0.00	0.67
	NS	31.3	0.0	5.7	10.1	47.1	2.43	0.00	0.97	2.13	5.53
	PE	4.7	0.0	1.2	1.2	7.1	0.20	0.00	0.03	0.12	0.35
	NB	27.9	0.0	4.1	6.4	38.4	1.63	0.00	0.51	0.95	3.09
	QC	162.6	1.8	38.3	47.1	249.8	2.46	0.00	0.01	0.12	2.59
	OT	361.7	10.1	77.2	85.8	534.8	19.57	0.57	4.07	4.98	29.19
	MB	37.0	0.2	7.2	8.2	52.6	1.50	0.00	0.21	0.00	1.71
	SK	35.5	0.3	9.0	8.3	53.1	2.14	0.08	0.54	1.73	4.49
	AB	97.3	0.0	24.6	27.5	149.4	4.94	0.03	1.37	7.43	13.77
	BC	83.9	0.6	22.4	45.8	152.7	3.66	0.00	0.69	0.24	4.59
Canada		860.6	13.0	192.4	246.4	1312.4	39.20	0.68	8.40	17.70	65.98

Table 6.13 CHREM estimates of annual energy consumption and GHG emissions as a function of energy source

House type or province		Energy (PJ)					GHG emissions (Mt of CO_2e)			
		Electricity	NG*	Oil	Wood	Total	Electricity	NG	Oil	Total
House type	SD	432.4	522.2	108.9	34.6	1098.1				
	DR	91.5	105.4	17.4	0.0	214.3				
Province	NF	14.8	0.0	9.5	3.1	27.4	0.04	0.00	0.63	0.67
	NS	17.9	0.0	23.1	6.1	47.1	3.87	0.00	1.66	5.53
	PE	1.2	0.0	4.2	1.7	7.1	0.12	0.00	0.23	0.35
	NB	17.7	0.0	9.8	10.9	38.4	2.38	0.00	0.71	3.09
	QC	207.1	1.2	30.9	10.6	249.8	0.34	0.06	2.19	2.59
	OT	141.1	344.9	48.8	0.0	534.8	8.28	17.45	3.46	29.19
	MB	20.1	32.5	0.0	0.0	52.6	0.03	1.68	0.00	1.71
	SK	11.6	41.5	0.0	0.0	53.1	2.43	2.06	0.00	4.49
	AB	27.5	121.9	0.0	0.0	149.4	7.58	6.19	0.00	13.77
	BC	64.9	85.6	0.0	2.2	152.7	0.29	4.30	0.00	4.59
Canada		523.9	627.6	126.3	34.6	1312.4	25.36	31.74	8.88	65.98

* Natural gas

For easier comparison of end-uses and energy sources, the estimates of Tables 6.12 and 6.13 were formed into proportioned bar charts which are shown in Figures 6.5 (page 203) and 6.6 (page 204). The figures indicate the proportion of energy use and GHG emissions attributable to each end-use and energy source and are shown for each house type, province, and Canada.

By examining the energy consumption as a function of end-uses shown in Figure 6.5 on page 203, it is clear that SH is the dominant end-use for all jurisdictions, requiring 60 – 70% of the energy used within the CHS. SC is a relatively insignificant end-use from an energy perspective. The end-uses of DHW and AL are similar in proportion, with AL being slightly larger. The only province which differs significantly in end-use energy consumption distributions is BC. Nearly half of the houses in this province correspond to the Vancouver climate which is notably warm (see HDD field in Appendix A). It is interesting to note how similar the energy consumption distribution is between house types. The SH proportion is slightly less for the DR house type due to its shared adiabatic wall.

The GHG emissions distributions as a function of end-uses show substantial differences in Figure 6.5. This is because of the variety of energy sources used to meet the SH and DHW loads, and the variation in electricity GHG EIFs as a function of province. Because of these relationships, further interpretation of the GHG emissions as a function of end-use requires additional information. It is interesting to note that in NS and AB (primarily coal generated electricity), SH has the least influence on GHG emissions. This is because the GHG EIF of the natural gas and oil used for SH is significantly less than the GHG EIF of electricity used for AL. In contrast, in the provinces of NF, QC, MB, and BC (primarily hydro generated electricity), SH has the most influence on GHG emissions. Although substantial portions of their SH is supplied by this zero-emission electricity, the balance of their SH is supplied by fossil fuels which then dominate the distribution. The SC represents only a minor contribution to the total GHG emissions because the energy consumption is small.

The distribution of energy sources as a function of energy consumption and GHG emissions is shown in Figure 6.6 on page 204. The distributions of energy consumption by house type are similar. However, DR houses have no wood related energy consumption, and this is offset by a higher proportion of electricity consumption. It can be seen that easterly provinces (NF, NS, PE, NB, QC) rely primarily on electricity and heating oil, with a notable proportion of wood. Westerly provinces (OT, MB, SK, AB, BC) use natural gas in place of heating oil. QC, a province which has ample access to cheap hydro powered electricity, predominantly uses electricity.

The relationship between energy consumption and GHG emissions for particular energy sources is also shown in Figure 6.6, and is much stronger than that associated with specific end-uses. As it is a renewable resource, there are no non-cyclic GHG emissions attributed to wood consumption. Although the Atlantic provinces (NF, NS, PE, NB) have similar distributions of energy consumption by energy source, their GHG emission distributions vary dramatically. This is due to variation in the electrical generation GHG EIFs as shown in Table 6.7 on page 190. The province of QC primarily uses electricity, but its GHG emissions come from the use of heating oil.

The Prairies provinces (MB, SK, AB) and BC exhibit energy source GHG emission distribution behaviour similar to Atlantic province, again based on electricity generation. As shown in Figure 6.6, the GHG emissions of MB and BC are dominated by natural gas use, as both provinces have hydro based electricity. The provinces of SK and AB have even GHG emissions distributions among electricity and natural gas, owing to their coal based electricity generation.

The proportions of energy consumption and GHG emissions of Canada shown in Figure 6.6 are similar. This indicates that the average national electricity GHG EIF is similar to that of natural gas, with respect to the energy source consumption distribution found in the CHS.

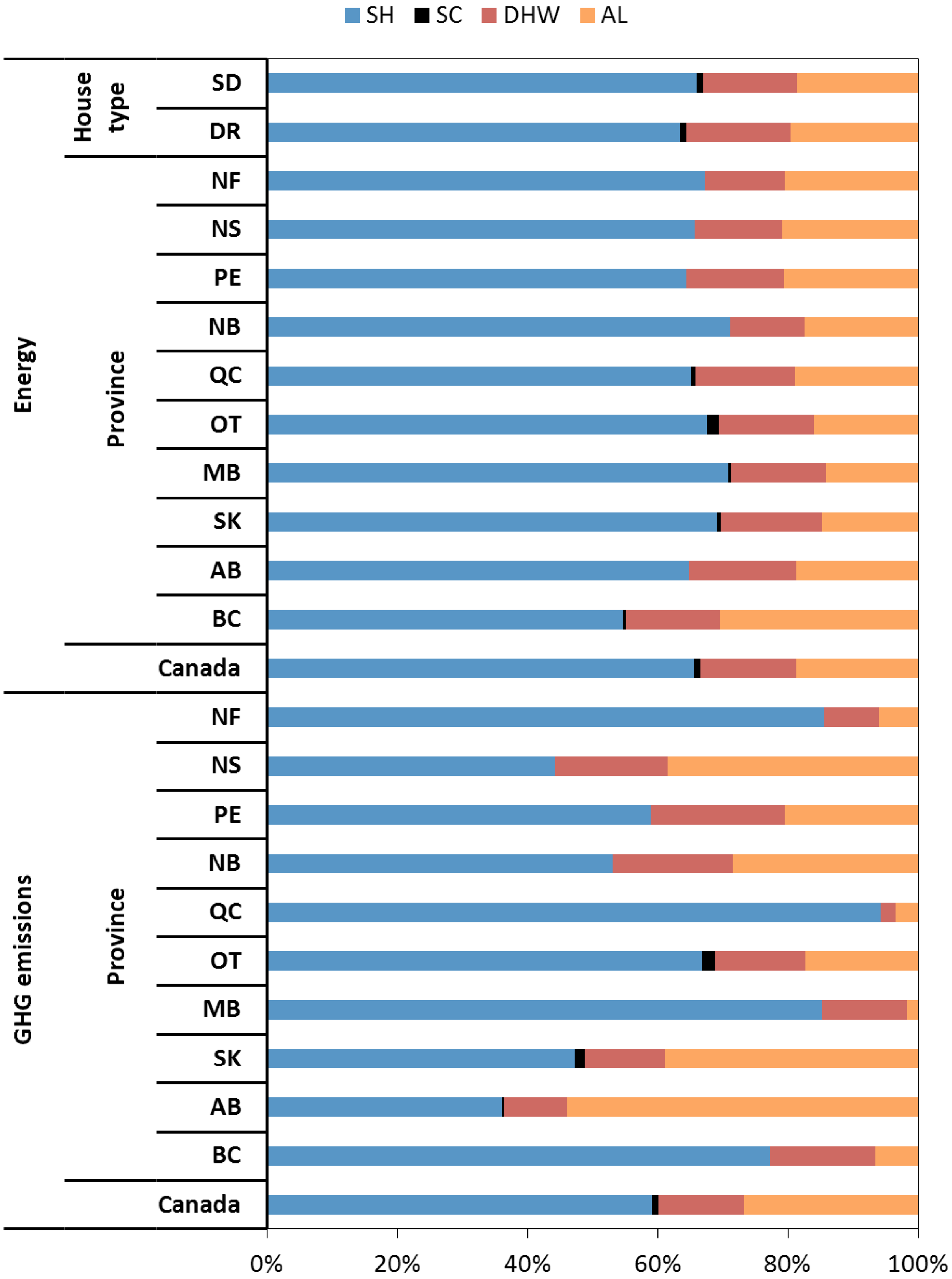


Figure 6.5 Distribution of the CHREM estimates of annual energy consumption and GHG emissions as a function of end-use

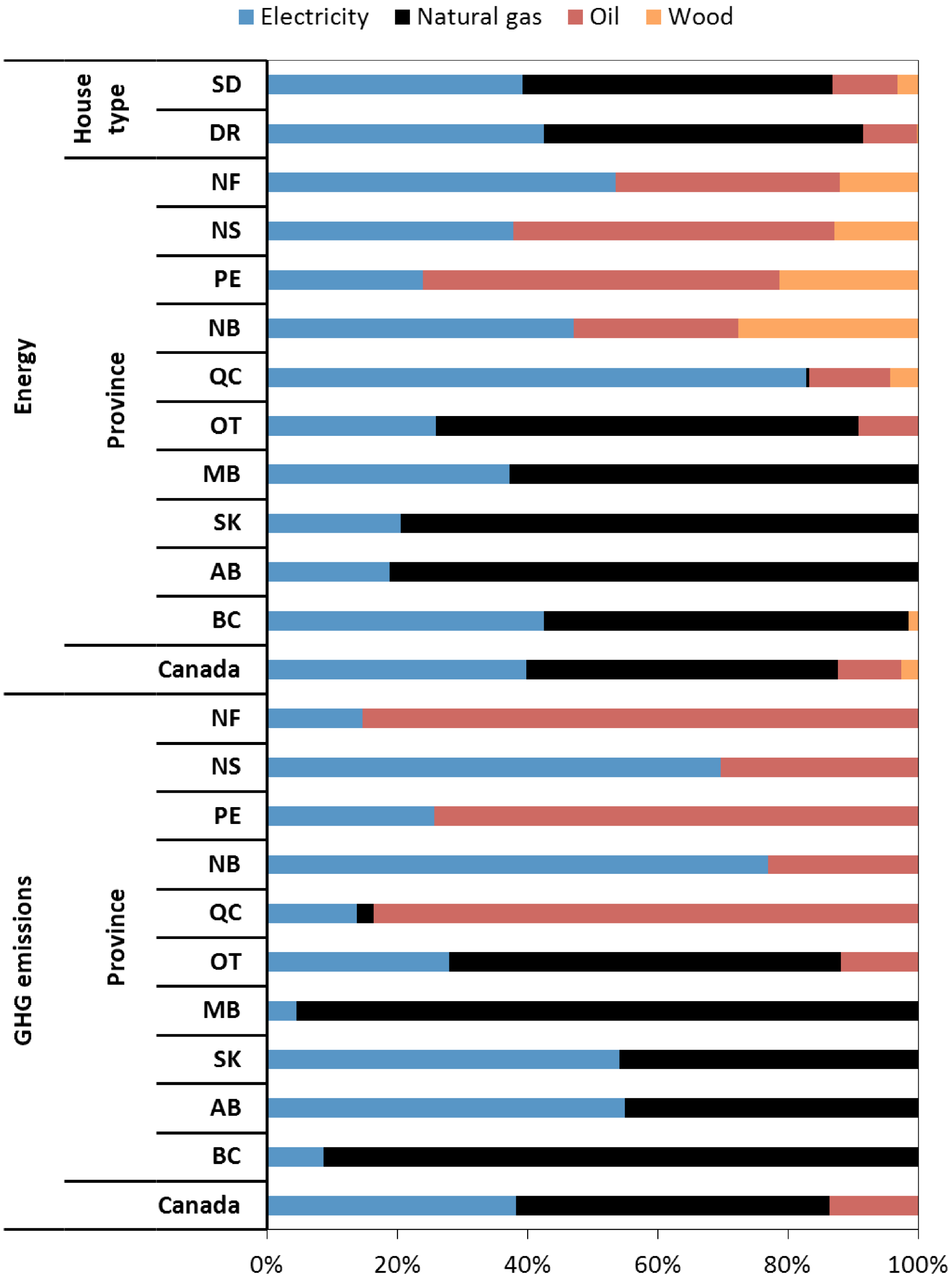


Figure 6.6 Distribution of the CHREM estimates of annual energy consumption and GHG emissions as a function of energy source

The ratio of the annual CHREM end-use estimations of GHG emissions and energy consumption shown in Table 6.12 can be used to assess the average GHG EIFs attributable to individual end uses. These ratios are shown by province and for Canada as a whole in Figure 6.7. Whereas Figure 6.3 on page 191 showed the provincial GHG EIF associated with each energy source (electricity, natural gas, heating oil), Figure 6.7 illustrates the influence and mix of these energy sources on a particular end-use.

As might be expected, the use of hydro generated electricity for most end-uses in the provinces of NF, QC, MB, and BC minimizes their GHG emissions. Because the GHG EIF of electricity and natural gas is similar for the province of OT, all of the end-use GHG EIFs shown in Figure 6.7 for OT are around 60 g of CO_2e per MJ. Due to the electricity generation energy sources in the provinces of NS, NB, SK, and AB, the GHG EIF of the SC and AL end-uses are much greater than the SH.

The circle markers in Figure 6.7 indicate the overall average EIF of the housing stock in each province, as a result of the combination of energy sources used to meet the end-uses.

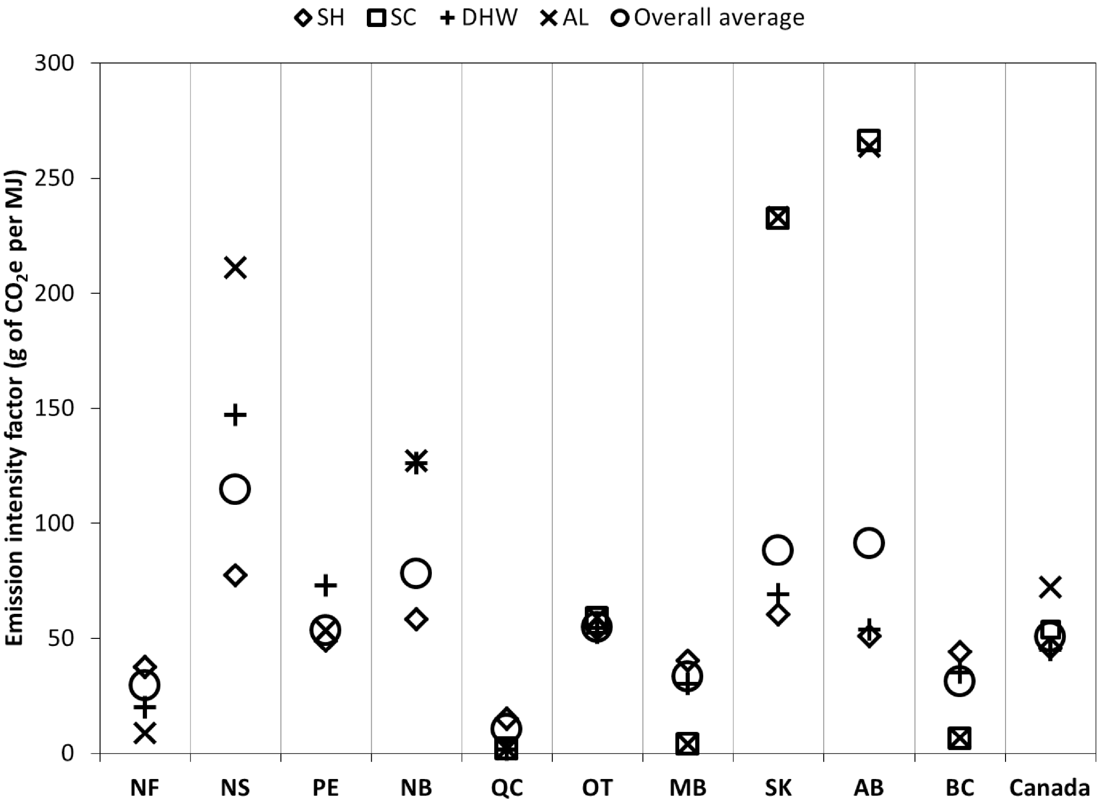


Figure 6.7 **CHREM estimates of annual average end-use GHG EIFs by province and for Canada**

6.3.3 CHREM Estimates of Monthly National Energy Consumption and GHG Emissions

The CHREM was used to investigate the change in energy consumption and GHG emissions of the CHS throughout the year. A complete listing of these values by province, end-use, and energy source is provided in Appendix D (by end-use) and Appendix E (by energy source).

The CHREM monthly national estimates of energy consumption and GHG emissions specific to end-uses is shown in Figure 6.8. It is apparent from Figure 6.8a that although SH is not required in the summertime, this end-use dominates all others due to its significant winter month magnitudes. DHW and AL are consistent energy consumers throughout the year. SC is only present between May and September. The GHG emissions of each end-use shown in Figure 6.8b are of similar distribution to the energy consumption. This is because the average GHG EIFs for electricity generation specified in Table 6.7 on page 190 are annual values. Farhat and Ugursal (2010) specified only marginal GHG EIFs as a function of month.

Figure 6.8 shows that energy consumption and GHG emissions of the CHS vary significantly with season, and are principally a function of SH requirements. Both energy consumption and GHG emissions peak in January due to SH. The energy consumption and GHG emissions during the months of June, July, and August are similar.

The CHREM monthly national estimates of energy consumption and GHG emissions specific to energy sources is shown in Figure 6.9. The natural gas energy consumption shown in Figure 6.9a is primarily a function of SH, but remains at approximately 10 PJ per month during the summer to support DHW. Electricity is also used to supply SH, as indicated by higher estimates during winter months. Electricity consumption does not decrease as dramatically as natural gas consumption during the summer. This is because electricity continues to supply AL. Furthermore, a small increase in electricity consumption can be seen during July and August to supply the SC end-use.

By comparing the relationships between energy sources in Figures 6.9 a and b, it can be determined that during the winter months the use of electricity produces less GHG emissions per unit energy than natural gas. This is because provinces which use considerable amounts of electricity for SH tend to have low average GHG EIFs. This relationship between GHG emissions of electricity and natural gas is opposite for summer months, because the proportion of electricity generated using dammed hydro decreases.

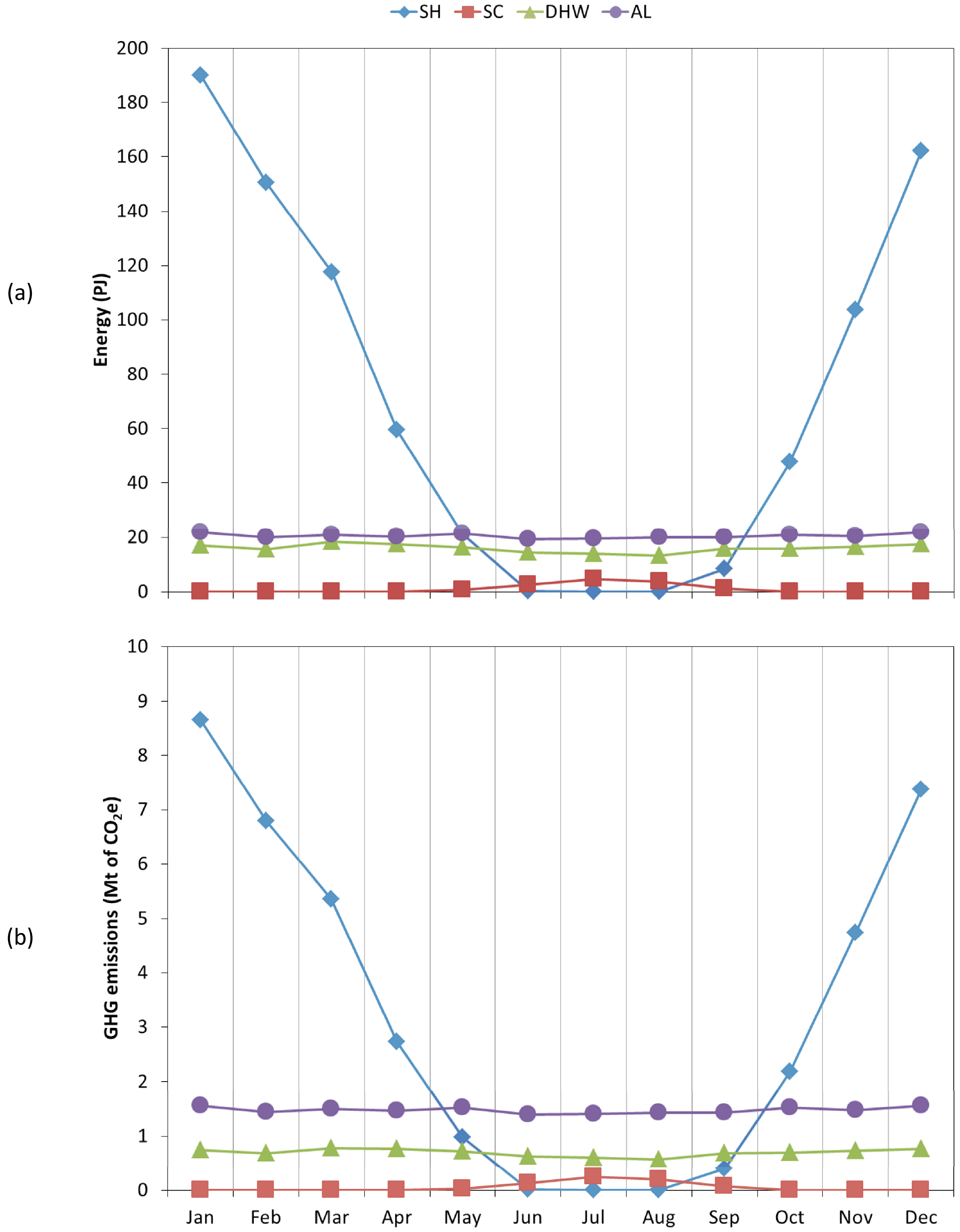


Figure 6.8 CHREM estimates of monthly national (a) energy consumption, and (b) GHG emissions by end-use

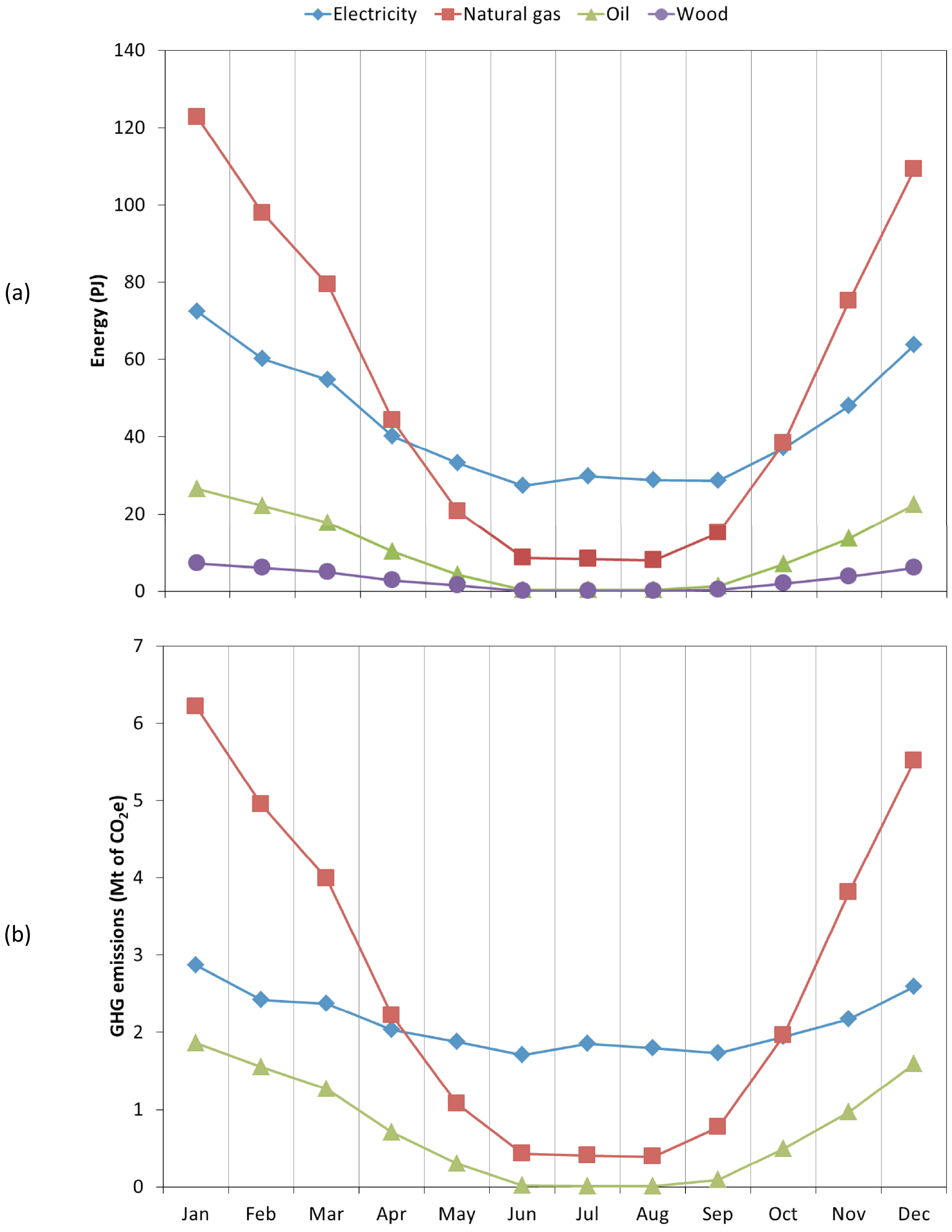


Figure 6.9 CHREM estimates of monthly national (a) energy consumption, and (b) GHG emissions by energy source

6.3.4 Comparison with Other Assessments

As the CHREM is a new model of the CHS, the end-use energy and GHG emissions estimates are compared with other model or survey estimates. Two recent evaluations are available. They are the SHEU-03 (OEE 2006), and the Residential End-Use Model (REUM, OEE 2006b). The SHEU-03 and the REUM were introduced in sections 3.3.2 (page 65) and 4.4.3 (page 105), respectively.

The SHUE-03 reports estimates of energy consumption by both house type and region and accumulates these by: total site, electricity, and natural gas. The REUM reports national estimates of both energy consumption and GHG emissions as a function of end-use. The REUM also reports SH and SC by house type. The REUM estimates for DHW and AL were adjusted as described in section 4.4.3 to represent only the SD and DR house types. This facilitates comparison with the CHREM.

6.3.4.1 Comparison with SHEU-03 Assessments Based on House Billing Data

A comparison of the CHREM and the SHEU-03 estimates for both house type and region is shown in Table 6.14. The CHREM estimate of total end-use energy consumption of the CHS is 11% greater than the SHEU-03. This trend is carried throughout all house types and regions, with the only notable exception being the Atlantic region. The CHREM estimates 38% more energy consumption than SHEU-03 for the Atlantic region. This is likely due to the significant use of wood as an energy source, as illustrated for the provinces of NF, NS, PE, and NB in Figure 6.6. Wood energy is particularly difficult for surveys to quantify due to the sparse volumetric delivery format (subject to splitting/stacking technique) and moisture content.

The CHREM and SHEU-03 estimates of natural gas consumption shown in Table 6.14 are in reasonable agreement. In certain cases, the electricity consumption estimates of the CHREM are considerably more than the SHEU-03 (e.g. 33%). This difference may be attributed in part to the different scoping of the CHREM and SHEU-03. The CHREM examined houses on a provincial level, and was capable of identifying differences in the energy source distributions of provinces within a particular region (see Figure 6.6). The SHEU-03 reported results on a regional level while surveying houses on a provincial level (OEE 2006). However, the provincial distribution of SHEU-03 samples was not equivalent to provincial house distributions (Statistics Canada 2006).

Table 6.14 Comparison of the CHREM and the SHEU-03 annual energy consumption estimates by house type and region for the SD and DR house types

House type or region		Energy type	CHREM (PJ)	SHEU-03 (PJ)	CHREM/SHEU-03 ratio
House type	SD	Total	1098.1	989.5	1.11
		Electricity	432.4	372.4	1.16
		Natural gas	522.2	494.6	1.06
	DR	Total	214.3	193.4	1.11
		Electricity	91.5	75.4	1.21
		Natural gas	105.4	105.4	1.00
Region	AT	Total	120.0	87.1	1.38
		Electricity	51.6	41.3	1.25
		Natural gas	0.0		-
	QC	Total	249.8	217.5	1.15
		Electricity	207.1	156.1	1.33
		Natural gas	1.2		-
	OT	Total	534.8	493.4	1.08
		Electricity	141.1	144.0	0.98
		Natural gas	344.9	311.1	1.11
	PR	Total	255.1	251.2	1.02
		Electricity	59.2	56.3	1.05
		Natural gas	195.9	192.8	1.02
	BC	Total	152.7	133.5	1.14
		Electricity	64.9	50.3	1.29
		Natural gas	85.6	76.4	1.12
	Canada	Total	1312.4	1182.9	1.11
		Electricity	523.9	447.8	1.17
		Natural gas	627.6	600.0	1.05

6.3.4.2 Comparison with REUM Assessments Based on Aggregate Billing Data

A comparison of the CHREM and REUM (average of years 2000–2004) estimates for both end-uses and energy sources as a function of energy consumption and GHG emissions is shown in Table 6.15. Overall, the CHREM estimates 14% greater energy consumption and 9% greater GHG emissions than the REUM. With regard to the DHW and AL end-uses, the totals are similar, but the individual contributions are different between the models, as described in section 4.4.3 on page 105. The SH and SC end-uses also vary between the models, but the SH magnitude dominates. The CHREM estimates greater energy consumption for all energy sources with the exception of wood. The CHREM estimates only half the wood use of REUM. This may be due in part to the use of wood as an alternative SH energy source, a characteristic not modeled by the CHREM. Further discussion of the differences of the CHREM and REUM energy consumption estimates is continued in the following section.

Table 6.15 Comparison of the CHREM and the REUM-00-04 national annual energy consumption estimates by end-use and energy source for the SD and DR house types

End-use or energy source		Energy			GHG emissions (CO_2e)		
		CHREM (PJ)	REUM-00-04 (PJ)	CHREM/ REUM-00-04 ratio	CHREM (Mt)	REUM-00-04 (Mt)	CHREM/ REUM-00-04 ratio
End-use	SH	860.6	714.4	1.20	39.20	34.50	1.14
	SC	13.0	16.2	0.80	0.68	1.00	0.68
	DHW	192.4	237.7	0.81	8.40	13.00	0.65
	AL	246.4	184.5	1.34	17.70	11.70	1.51
Energy source	Electricity	523.9	413.1	1.27	25.36	25.60	0.99
	Natural gas	627.6	533.5	1.18	31.74	25.30	1.25
	Oil	126.3	103.8	1.22	8.88	7.20	1.23
	Wood	34.6	91.2	0.38	0.00	1.00	0.00
	Total	1312.4	1152.8	1.14	65.98	60.30	1.09

6.3.4.3 Differences in the Assessment Methods

In general, there is reasonable agreement between the national estimates of the CHREM, SHEU-03, and REUM. The CHREM consistently estimates greater values of energy consumption and GHG emissions for the significant end-uses and energy sources. As described in section 4.4.3, it is important to consider the differences in the estimation method and underlying assumptions when comparing the CHREM, SHEU-03, and REUM.

The SHEU-03 is a survey of households, and as such collected information on the housing stock from a representative sample and scaled these results to a national context. Of the 4551 participating households, energy supplier billing data was acquired from approximately half (a combination of consent rate and data received data rate, OEE 2006). In this fashion the SHEU-03 estimates are a bottom-up estimation. They rely on actual house billing data which is a great strength. However, it is likely that only easily accessible billing data was made available, and the data may be isolated to particular regions due to supplier response. Furthermore, the survey was conducted with a regional context, as opposed to a provincial context.

The top-down approach of the REUM relies on aggregate billing data, annual stock appliance assessments (primarily related to sales data), approximate usage profiles, and appliance unit energy consumption. The primary strength of the REUM is that the response rate of energy suppliers for aggregate data is likely high. However, it struggles in disaggregating this among end-uses due to the wide variety of thermal envelopes and energy conversion systems present in the CHS.

The commonality between the SHEU-03 and REUM is that they rely on billing data. This is often an accurate source of information so long as it is comprehensive (i.e. all energy sources are included) and is acquired from representative houses and energy suppliers well distributed throughout Canada. One of the best attribute of billing data is that it is irrespective of the thermal envelope, active energy conversion systems, and occupant control (e.g. DHW use, heating setpoint). However, the use of billing data suffers from unreported energy deliveries, an example being wood. Thus, the national energy consumption values of the SHEU-03 and REUM are likely less than the actual CHS energy consumption.

In contrast, the CHREM estimates are based on bottom-up methods and simulation which captures the wide variation in the CHS. Each end-use is specifically modeled based on its characteristics. This allows the CHREM to clearly differentiate between different end-uses and energy sources. The assumptions that were made in order to simulate the CHREM are of critical importance. Figure 6.5 shows that SH is the dominant end-use energy consumption, and in most cases the end-use which results in the most GHG emissions. Therefore, the principal assumption that most strongly affects energy consumption and GHG emissions is that of the SH control strategy.

As described in section 5.8 on page 172, all houses of the CHREM were modeled with a fixed temperature setpoint of 21 °C, and have SH available during the period of September 17 – June 3. In reality, occupants tend to set the temperature back during vacation periods, and may employ a setback type thermostat. Furthermore, occupants may make a subjective assessment to set the thermostat to off during certain days of the spring/fall seasons. Because of the fixed setpoint and SH availability, it is expected that the CHREM would estimate energy consumption greater than the actual value of the CHS.

To examine the effect of the temperature setpoint, a heating setpoint value of 19 °C was applied to the CHREM, and the houses were re-simulated. The total end-use energy consumption dropped to 90% of the original estimate. This illustrates that the choice of temperature setpoint is indeed a principal assumption that strongly affects energy consumption.

Occupancy also plays a role in the CHREM estimating greater energy consumption than SHEU-03 and REUM. The CHREM assumes continuous occupancy of the housing stock. Periods of non-occupancy, such as vacations and illness, tend to reduce energy consumption.

6.3.5 Verification of the CHREM Estimating Process using Billing Data

One of the critical assessments of any energy model is its comparison with a known or measured value. For the CHREM, this involves comparing the distinct house estimates with actual billing data. A number of different information sources were examined to determine if suitable billing data and house information was available.

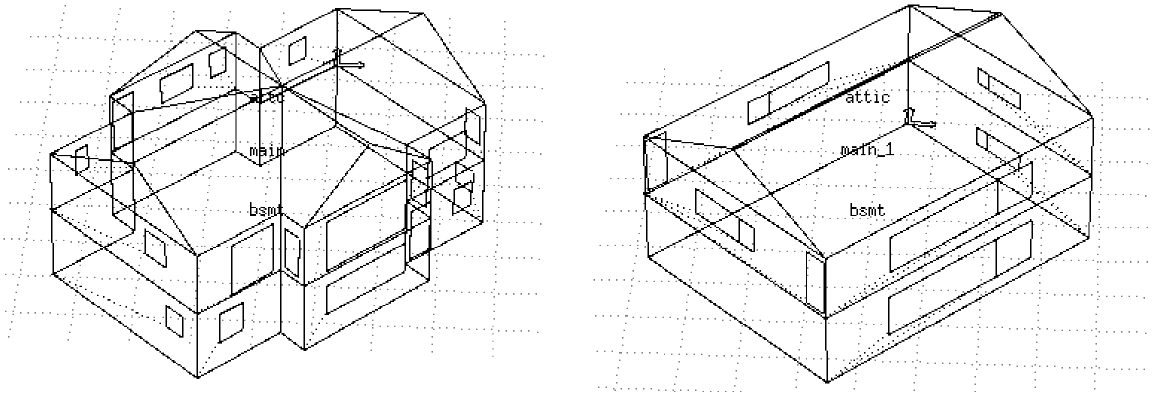
> The CSDDRD is based upon the EnerGuide for Houses Database (EGHD, Blais et al. 2005). The EGHD consists of house energy audit information that was input to the HOT2XP building energy analysis software (CANMET 2008b) by professional energy auditors. The interface does have input fields for billing data; however, an assessment of the data indicated it was unreliable. The results of the HOT2XP

> energy analysis are available for each house of the CSDDRD, but these are energy estimates as opposed to billing data.
>
> The SHEU-03 has billing data. However, the survey primarily focuses on the AL characteristics and does not contain sufficient information on the thermal envelope for building energy simulation. Furthermore the database is unavailable to the public (OEE 2006).
>
> A database of descriptions complete with billing data for 2524 houses was developed for Canada by Farahbakhsh et al. (1998). The database is available, but was intended for use with the HOT2000 building energy analysis software (CANMET 2008). Thus, the data does not contain sufficient information to develop a three dimensional building thermal envelope. If this dataset were to be used it would require a completely different set of assumptions and method from that described in Chapter 5.

As shown, there is no database that contains sufficient information and billing data suitable for assessing the CHREM estimation accuracy or calibrating the CHREM. This is because surveys or building assessments tend to focus either on the thermal envelope and energy conversion equipment, or the appliance and occupancy characteristics. In most surveys or building assessments the information acquired is insufficient to conduct a detailed thermodynamic analysis of the house.

In lieu of a database with sufficient information and billing data to examine the estimation capabilities of the CHREM, the author's house was utilized. It is a one-storey bungalow with a walkout basement, located just outside Halifax, NS. The basement and main level are 115 m^2 each, have an aspect ratio of 1.3, and are typical wood framed construction with 140 mm thick fiberglass batt cavity insulation. There is 29 m^2 of double-glazed clear-glass windows, with the majority facing southeast. Two insulated doors are present. The house air leakage was characterized with a blower door test (the results are shown in Figure 5.19 on page 160), and a heat-recovery ventilator is present. The SH system is provided by an air-source heat pump (rated performance 3.0 COP). The DHW system is a conventional 270 L storage tank with 4500 W electric elements and insulated piping. Two working occupants inhabit the dwelling. Common appliances include a refrigerator and freezer, stove, clothes washer and dryer, and microwave, as well as a host of normal electronic items. Because the SH, DHW, cook stove, and clothes dryer all use electricity, this is the only energy source provided to the house. The annual electricity consumption of the house, as determined from electricity billing data, is 58.8 GJ (16,319 kW·h).

The input data of the author's home was provided to the CHREM in exactly the same fashion as the CSDDRD, so as to exercise the interpretation and house model generation methods defined in Chapter 4 and Chapter 5. To illustrate the adequacy of the CHREM geometric and surface interpretation, a comparison with a realistic representation was made. Figure 6.10a shows a rendering of the author's house with each unique surface described and the house footprint, layout, and roof ridgelines followed exactly. Figure 6.10b shows the CHREM interpretation based on the information provided in the CSDDRD format. It is obvious that the CHREM rectangularized the footprint but maintained the aspect ratio. The roof ridgeline follows the longer of the sides. The amalgamated windows were placed on the appropriate sides, including the walkout basement. The simulated space heating energy requirements of the two representations shown in Figure 6.10 differ by less than 5%, indicating the CHREM provides an adequate three dimensional and surface representation of the house that is suitable for whole building energy performance simulation.



(a) (b)

Figure 6.10 ESP-r rendering of the author's home by (a) geometrically representative of each unique surface, and (b) as developed using the CHREM

The results of the CHREM simulation of the author's house are shown in Table 6.16 for two cases. The base case is exactly how the CHREM interprets and generates the house for typical simulation. A modified case was included to account for variations in the occupant control, of which the author is aware, that strongly influence energy estimations. There were two changes to the modified case.

- The heating temperature setpoint was reduced from 21 °C to 18 °C. This reduction is highly representative of the house, which conforms to a setback thermostat control. During the morning and evening the house is maintained at 20 °C. Throughout the day (both occupants go to work), and overnight the house is maintained at 16 °C. The temperature periods are of equal length, and a lockout was imposed on the SH system to inhibit the auxiliary heating from being used during a setpoint temperature change.
- The occupants do not use the SC functionality of the air-source heat-pump.

Table 6.16 shows that in the base case the CHREM overestimates the end-use energy consumption by 23%. It should be noted that the SH energy consumption is significantly less than the AL energy consumption and also less than the DHW energy consumption. This is because of the use of the air-source heat-pump technology. When the modifications are made to the simulation in accordance with actual house control operations, the CHREM overestimates the energy consumption by 7%. It should be recognized that the author has an interest in energy consumption, and as a result, actively promotes the turning off of appliances and lighting within the house. This would lead the CHREM statistical method to overestimate the AL energy consumption, as it was calibrated with billing data from randomly selected households. This occupancy effect was not accounted for in the modified CHREM simulation, and is likely the cause of the continued overestimation of energy consumption by 7%.

Table 6.16 Estimation of the author's house annual end-use energy consumption using the CHREM method with a base and modified case

	Statistic	CHREM (base)	CHREM (modified) Heat. temp. setpoint of 18 °C and no SC
Energy (GJ)	SH estimate	16.9	11.8
	SC estimate	4.3	0.0
	AL estimate	32.8	32.8
	DHW estimate	18.2	18.2
	Total estimate	72.3	62.9
	Billing data	58.8	58.8
	Total est./Billing data ratio	1.23	1.07

6.4 Conclusion

Of the 16,952 houses contained in the CSDDRD, well over 99% were successfully generated, simulated, and analyzed using the CHREM. Energy consumption results were examined at two levels (zone and end-use) and were used to calculate GHG emissions. This results technique allowed for the successful identification of houses with issues, identification of building simulator problems, and aided in the explanation of the range of end-use energy consumption estimates.

An assessment of the statistical range of the results was conducted and found to correspond with the wide variety of thermal envelopes, energy conversion technologies, and occupancy use that is found in the CHS. The results of the CHREM were scaled to represent the CHS with consideration given to the provincially specific electricity generation GHG EIFs. In total, the CHREM estimates the energy consumption and GHG emissions of the CHS (SD and DR house types) to be 1312.4 PJ and 65.98 Mt of CO_2e, respectively.

The CHREM estimates were compared with the findings of a housing survey that collected billing data, and a top-down energy model based on aggregate billing data. Additionally, the CHREM estimate of the author's house was compared to actual billing data. The CHREM tends to estimate 11 – 14% greater end-use energy consumption than these comparison estimates. It should be noted that the CHREM was not calibrated with billing data as no suitable database exists. The CHREM also demonstrated its flexibility by conducting additional simulations with modified assumptions for further comparison. Based on the end-use energy consumption distributions illustrated in Figure 6.5, the heating temperature setpoint was identified as the assumption which most strongly influences the CHREM estimates.

It is clear from the results of these additional simulations that the assumptions of the CHREM can significantly affect the end-use energy consumption estimates. Given appropriate assumptions of control and occupancy, the CHREM produces estimates within a reasonable degree of accuracy.

Chapter 7 Evaluation of the Thermal Effects of Windows on the Canadian Housing Stock – a Demonstration of the CHREM

Typical window construction of the Canadian housing stock (CHS) is such that it has low effective thermal resistance, resulting in significant heat loss during the heating season. But windows also admit solar radiation into the dwelling (solar gain). During certain periods, this solar gain can partially or fully offset the heat loss, and may actually contribute to overheating. The previous chapter described the Canadian Hybrid Residential End-Use Energy and GHG Emissions Model (CHREM) assessment methods. As these include both zone *energy requirement* and end-use *energy consumption* summaries, it is possible to use the CHREM to evaluate the influence of windows on the CHS. Such an evaluation can examine the heat loss through the windows, and compare it to the heat gained via short wave (SW) solar radiation that enters the house. Also, using the CHREM, the impact of window upgrades on the energy consumption and GHG emissions can be identified.

This chapter presents a demonstration of the CHREM capabilities by examining the characteristics of the current window stock of the CHS, and a potential upgrade scenario. The existing types of windows and their placement on the houses of the CHS are reviewed. The heat flux impacts due to windows are then evaluated for a range of window types, and an estimate of the heat flux contributions of windows is made for the CHS. These findings are compared and a window upgrade scenario is proposed. Using the CHREM, a window upgrade scenario is introduced to available houses, and the impacts upon both energy consumption and GHG emissions are estimated.

7.1 Introduction

Interest is growing in the use of passive solar technologies as a method to offset space heating (SH) end-use energy consumption in dwellings. Fenestration systems such as advanced windows provide an opportunity to reduce conventional energy consumption by reducing heat loss and increasing the capture and utilization of the renewable solar energy. In addition they provide an aesthetically pleasing environment and natural lighting. Because of the important role windows play in the dwelling environment, an analysis of the present CHS was undertaken using the CHREM. The objective is to determine the impact that windows presently have on the SH energy consumption and to assess the impact of retrofit upgrades. Assessing the contribution of windows to the total energy consumed by the housing stock requires complicated simulation and results analysis to account for all building components and the variety of heat fluxes. There are two aspects of windows which ease this task: i) most of the SW radiation that passes through a window is absorbed within the thermal zone, and ii) windows are opaque to long-wave (LW) radiation. However, there are aspects of windows that also impede assessment, such as:

- The location of the energy control volume around the thermal zone used for assessment purposes can make solar gains appear large or non-existent. For example, if the control volume is drawn around the exterior of the zone surfaces, then absorbed solar radiation will appear high. However, a significant portion of it quickly rejects from the zone to ambient air via convection or LW radiation to the surroundings. Alternatively, if the control volume is drawn around the interior air mass, then the solar gain is indistinguishable, as it enters the air mass via convection from the interior surfaces.
- There are conditions during which it is difficult to identify useful or adverse solar gains. This is because of control strategies, such as opening windows, and other heat gains such as appliances and lighting (AL). For example, consider a thermal zone which is passively rejecting 1 kW to cooler surroundings, requiring the addition of heat. However, because of a 1 kW solar heat gain and 1 kW of AL heat gain, the zone achieves the cooling setpoint, and the active SC system removes 1 kW from the zone to maintain the temperature setting. In this case, 1 kW of the heat gains is useful, offsetting the passive heat loss. The other 1 kW is adverse, requiring the use of the SC system. A hierarchal status must be assigned to the solar heat gain and AL heat gain to determine which is useful or adverse.
- Windows are frequently shaded by exterior obstructions (e.g. other buildings or trees) and there is a lack of data which define these obstructions. However, the impact of exterior obstructions on SH and SC energy consumption can be substantial (Nikoofard et al. 2009).

Windows are an area of active development and have undergone significant improvements in the past decades. These may be grouped into two areas: “center of glass” and “glass edge” (Mitchell et al. 2003). Regarding the center of glass, the migration from single-glazed (SG) to double-glazed (DG) windows has had a significant impact by almost doubling the thermal resistance. More recently, triple-glazed (TG) windows have become commonly available for residential applications. The gaps between the glazing layers come in a variety of widths, typically ranging from 6–13 mm with a slightly increasing effective thermal resistance as a function of thickness. The fill gas in the gaps has evolved from dry-air or nitrogen, to argon and also krypton, increasing the effective gap thermal resistance by 10% or more. Low-emissivity (low-e) coatings may be applied to reduce the LW radiation losses between glazing layers. Coatings such as these can have a major impact on the effective gap thermal resistance, in some cases more than doubling the value. However, coatings also result in increased SW radiation reflection and absorption within the window. This restricts the amount of light that may be used or stored within a dwelling to offset conventional energy consumption.

Regarding glass edge, different materials have been used to seal the gap and space the glazing layers, including aluminum, plastics, and silicon foams. These seek to reduce the conductive heat flow paths along the outer seal of the window. The frame of the window also plays a role as it conducts heat and also provides the seal and sliding mechanism which allows a window to open and close, presenting the opportunity for air leakage. Many frame types (e.g. single-hung, casement) and frame materials (e.g. wood, vinyl) have been developed to fit the application and aesthetic requirement.

7.2 Analysis of Window Data of the Canadian Housing Stock

Window information is supplied by the Canadian Single-Detached and Double/Row Housing Database (CSDDRD). The CSDDRD includes detailed information of the windows of each house. Windows are individually specified for each side of the house, and contain the following descriptive information:

- Height, width, area, and facing direction
- Vertical and horizontal location with respect to eaves
- Number of glazing layers
- Glazing layer coatings
- Gap width and fill gas
- Gap seal and spacer type
- Frame type
- Frame material

A critical examination of the CSDDRD was completed and indicated that the detailed height/width and vertical/horizontal location data are largely unreliable, as determined by inappropriate values. However, the data of window areas and the facing direction, as well as glazing characteristics are valid.

A complete review of the window types present in the CSDDRD was given in section 5.5.3.3 on page 148. This included the window characterization as a function of both thermal and optical properties. There is no available information regarding exterior obstructions that shade components of the house, and as such, the houses are considered non-shaded for this demonstration.

The window parameters may be examined as a function of the following characteristics: window facing direction, type of house, house vintage, and region. The analysis of window types is indicative of the retrofit potential and how it varies, for example, by house characteristics. Such analysis may be used as a guide when evaluating the potential penetration levels of retrofit upgrades.

In the CSDDRD, the windows are represented by a thermal and optical code. A key to these codes was provided in Tables 5.8 (page 148) and 5.9 (page 152). A frequency distribution analysis of the window code for each side of each house of the CSDDRD was conducted. It was found that only 8 of the 25 unique window codes were present in more than 0.5% of the houses. For all subsequent analysis (e.g. by vintage or region), these 8 important window codes reoccurred, and their properties are shown again in Table 7.1. All three glazing layer types: SG, DG, and TG, are significant in the CHS.

Table 7.1 Subset of the CHREM window database that is significant among the CHS

Window code	Glazing layers	Coating	Fill gas	Gap size (mm)	Inside gap resistance (RSI)	Outside gap resistance (RSI)
100	SG	Clear				
200	DG	Clear	Air	13	0.19	
202	DG	Clear	Air	6	0.14	
231	DG	Low-E 0.20	Air	9	0.28	
234	DG	Low-E 0.20	Argon	9	0.37	
301	TG	Clear	Air	9	0.16	0.18
331	TG	Low-E 0.20	Air	9	0.27	0.18
334	TG	Low-E 0.20	Argon	9	0.36	0.21

The window codes in the CSDDRD are listed with regards to front, right, back, and left sides of the house, along with front orientation. Front orientation is defined by cardinal directions (S, E, N, and W) and intermediate directions (SE, NE, NW, and SW). To reduce the current analysis to the four cardinal directions, the intermediate directions SE and SW are considered S, and NE and NW are considered N.

An analysis of window types as a function of cardinal direction was conducted. This was completed by two methods: window count and window surface area. The count method simply bins each occurrence of a window type for a given direction. The surface area method is similar, but instead of binning the occurrence, it bins the corresponding window surface area. The surface area method is more applicable for energy investigation as it attributes more significance to larger windows. Interestingly, both methods produced similar distribution of results, indicating that window size is not strongly correlated to window type for a given cardinal direction.

Table 7.2 shows the distribution of window types for each cardinal direction using the surface area method. DG windows with clear glass and a 13 mm air filled gap (code 200) are the dominant type for all directions, and thus the CHS in general. SG windows (code 100) are also significant. Table 7.2 also shows that the distributions of window types, for the two considered house types, single-detached (SD) and double/row (DR), are very similar. The similarity of window type distributions for cardinal directions and house types is expected as homebuilders tend to install similar window types on all four sides of the house.

Table 7.2 Distribution of window types by surface area corresponding to each cardinal direction and each house type

	Cardinal direction (%)				House type (%)	
Window type (code)	S	E	N	W	SD	DR
100	7.4	8.1	7.0	8.2	7.7	6.8
200	74.4	75.0	74.9	74.4	74.0	79.2
202	5.3	5.1	5.9	5.4	5.7	3.9
231	3.5	3.2	3.4	3.2	3.4	3.2
234	6.6	5.9	6.2	6.1	6.4	5.3
301	1.6	1.6	1.6	1.7	1.7	0.9
331	0.2	0.2	0.2	0.3	0.2	0.1
334	0.6	0.5	0.6	0.6	0.6	0.3

Window type distributions as a function of vintage or region are shown in Table 7.3. An obvious decreasing trend for SG windows (code 100) is seen for newer homes, with a negligible amount included in recent construction. This has not been offset by an increase in the standard DG window type (code 200). Instead, homeowners have been opting for low-e coatings and argon fill gas. The code series 23X shows a significant increase in homes built from 1990–2003. It may also be seen that TG windows (code series 3XX) have been applied somewhat uniformly to all vintages, and as such do not appear to be gathering market share from DG windows. It may be interpreted that TG windows are primarily used in retrofits.

Table 7.3 also shows window type distributions as a function of region. The regions are Atlantic (AT), Quebec (QC), Ontario (OT), Prairies (PR), and British Columbia (BC). The province of BC has a high level of SG and “thin” (6 mm) DG windows, owing at least partially to its mild climate relative to other Canadian regions. The PR region shows increased use of TG windows, owing to its cold climate.

Table 7.3 Distribution of window types by surface area corresponding to each house vintage and each region

	Vintage (%)					Region (%)				
Window code	Prior to 1946	1946–1969	1970–1979	1980–1989	1990–2003	AT	QC	OT	PR	BC
100	15.7	11.8	9.3	2.1	0.4	7.7	3.1	5.3	3.0	26.3
200	73.8	73.7	71.1	78.5	76.1	82.7	77.8	77.9	71.3	59.2
202	2.6	3.4	8.6	8.6	4.3	2.7	4.5	5.4	3.1	11.4
231	1.9	2.6	2.3	2.4	6.9	1.6	4.6	2.8	5.6	1.6
234	3.8	5.6	5.9	5.4	9.7	4.7	7.6	7.7	5.6	1.3
301	1.5	1.9	1.5	2.0	1.0	0.1	1.2	0.3	7.5	0.2
331	0.2	0.2	0.2	0.2	0.3	0.0	0.2	0.0	1.0	0.0
334	0.4	0.6	0.7	0.5	0.7	0.0	0.5	0.1	2.7	0.0

7.3 The impact of Window Type on Heat Transfer

The CHREM was used to examine the heat flux impacts of different windows upon a house, in preparation for selecting a particular upgrade to examine for the CHS. As discussed in section 7.1, the assessment of windows is complicated due to control mechanisms (e.g. opening windows), as well as hierarchal competing energy fluxes (e.g. solar gain, internal gains). To avoid these conditions for this analysis, the house was only examined during the predominant heating season. During this period, space cooling (SC) is not used and the windows are not opened. Figure 7.1 shows the monthly variation of heating degree days for a variety of Canadian cities (Environment Canada 2009). Heating degree days may be used as a proxy for space heating energy intensity requirements. It is evident that the period of November through March is a significant heating period regardless of location, and this period was selected for the analysis.

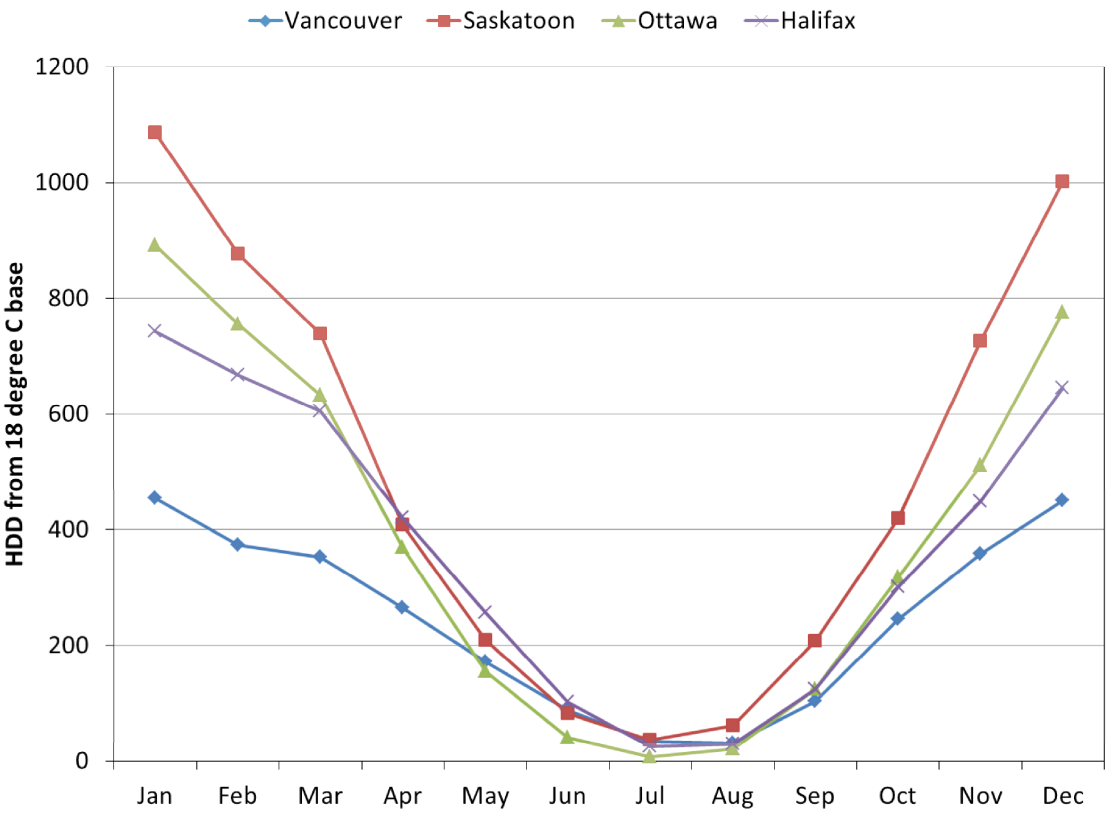


Figure 7.1 Heating degree days of Canadian cities located in different regions and climates

Four variations of window types were applied to a house, and the results were analyzed using the CHREM method specified in section 6.2.2 and with reference to the nodal analysis points of Figure 5.2 on page 119. The four window types are:

- No windows were located on the house. In this case there is no SW radiation absorbed within the zone and all heat losses are attributed to the opaque surfaces.
- SG windows consisting of a single pane of clear glass.
- DG windows using clear glass (i.e. not coated) and separated by a 13 mm gap filled with air. This window type (200) is the dominant window type in the CHS.
- Triple glazed (TG) windows employing the lowest emissivity coating (0.10) and 13 mm gaps filled with argon. This is the most thermally resistant window in the CHREM database.

The results of the heat flux analysis for these window variations are shown in Table 7.4. As windows are a transparent surface type, the heat transfers of interest are the conduction (CD) heat loss and SW radiation gains. However, the LW radiation also plays a role in transferring heat from the opaque surfaces to the transparent surfaces, and the convection (CV) change affects the required space heating (SH). The LW internal gains and the heat advection (HA) are unaffected by the change in window type. Because the period evaluated is limited to a portion of the heating season, the SC and sensible heat storage are also unaffected.

Table 7.4 Example of the heat transfer impacts during the analysis period due to variations of window types

Node	Heat flux or storage (GJ)	Installed windows (variations)			
		No windows	SG	DG, Clear glass, 13 mm air filled gap	TG, Low-E 0.10 coating, 13 mm argon filled gap
Opaque	CD	-32.0	-34.5	-35.0	-35.0
	CV	25.0	28.5	23.2	21.5
	SW	0.0	17.9	14.4	8.8
	LW from internal gains	6.9	6.7	6.7	6.7
	LW between inward facing surfaces	0.0	-18.5	-9.3	-1.9
	Sum of preceding fluxes	*0.0*	*0.0*	*0.0*	*0.0*
	Sensible heat storage	0.0	0.0	0.0	0.0
Transparent	CD	0.0	-30.4	-14.6	-3.9
	CV	0.0	11.0	4.6	1.0
	SW	0.0	0.6	0.5	0.7
	LW from internal gains	0.0	0.2	0.2	0.2
	LW between inward facing surfaces	0.0	18.5	9.3	1.9
	Sum of preceding fluxes	*0.0*	*0.0*	*0.0*	*0.0*
	Sensible heat storage	0.0	0.0	0.0	0.0
Airpoint	CV to inward facing surfaces	-25.0	-39.5	-27.8	-22.5
	CV from internal gains	8.1	8.1	8.1	8.1
	HA (mechanical ventilation)	-17.2	-17.3	-17.3	-17.3
	HA (AIM-2, windows)	-4.3	-4.3	-4.3	-4.3
	HA (zone-zone)	0.0	0.0	0.0	0.0
	SC	0.0	0.0	0.0	0.0
	SH	38.4	53.0	41.3	36.0
	Sum of preceding fluxes	*0.0*	*0.0*	*0.0*	*0.0*
	Sensible heat storage	0.0	0.0	0.0	0.0

The heat transfers of interest from Table 7.4 are illustrated in Figure 7.2. The window type variations are separated from the house that has no windows, as they follow substantially different trends. Figure 7.2a shows that window type does not substantially affect the CD heat loss of the opaque surfaces. However, is strongly affects the LW radiation transferring from opaque to transparent surfaces. TG windows reduce this transfer as their inner pane is similar in temperature to the opaque inward facing surfaces. The quantity of SW radiation absorbed by the opaque surfaces decrease with increasing number of glazing layers and the application of a Low-E coating. This is because increased glazing layers and the use of a coating cause more SW radiation to either reflect or be absorbed. Although the SW radiation is reduced by the TG window, the LW radiation trend dominates, resulting in less CV heat transfer from the airpoint to the opaque surfaces.

Figure 7.2b shows that the CD heat loss of the transparent surfaces drops significantly with each added glazing layer and coating. Because absorbed SW radiation plays an insignificant role within the transparent surface, the additional layers and coating dramatically reduce the CV heat transfer from the airpoint to the transparent surfaces.

Figure 7.2c indicates the cumulative effect of windows on the energy required from the SH system. In comparison with a house that has no windows, the addition of SG windows requires substantially more SH energy. The addition of glazing layers reduce this SH energy requirement. The TG and coated window type begins to approach the effective thermal resistance of the opaque surfaces, and due to the SW radiation which it admits, results in a lower SH energy requirement than a house without windows. In the case of the TG window, the occupant experiences the aesthetically pleasing nature of windows and natural light, without sacrificing energy efficiency, as compared to a house with no windows.

For this particular house, in this particular climate, the upgrading of window types presented in Table 7.4 from SG to DG, and DG to TG, reduces the SH energy requirement by 22% and 13%, respectively. It should be noted that these energy requirement impacts are strongly affected by the region, and the other surface constructions of the thermal envelope.

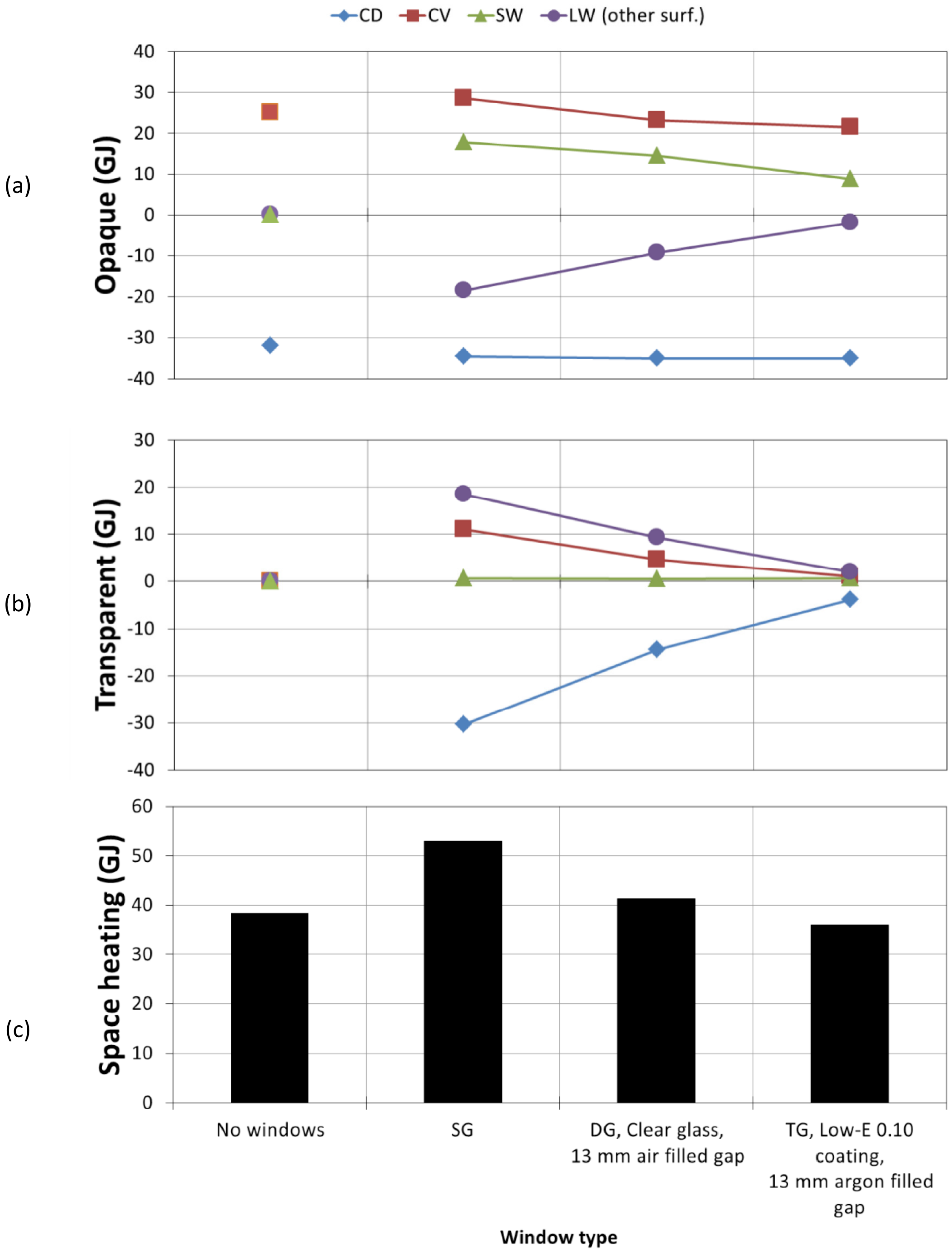


Figure 7.2 Heat transfer and energy consumption variations of interest during the analysis period for different window types shown in groups (a) opaque surfaces, (b) transparent surfaces, and (c) the required energy from the space heating system

7.4 Assessment of the Heat Transfer Contributions of Windows within the CHS

The assessment method of the preceding section was applied to the entire CHS using the CHREM, in an effort to identify the impacts upon energy requirements due to the presence of windows. The window types, as defined by the CSDDRD, were simulated for each house and heat transfer mechanisms of interest are reported. Table 7.5 shows these estimates which are summarized as a function of window type. As before, only the heating season from November through March was examined.

Table 7.5 Heat transfer contributions of windows during the analysis period for the CHS, summarized by window type

	Thermal envelope heat losses (PJ)				Solar heat gain	Window contributions	
Window code	Mech. vent. HA	AIM-2 HA	Opaque CD	Trans. CD	Absorb. SW (PJ)	SW/ Trans. CD	SW/All losses
100	-0.10	-15.30	-25.41	-8.77	4.06	46.2%	8.2%
200	-5.29	-183.17	-326.10	-74.06	50.52	68.2%	8.6%
202	-0.36	-12.55	-22.18	-5.87	3.56	60.7%	8.7%
231	-0.31	-9.10	-14.83	-3.15	2.47	78.6%	9.0%
234	-0.83	-14.40	-27.36	-5.04	4.54	90.1%	9.5%
301	-0.16	-3.57	-9.23	-1.42	1.07	75.7%	7.5%
331	-0.02	-0.53	-1.24	-0.16	0.15	91.5%	7.5%
334	-0.14	-1.22	-3.20	-0.41	0.39	93.9%	7.8%
All types	-7.25	-240.71	-431.45	-99.22	67.02	67.5%	8.6%

The house thermal envelope heat losses shown in Table 7.5 may be summarized as follows:

- During the heating season the thermal envelope loses heat (shown as negative values) due to:
  - HA caused by mechanical ventilation and natural zone-ambient air exchange (modeled by AIM-2).
  - CD losses across the opaque and transparent surfaces which are shown separately.
- The heat gains required to support the envelope losses come from SH, internal gains (e.g. appliance and lighting, occupants), and absorbed SW radiation that is admitted through the windows. As this investigation is focused solely on window contributions, the only heat gain shown in Table 7.5 is that due to the SW radiation.
- The window contributions are assessed in two ways:
  - The ratio of absorbed SW radiation to the transparent CD indicates the relationship between window gains and window losses. It is apparent from Table 7.5 that windows do not admit as much SW radiation during the heating season as they lose via CD.

- The ratio of absorbed SW radiation to the total thermal envelope heat loss indicates the contribution of windows to supporting the total heating load, inclusive of the transparent surface CD loss. If the windows of the CHS were painted opaque, this contribution would be eliminated and the SH system would be required to supply the additional energy.

The window contributions listed in Table 7.5 are illustrated in Figure 7.3 to identify trends. The window types are grouped by number of glazing layers and ordered according to effective thermal resistance. It is apparent that as the thermal resistance qualities of the window are increased, the admitted SW radiation offsets a larger proportion of the window heat loss. This occurs even though the admitted SW radiation decreases. A different trend appears when comparing the contribution of the window, via admitted SW radiation, to the total thermal envelope losses. This trend is essentially flat, indicating no strong relationship. This is primarily because the installation of more thermally resistant windows often occurs concurrently with upgrades or installation of more thermally resistant opaque surfaces (e.g. adding insulation to walls). Thus, the total thermal envelope loss may decrease significantly, but the proportions stay the same.

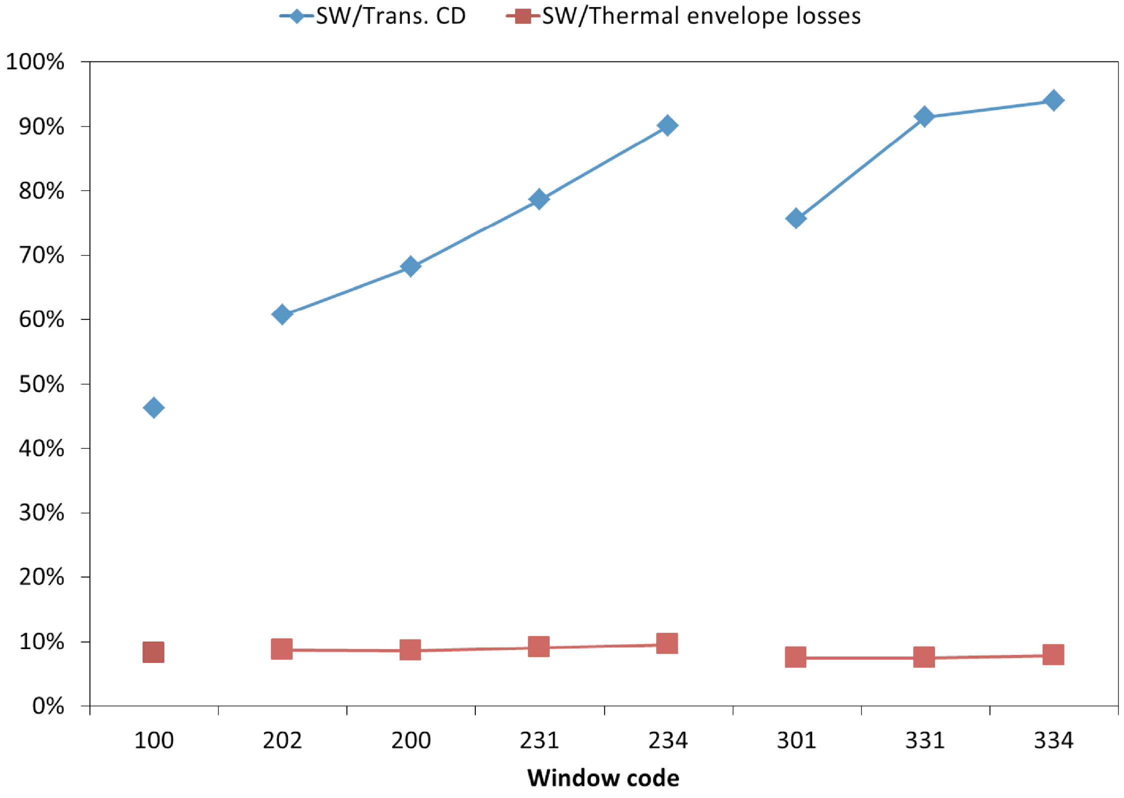


Figure 7.3 **Summary of the heat transfer contributions of windows during the heating season to the transparent conduction and building envelope thermal losses**

The contribution of windows as a function of region is shown in Figure 7.4. Only the province of BC tends to differ for the relationship of absorbed SW radiation to transparent surface heat loss. The proportion of window losses that are met with SW radiation admitted by the windows is less for BC. This is due to the high proportion of SG windows installed in that particular region, as was shown in Table 7.3. The relationship of absorbed SW radiation to total thermal envelope losses is not shown in Figure 7.4 as it does not differ significantly.

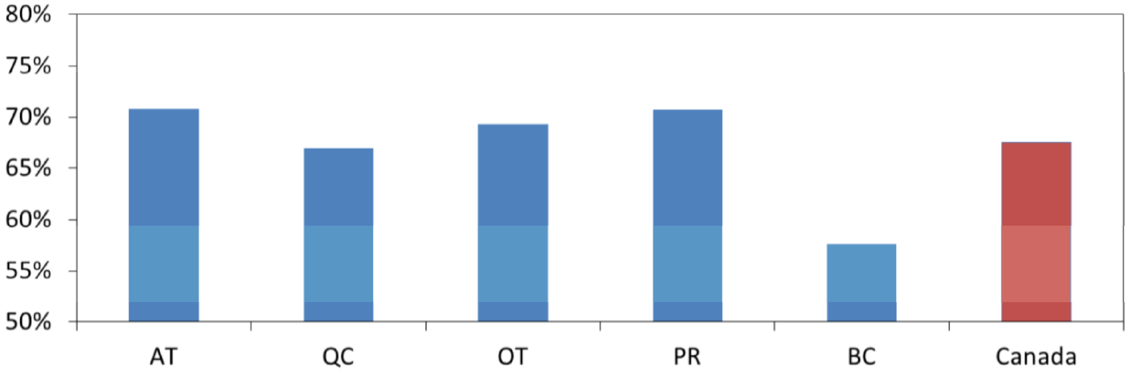


Figure 7.4 Relationship of absorbed SW radiation to transparent conduction as a function of Canadian region

7.5 Impact on Energy Consumption and GHG emissions due to Window Upgrades in the CHS

The analysis shown in section 7.2 identified that windows tend to be uniformly distributed by direction and house type; however variations in window type exist as a function of house vintage or region. Section 7.3 showed that the upgrade from SG to DG windows has substantial energy savings during the heating season, and that the upgrade from DG to TG windows has a significant, but lesser savings. Two upgrade scenarios were conducted: a specific upgrade of SG windows to TG windows, and uniform upgrade of all windows to TG windows.

7.5.1 Specific upgrade of SG Windows to TG Windows

The upgrade of existing SG windows to TG windows was investigated using the CHREM. This is a likely scenario, as window replacement with the same size and shape window is relatively easy, and TG windows are readily available. The impact on energy consumption and GHG emissions due to this upgrade requires a model such as the CHREM, to both identify and simulate these houses with SG windows. Such a simulation will account for the penetration rates and local climatic conditions, but is also capable of modeling the detailed heat transfer processes as shown in Figure 7.2. For example, the LW radiation transfer between opaque and transparent surfaces is significant. Therefore the impacts on energy consumption are also affected by the opaque construction, a relationship considered by the CHREM.

The simulation was carried out throughout an annual period, as it focuses solely on the SH and SC end-use energy consumption and GHG emissions. Although Table 7.2 shows that SG windows represent about 7% of windows by area in the CHS, over 15% of the houses have at least one side that is predominantly SG windows. Each of these houses was simulated to determine the impact of a uniform upgrade from SG to TG windows. The replacement windows correspond to code 323, a TG, Low-E 0.10 coated window, with an argon filled 13 mm gap. The thermal and optical properties of the replacement window code 323 are given in Table 5.9 (page 152) and Table 5.10 (page 153).

The CHREM estimates this upgrade of SG windows would reduce the energy consumption and GHG emissions of the CHS by 14.5 PJ and 696 kt of CO_2 equivalent, respectively. In comparison with the national end-use energy consumption and GHG emissions estimates shown in Table 6.12 (page 200), these represent savings of approximately 1.1%. The SH end-use constitutes over 99% of these savings. A breakdown of the savings by energy source for the house types and provinces is shown in Table 7.6. The savings are shown as negative values as they are the difference in energy consumption and GHG emissions from the base case to the upgraded case. It is important to recognize that the GHG emissions savings for electricity are calculated using the provincial monthly marginal emission intensity factors and transmission/distribution factors, as applied to the monthly electricity energy consumption differences.

Table 7.6 Estimates of annual energy consumption and GHG emissions savings by replacing all SG windows in the CHS with TG low-emissivity (0.10) argon filled 13 mm gap windows

House type or province		Energy savings (TJ)					GHG emissions savings (kt of CO_2 equivalent)			
		Electricity	NG*	Oil	Wood	Total	Electricity	NG	Oil	Total
House type	SD	-1634	-8204	-1849	-892	-12581				
	DR	-336	-1332	-194	-10	-1873				
Province	NF	-6	0	-154	-29	-189	0.0	0.0	-10.9	-10.9
	NS	-21	0	-312	-93	-425	-2.1	0.0	-22.1	-24.2
	PE	0	0	-43	-34	-77	0.0	0.0	-3.1	-3.1
	NB	-68	0	-238	-553	-859	-16.0	0.0	-16.8	-32.9
	QC	-837	-18	-379	-52	-1286	-1.1	-0.9	-26.8	-28.9
	OT	-365	-3447	-917	0	-4729	-43.6	-174.8	-64.9	-283.4
	MB	-51	-330	0	0	-381	0.0	-16.7	0.0	-16.7
	SK	-23	-385	0	0	-407	-1.6	-19.5	0.0	-21.1
	AB	0	-517	0	0	-518	0.0	-26.2	0.0	-26.3
	BC	-599	-4841	0	-141	-5583	-3.1	-245.6	0.0	-248.7
Canada		-1970	-9537	-2043	-901	-14453	-67.7	-483.8	-144.6	-696.1

* Natural gas

The major trends of energy and GHG emissions savings from Table 7.6 are illustrated in Figure 7.5. The provinces of OT and BC dominate the distribution of savings across Canada. Although BC has greater energy savings, OT saves the most GHG emissions. This is primarily due to the electricity generation energy sources used in the respective provinces. As shown in Table 6.7 on page 190, OT has a marginal electricity GHG emission intensity factor averaging 433 g of CO_2e per kW·h. In contrast, the factor for BC is only 18 g of CO_2e per kW·h.

The province of BC was identified in Table 7.3 as having a high proportion of SG windows. Although OT does not have such a high proportion of SG windows, its large number of total houses results in the effects of this upgrade being significant. Based on Figure 7.5, a retrofit program for the replacement of SG windows should focus on these two particular provinces.

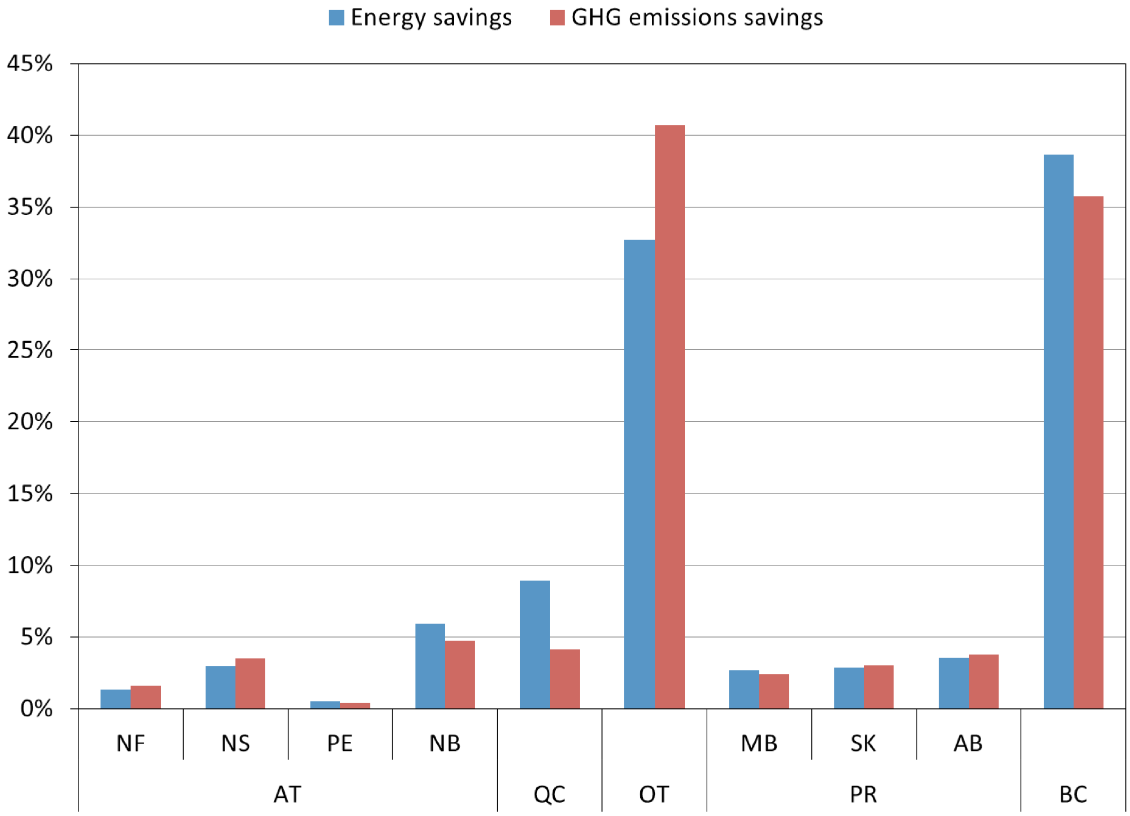


Figure 7.5 **Distribution of energy consumption and GHG emissions savings among provinces of Canada due to an upgrade of SG windows with TG low-emissivity (0.10) argon filled 13 mm gap windows**

7.5.2 Uniform Upgrade of All Windows to TG Windows

The results of the preceding section demonstrated the ability of the CHREM to apply a specific upgrade to suitable houses and evaluate the effects on energy consumption and GHG emissions from a provincial perspective. In an effort to illustrate more significant effects on the CHS, a second scenario was considered. In this case, all windows of the CHS were upgraded to the TG, Low-E 0.10 coated window, with an argon filled 13 mm gap (code 323).

The CHREM predicts energy savings of 78.5 PJ and GHG emissions savings of 3.79 Mt of CO_2 equivalent. In comparison with the national end-use energy consumption and GHG emissions estimates shown in Table 6.12 (page 200), these represent an energy savings of 6.0% and a GHG emissions savings of 5.7%.

Unlike the upgrade of SG windows in the preceding section, the uniform upgrade of all windows across Canada results in a distribution of energy consumption and GHG emissions similar to the distributions of dwelling count by province. This is because DG windows represent approximately 75% of the window stock, regardless of region. Therefore, the uniform window upgrade scenario is applicable to all provinces.

The impacts of the uniform window upgrade scenario upon energy consumption and GHG emissions specific to individual provinces is shown in Figure 7.6. The impacts to the province of BC are greatest due to the replacement of the SG windows. The other provinces have energy consumption savings of approximately 5%. However, GHG emissions savings of the other provinces is specific. Provinces with high electricity generation GHG EIFs (NS, SK, and AB) have less impact on GHG emissions savings than other provinces. This is because the uniform window upgrade strongly affects SH energy consumption which is serviced by a variety of energy sources, but has negligible impact on AL energy consumption which is primarily serviced by electricity.

Figure 7.7 shows the distribution of energy consumption and GHG emissions savings among end-uses and energy sources for the uniform window upgrade of the CHS. The SH end-use dominates the savings, as many Canadian houses require insignificant SC, and most lack SC equipment. Most of the energy and GHG emissions savings is attributable to natural gas, as this is the predominant SH energy source for much of Canada.

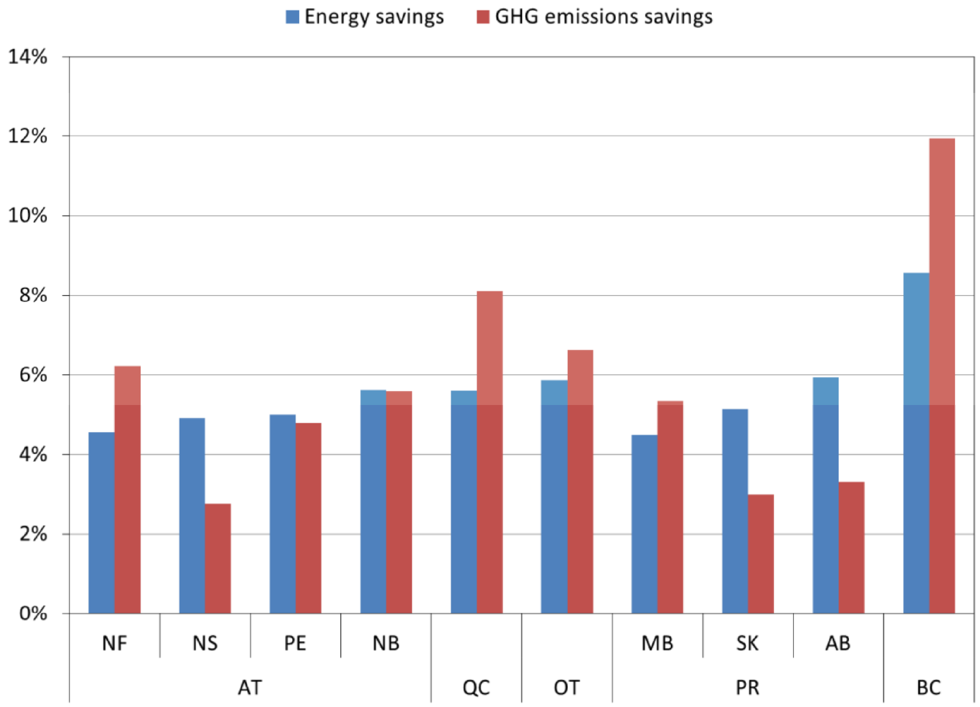


Figure 7.6 **Energy consumption and GHG emissions savings specific to individual provinces of Canada due to an upgrade of all windows to TG low-emissivity (0.10) argon filled 13 mm gap windows**

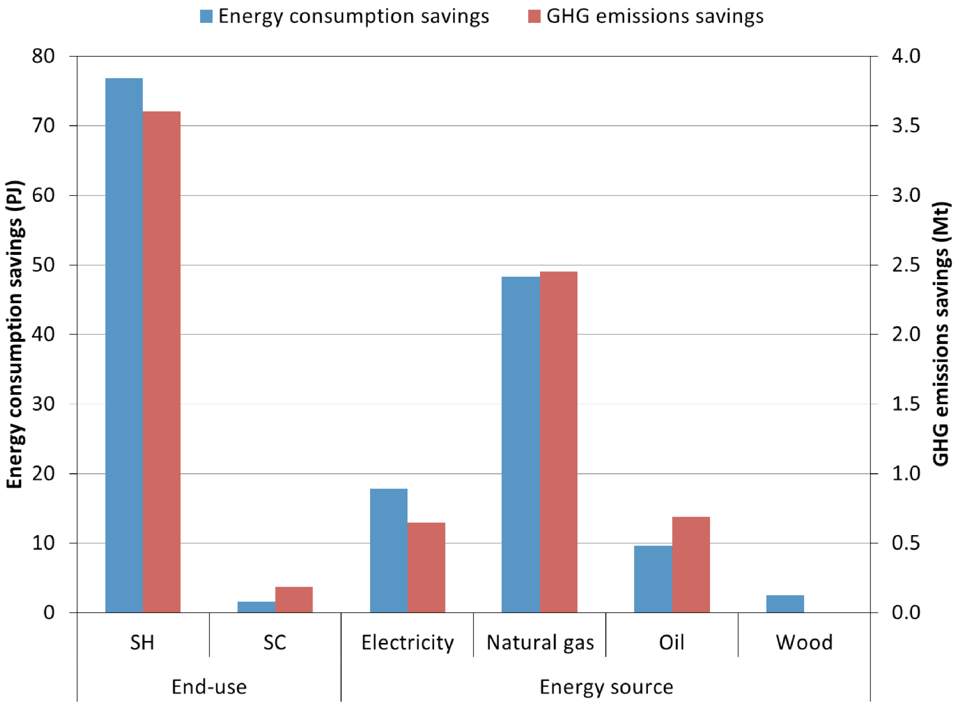


Figure 7.7 **National annual energy consumption and GHG emissions savings specific to end-uses and energy sources due to an upgrade of all Canadian windows to TG low-emissivity (0.10) argon filled 13 mm gap windows**

7.6 Conclusion

This chapter presents a demonstration of the CHREM by examining the impact windows have upon energy consumption and GHG emissions within the CHS. This demonstration shows that the CHREM is capable of the following:

- Identifying the present status of windows in the CHS on a detailed level inclusive of window type, facing direction, house type, and region. Additionally, houses with the potential for upgrading were selected for simulation.
- Analyzing the detailed heat transfer mechanisms and assessing the contribution of windows within the CHS.
- Performing a simulation of upgraded houses, and comparing the change in energy consumption and GHG emissions. The assessment of GHG emissions considers the marginal electricity generation emission intensity factors and transmission/distribution energy savings.

The windows installed in the CHS tend to have uniform distribution by house type and facing direction. Differences in window types appear when considering house vintage or region. A heat transfer analysis of windows during the heating season showed that the admitted SW radiation offsets approximately 8.6% of the SH needs of houses, regardless of window type. However, window type strongly influences the proportion of heat loss through the window that is offset by SW radiation admitted through the window. The use of SG windows admits the most SW radiation, but only offsets approximately 46% of the high window heat losses. In contrast, TG low-E windows offset nearly all of the window heat loss with admitted SW radiation.

An analysis of upgrading all SG windows in the CHS to the most thermally resistant TG window was conducted. This upgrade was selected as windows are easily replaced and the energy savings were shown to be significant in a single house analysis. Although SG windows only represent 7% of window area in the CHS, they are present in more than 15% of houses. This is because houses may have a variety of installed window types, a characteristic captured using the CHREM. The CHREM estimates that this upgrade would reduce energy consumption and GHG emissions by 14.5 PJ and 696 kt of CO_2 equivalent, respectively. This is equivalent to a 1.1% reduction of the end-use energy consumption and GHG emissions of the CHS. Although this may seem small, such an upgrade is relatively easy and only affects a portion of the CHS. An analysis by region showed that the majority of the savings occur in the provinces of OT and BC. A retrofit program focusing on such an upgrade could be limited to these two provinces.

A uniform upgrade of all windows in the CHS to the most thermally resistant TG window type was simulated. This uniform upgrade was estimated to reduce energy consumption and GHG emissions of the CHS by nearly 6%.

Chapter 8 Conclusion

Worldwide, the housing stock is a major consumer of end-use energy, and Canada is no exception (Saidur et al. 2007). Both the rate at which we consume energy and our use of non-renewable energy resources have come under pressure to change. These changes may occur to some extent by conservation techniques (e.g. lowered heating setpoint temperature). However, due to living standard expectations, these changes will primarily rely on technology. Many technological opportunities exist to reduce the conventional energy consumption and GHG emissions of the Canadian housing stock (CHS). This can be achieved by a combination of strategies that includes: improving end-use energy efficiency, introducing alternative energy conversion technologies, and increasing the use of renewable energy resources.

A critical aspect to the justification of selecting a technology is an assessment of its impact upon energy consumption and GHG emissions. Such estimates are useful for decision makers, energy analysts, energy suppliers, and utilities to evaluate and parametrically compare the impact of a wide range of energy efficiency measures and technology strategies on the housing sector. The results of such an analysis can be utilized to develop policy and programs to support dwelling upgrades or new technologies that meet energy consumption or GHG emissions reduction targets. Other aspects for the justification of a technology include economic and social implications, but these are beyond the scope of this dissertation.

8.1 Summary

The accurate estimate of the impact of a new technology on energy consumption and GHG emissions of the housing stock requires a versatile, reliable, detailed, and high-resolution analytical model. Chapter 2 critically examined the strengths and weaknesses of the numerous modeling approaches, methods, and techniques. Of these, only the bottom-up engineering modeling method has the capacity to adequately represent new technologies, such as co-generation and renewable energy systems. This method is suitable for modeling energy consumption and GHG emissions of end-uses that are described using thermodynamics. Space heating (SC), space cooling (SC), and the performance of the domestic hot water (DHW) system are examples of such end-uses. In contrast, the use of

DHW and the use of appliances and lighting (AL) are principally affected by occupant behaviour. The bottom-up engineering method suffers from the inability to capture the effects of occupant behaviour as they are not based on thermodynamics.

Bottom-up statistical models have been shown to more accurately estimate the occupant use of DHW and AL (Aydinalp-Koksal and Ugursal 2008). Statistical methods have the capacity to incorporate demographic conditions and non-thermodynamic relationships. It is of critical importance to consider the DHW and AL, as these end-uses constitute a significant portion of energy consumption within a house. Furthermore, a portion of the DHW energy consumption and a majority of the AL energy consumption generate heat within the house, and this may offset SH and increase SC requirements.

Both the bottom-up engineering and statistical modeling methods rely on input information to estimate energy consumption and GHG emissions. This information must be representative of the housing stock, and include a sufficient level of detail to characterize the thermal envelope, energy conversion systems, and occupants. The CHS is comprised of over eleven million households (OEE 2006) spread across the second largest nation in the world by total area (UN 2007). This gives the CHS distinct regional and provincial characteristics such as: climate, house type, size, layout, building materials, active energy conversion system types, and energy sources. Additionally, there is strong provincial aspect to the GHG emissions resulting from the use electricity (Farhat and Ugursal 2010).

8.1.1 The Status and Limitations of Existing Energy and GHG Emissions Models of the CHS

Canada has a significant and reputable history of characterizing energy consumption and GHG emissions of the housing stock. This history consists of surveys, programs, and analytical models.

Numerous surveys have been conducted to gather energy consumption related information, with the principal being the Survey of Household Energy Use (SHEU, OEE 2010). The monthly bin-type building energy analysis software, HOT2000, was developed to assess and compare conventional household energy performance (CANMET 2008). The EnerGuide for Houses program conducted detailed investigation of the thermal envelope and energy conversion systems, resulting in the EnerGuide for Houses Database (EGHD). The EGHD consists of over 200,000 houses (Blais et al. 2005). Recently, Farhat and Ugursal (2010) estimated the average and marginal electricity GHG emission intensity factor (EIF) for each province. The Government of Canada is presently developing HOT3000 software which will utilize the ESP-r building performance simulation engine (Haltrecht et al. 1999). ESP-r is capable of modeling of new technologies such as alternative and renewable energy systems (Clarke 2001).

The top-down Residential End-Use Model (REUM) was developed to track energy consumption and GHG emissions fluctuations over time (OEE 2006b). The bottom-up engineering Canadian Residential Energy End-use Model (CREEM) was developed to assess the impacts on energy consumption and GHG emissions due to a variety of energy efficiency upgrades (Farahbakhsh et al. 1998, Fung 2003). The CREEM uses the HOT2000 software to assess 16 house archetypes that were augmented with the unique information of 8,767 houses. Aydinalp et al. (2004, 2002) developed a bottom-up statistical method which uses neural networks (NN) to assess the energy consumption of the CHS.

The existing energy consumption and GHG emissions models of the CHS have demonstrated specific methods and use of information. Each method has strengths and weaknesses.

- Because the REUM is a top-down energy model, its estimates of aggregate energy consumption and GHG emissions a likely close to the actual values. However, it is incapable of estimating the impact due to the implementation of new technologies.
- The bottom-up engineering CREEM model can estimate the impact on energy consumption and GHG emissions due to certain energy efficiency measures. However, because the CREEM relies on 16 thermal envelope archetypes, it does not account for the wide variety found in the CHS. It accounts for occupant behaviour using rudimentary appliance rating and use factors. The reliance on the HOT2000 building energy analysis software inhibits the CREEM from estimating the impact of new technologies. And CREEM relies on GHG EIFs that are based on average electricity generating sources, not those that respond to incremental changes in demand.
- The bottom-up statistical NN models have increased prediction accuracy, and can account for the effects of occupant behaviour on DHW and AL use. However, the statistical method is incapable of estimating the impact due to the implementation of new technologies.

These strengths and weaknesses of energy consumption and GHG emissions modeling are not limited to Canada. Kavgic et al. (2010) recently identified similar issues while conducting a worldwide review of residential sector stock models aimed at assessing new technologies.

8.1.2 Advancement of the State-of-the-art of Energy and GHG Emissions Modeling

Considering the capabilities of the existing models, there is a need for a comprehensive modeling tool that can be used to study the impacts of alternative and renewable energy technologies on the energy consumption and GHG emissions of the CHS. This dissertation advances the state-of-the-art of residential sector energy consumption and GHG emissions modeling by creating a new model which specifically addresses the weaknesses of existing model described in the preceding section. The new model is titled the Canadian Hybrid Residential End-Use Energy and GHG Emissions Model (CHREM).

There CHREM introduces three major advancements to the state-of-the-art of residential sector energy consumption and GHG emissions modeling:

1) An algorithm was developed and used to select the CHREM database of 16,952 houses which statistically represent the CHS. The database is titled Canadian Single-Detached and Double/Row Housing Database (CSDDRD). The house files that comprise the CSDDRD were selected from the EnerGuide for Houses Database that contains detailed thermal envelope and energy conversion system information of over 200,000 unique house energy audits (Blais et al. 2005). Each unique house description came from an energy audit of a real Canadian house. The audit characterized the building thermal envelope and its energy conversion systems. The large number of houses in the CSDDRD accounts for the wide variety found in the CHS. It also allows for the identification of houses which are suitable for specific technology applications. The CSDDRD contains sufficient information to develop a thermodynamically representative house that is suitable for detailed building energy performance simulation. Specific geometric information is included which enables the assessment of directionally dependent solar energy technologies, and solar gains which are admitted through windows.
2) A “hybrid” modeling method was developed which integrates the bottom-up statistical and engineering methods.
    a) The statistical method constitutes the first half of the CHREM hybrid modeling approach. The statistical method relies on the CSDDRD and employs the NN technique to estimate the annual use of DHW and AL. These specific end-uses are strongly affected by occupant behaviour. The annual use results are then distributed onto representative timestep use profiles. The timestep profiles allow the AL and DHW use estimates to be included within the CHREM bottom-up engineering method. This inclusion allows for the interrelated energy consumption effects of end-uses as described in section 8.1.
    b) The engineering method constitutes the second half of the CHREM hybrid modeling approach. The engineering method relies on the CSDDRD and the statistical method timestep use profiles of DHW and AL to create a representative thermodynamic description of each house. This detailed description includes: geometrical layout; specific treatment of each thermal zone; properties and dimensions of each material layer of the floors, walls,

ceilings, windows, and doors; air-leakage characteristics; and specification of all heating, ventilation, and air-conditioning equipment. The engineering method utilizes the ESP-r building energy performance simulator to conduct an annual simulation of each house, and estimates the end-use energy consumption.

3) A method was developed for the accumulation and treatment of energy results. This method is used to assess the energy transfer mechanisms within the house, and energy consumption attributable to each end-use. It specifically considers the internal gains within each zone, and end-uses which directly exhaust heat from the dwelling. The GHG emissions are calculated from the monthly end-use energy consumption with respect to the energy source GHG EIF. In the case of electricity, the provincially specific average electricity generation GHG EIF is used. When new technologies are applied to the CHS, the provincially specific marginal electricity generation EIF is applied to the incremental difference in electricity consumption.

The recent review article of residential sector stock models by Kavgic et al. (2010) recognized the unique hybrid approach specific to the CHREM, stating "Some of the more sophisticated models combine, in a more fundamental way, components where both building physics and statistical approaches have been applied".

The CHREM will be made available in the public domain for research use. Access to the CHREM can be obtained by contacting the author (Lukas.Swan@Dal.Ca).

8.2 Specific Advancements and Results

The CHREM is a research tool that was specifically developed to assess the impacts of new technologies when applied to the CHS. As such, it is a bottom-up modeling approach with strong technical aspects. The CHREM is fundamentally superior to other housing stock energy consumption and GHG emissions models because of its input data, its hybrid modeling method, its treatment of the end-use results, and the capability of assessing the impact on energy consumption and GHG emissions due to the application of new technologies.

A detailed CHREM flowchart is shown in Figure 8.1 on page 245. It visually divides the CHREM into three areas: database, statistical method, and engineering method.

The CHREM database (the CSDDRD) is the backbone of the model, providing information to both the CHREM statistical and engineering methods. The CHREM database, presented in Chapter 3, was developed using a new algorithm that selects house samples from the EGHD (CANMET 2006) that statistically match relevant housing stock distributions defined by SHEU-03 (OEE 2006).

The CHREM statistical method, presented in Chapter 4, augments the CHREM database with Census data (Statistics Canada 2006). It employs two NNs (Aydinalp et al. 2002) to calculate the use of AL and DHW for each house. The most appropriate occupant use profiles (Knight et al. 2007) are selected for each house and this information is passed to the CHREM engineering method for inclusion in total building energy performance simulation.

The CHREM engineering method, presented in Chapter 5, constructs a thermodynamic description of each house of the CHREM database. These descriptions are suitable for detailed building energy performance simulation using the ESP-r program. Weather data from the Canadian Weather for Energy Calculations (Numerical Logistics 2010) is provided to ESP-r, and an annual simulation is conducted for each house.

The CHREM results assessment method, presented in Chapter 6, is applied to the output of the ESP-r simulations to identify the contribution of each end-use and energy source to the total energy consumption. GHG EIFs are applied to the energy consumption to estimate the resultant GHG emissions. Both the energy consumption and GHG emissions estimates are then scaled to be representative of the CHS.

The point of implementation for new technologies is shown within the CHREM engineering method in Figure 8.1. Information from the CHREM database is used to identify houses which meet specific suitability requirements of the new technology. An example of this was shown in Chapter 7 with the assessment of window type penetration levels. The subset of suitable houses and the thermodynamic information of the new technology are then used to generate a new description of the house. These altered houses are then simulated, and the difference in end-use energy consumption and GHG emissions with respect to the original case is calculated. Special consideration is given to the GHG emissions associated with an incremental change in electricity use.

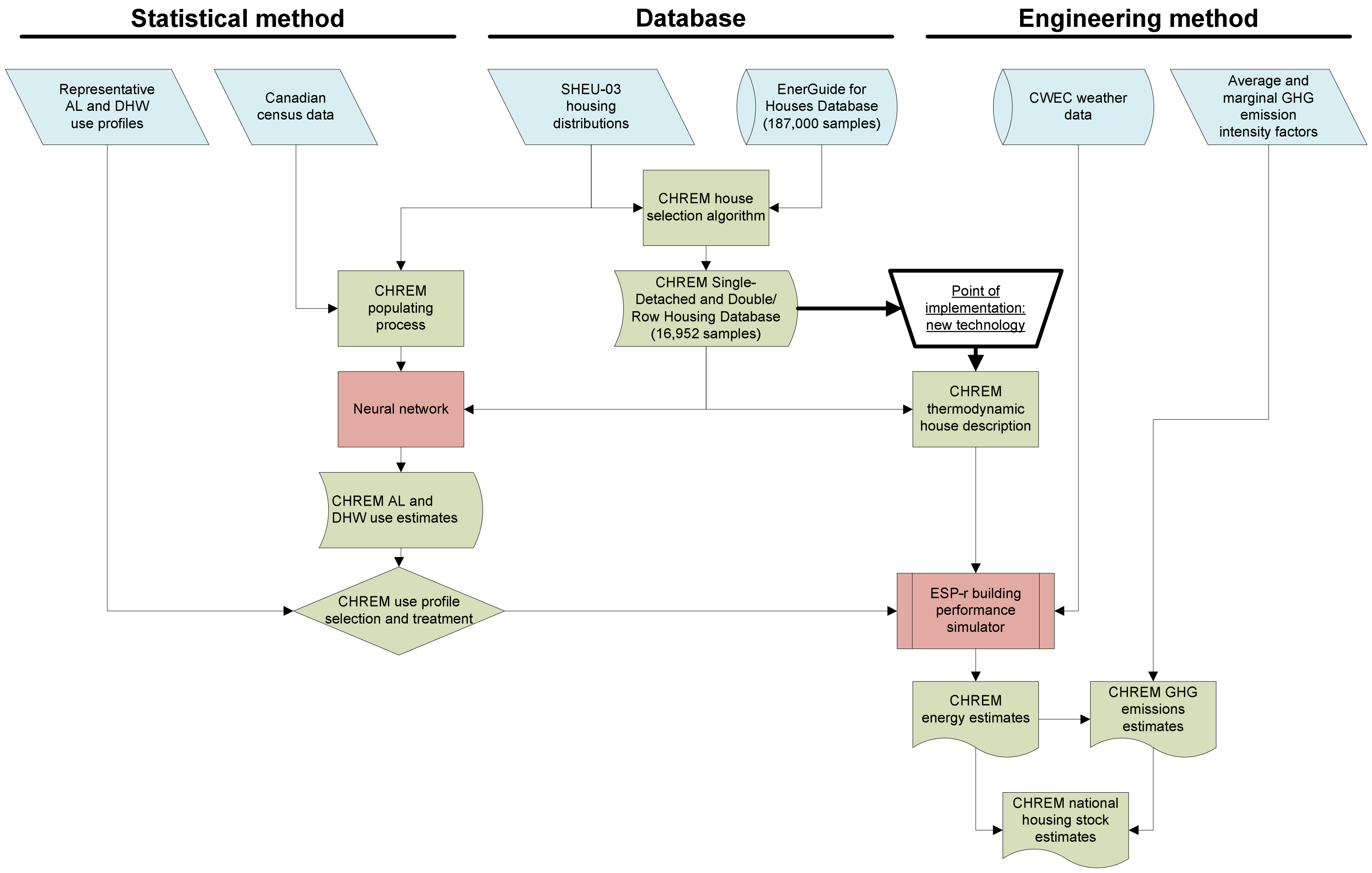


Figure 8.1 Detailed CHREM flowchart

8.2.1 CHREM Database Advancements and Results

A comprehensive review of information sources was conducted to identify data suitable for detailed building energy performance simulation. The SHEU-03 contains statically representative distributions of the CHS based on an unbiased survey of 4,551 houses (OEE 2006). These distributions include a variety of information related to the thermal envelope, energy conversion systems, and small appliances, but lack detailed information suitable for building energy performance simulation. The EGHD contains detailed thermal envelope and energy conversion system information of over 200,000 unique house energy audits (Blais et al. 2005). However, the EGHD is a culmination of homeowner requested energy audits and is therefore not representative of the CHS.

A new algorithm was developed to select houses from the EGHD which statistically match specific categories. The available categories of the SHEU-03 and EGHD were compared, and the following categories were used for selection of houses:

- House type (singe-detached or double/row)
- Region (Atlantic, Quebec, Ontario, Prairies, British Columbia)
- Vintage (1900–1945, 1946–1969, 1970–1979, 1980–1989, 1990–2003)
- Storeys (1 through 3 including half storeys)
- Living space floor area (25–56 m^2, 57–93 m^2, 94–139 m^2, 140–186 m^2, 187–232 m^2, 232–300 m^2; excluding basement or crawl space)
- Space heating energy source (electricity, natural gas, oil, wood, propane)
- DHW energy source (electricity, natural gas, oil)

The EGHD was critically examined, and only original house audits with valid data were used in the selection process. The selection algorithm sequentially proceeded through the 121,456 unique houses of the EGHD, selecting those which matched the SHEU-03 distributions. As the sequential algorithm processed and selected houses, the availability in the desired distributions is reduced. Upon first completion, it was found that certain selection categories were underrepresented. The source data was reordered to place houses with these underrepresented characteristics first, in an effort to promote their selection.

The algorithm then selected 16,952 houses from the EGHD which are similar to the distributions of the SHEU-03. Examples of this similarity are shown in Figures 3.5 and 3.6 on pages 74 and 75, respectively. The houses form the CHREM database, the CSDDRD, and are intended for coupling to building energy performance simulation. The CSDDRD is over twice the size of other databases identified in Chapter 2. It is superior to other databases (e.g. the augmented archetypes of the CREEM) because it preserves the integrity of individual houses. The CSDDRD has unique characteristics that advance the state of databases intended for the energy performance simulation of the housing stock:

1) There are 16,952 houses in the CSDDRD, with each having unique thermal envelope and energy conversion system data acquired from an energy audit.
    a) The number of houses captures the variety of characteristics found throughout the CHS.
    b) The number of houses is statistically significant for analysis of potential penetration levels of a new technology.
    c) Each house of the CSDDRD represents approximately 500 houses of the CHS with respect to region.
2) Representation is given to each major region of Canada. This includes the identification of the nearest climatic data location. A count of the CSDDRD houses by province and house type is given in Table 8.1 on page 248.
3) The CSDDRD data is sufficient to create a detailed thermodynamic description of each house.
    a) The presence of the foundation zone and each level of the main living area are defined. The floor area and height of each zone is specified.
    b) Each material layer of the floors, walls, and ceilings are defined. This allows for the determination of both insulating and thermal mass effects.
    c) Airtightness characteristics were determined by the use of a blower door test.
    d) The SH, SC, DHW, and ventilation equipment is specified individually with respect to both equipment type and energy source.
4) Directionally specific information of windows and house aspect ratio is included. This is a critical aspect to the CSDDRD as it is expected that it will be used in the assessment of solar technologies.

The Census 2006 (Statistics Canada 2006) distribution of the housing stock by province was used to extend the CSDDRD from regional to provincial analysis. This facilitates the consideration of provincially specific electricity generation GHG EIFs.

Table 8.1 Count of houses in the CSDDRD by province and house type

Province	Single-detached	Double/row	Combined
NF	180	22	202
NS	630	84	714
PE	65	14	79
NB	396	17	413
QC	2882	798	3680
OT	5404	1231	6635
MB	859	78	937
SK	189	13	202
AB	1655	350	2005
BC	1770	315	2085
Canada	14030	2922	16952

8.2.2 CHREM Statistical Method

Aydinalp and Ugursal (2008) identified that the NN statistical method has greater prediction capability than other bottom-up methods, and is capable of encompassing the effect of occupant behaviour and demographic conditions. Because the use of DHW and AL is primarily dependent upon occupant behaviour, this statistical method was selected as the first half of the hybrid approach used by the CHREM. The DHW and AL estimates are then imposed within the CHREM engineering method to account for the interrelation between end-uses.

8.2.2.1 Advancements

The existing NNs require a set of input information to calculate the annual end-use energy consumption of DHW and AL (Aydinalp et al. 2002). The input information requires occupant and demographic data which is not included in the CSDDRD. The SHEU-03 contains some of this data, but is unavailable to the public. The annual end-use energy consumption estimated by the NN is not disaggregated by energy source (e.g. electricity, natural gas). Furthermore, the annual energy consumption cannot be directly integrated with the CHREM engineering method.

Each of these deficiencies was addressed by new methods which advance the use of statistical models and the hybrid approach:

1) A new method was developed to populate the NN input information that was not included in the CSDDRD. This populating method was conducted using distributions from multiple data sources, and at the highest resolution of available data (e.g. provincial, national). Correlations were made between the CSDDRD and the populating data for: DHW system energy factor, population density, and climatic

information. Provincial relationships between numbers of adults, numbers of children, and employment ratio were preserved. The populated data was also used in the CHREM engineering method to impose heat gains within the house due to occupant presence.

2) The estimations of the NN were converted and separated to support the treatment of specific end-uses.
    a) The DHW energy consumption was converted to DHW volume draw using the same system assumptions as the NN. The use of DHW volume draw permits the CHREM engineering method to assess the performance of the DHW energy conversion system. Solar DHW systems are a key technology for evaluation using the CHREM.
    b) The clothes dryer presence was removed from the AL NN to identify its specific contribution. The portion of the AL energy consumption attributable to the clothes dryer is exhausted from the house, whereas the remaining AL energy consumption becomes heat within the house.
3) The annual estimates of DHW volume draw and AL energy consumption were distributed onto representative timestep use profiles. The origination of the profiles is discussed by Jordan and Vajen (2001) and Armstrong et al. (2009).
    a) The profiles were reorganized and grouped into DHW, AL-clothes-dryer, AL-cook-stove, and AL-other. These groups facilitate the exhausting of the clothes dryer outside the building, and the potential for the clothes dryer and cook stove to be powered by electricity or natural gas.
    b) A set of all combinations of use profile groups was created in a format suitable for the ESP-r building performance simulator. Due to variations in demand level, 27 combinations were developed.
    c) An algorithm was developed to select the most appropriate combination of use profile groups for each house of the CSDDRD. Because the NN annual estimates are not equal to the annual use of each profile, a ratio of the two was calculated. This ratio is used to modify the profile such that the annual values imposed within the CHREM engineering method are equal to that estimated by the CHREM statistical method.

8.2.2.2 Results

The principal energy consumption estimates of the CHREM statistical method are shown in Table 8.2, and are compared to the top-down REUM estimates. The combined estimates of the two models are similar, with the CHREM estimating 6% more energy consumption. This is an acceptable level of agreement between the models. Differences appear when comparing the AL and DHW energy consumption individually. In comparison with the REUM, the CHREM estimates considerably more AL energy consumption, and considerably less DHW energy consumption. This difference is attributed to the modeling technique.

The top-down approach of the REUM relies on aggregate energy billing data and uses annual stock appliance assessments, approximate usage profiles, and appliance unit energy consumption to disaggregate total energy consumption among end-uses. In contrast, the CHREM energy estimates are based on the bottom-up approach, and capture the interrelation of appliances and occupants via a NN technique. The ability to independently assess end-uses is a strength of the CHREM.

Because of the level of model agreement in combined energy consumption of the AL and DHW end-uses, and the strengths and weaknesses of the modeling approaches, the CHREM energy consumption estimates are proposed as a new relationship between these two occupant influenced end-uses.

Table 8.2 Comparison of national AL and DHW annual end-use energy consumption estimates for SD and DR house types

	Energy (PJ)		
End-use	CHREM	REUM 2000-2004	CHREM/REUM ratio
AL	246.8	184.6	1.34
DHW	200.7	237.6	0.84
Combined	447.5	422.2	1.06

8.2.3 CHREM Engineering Method

The SH, SC, and DHW system functionality are primarily dependent upon the house thermal envelope and the thermodynamic characteristics of the energy conversion equipment. The bottom-up engineering method was selected to model these end-uses for the following reasons:

- The engineering method can explicitly account for, and model, the thermodynamic characteristics of the house thermal envelope and energy conversion equipment.
- The engineering method allows for the interrelation between end-use energy consumption.
- The engineering method has the unique capability to model new technologies.

The bottom-up engineering method forms the second half of the CHREM hybrid approach, utilizing the CHREM database and the CHREM statistical model DHW and AL use profiles. The CHREM engineering method estimates the end-use energy consumption and GHG emissions of the CHS, and the change in these values due to the implementation of new technologies.

8.2.3.1 Advancements

Previous bottom-up engineering models of the CHS relied on the inherently limited building energy analysis software HOT2000 (CANMET 2008). In contrast, the CHREM utilizes the building energy performance simulator ESP-r, which is capable of modeling new technologies (ESRU 2002, Clarke 2001). Specific rationale for the selection of ESP-r included the ability to handle complicated heat flux and plant equipment, as well as availability and open-source format suitable for adding support for new technologies. The Government of Canada has also selected ESP-r for its next generation house simulator (Haltrecht et al. 1999). This has resulted in support being added to ESP-r for many of the characteristics and present technologies of the CHS.

The ESP-r simulator requires a detailed thermodynamic house description to operate. The following advancements were made in the area of translating database values into unique house descriptions.

1) A map was created linking house locations to available locations of the Canadian Weather for Energy Calculations (CWEC, Numerical Logistics 2010). Of the locations listed in the CSDDRD, 31 did not have a direct CWEC match. A method was developed to compare heating degree days and longitude/latitude for the selection of a suitable substitute CWEC location.
2) A new algorithm was developed to divide the house into discrete thermal zones.
    a) The house footprint was rectangularized while maintaining the aspect ratio and orientation.
    b) Each level was defined as a thermal zone. This allows for variations in floor area and wall surface area while maintaining the overall height and directionally dependent exposure of the house.
    c) In the event that two connected levels varied in size, an appropriate area of exposed floor or exposed ceiling was included.
    d) Consideration was given to the attic or roof-space design to facilitate solar technologies. Flat, gable, and hip type roofs were accommodated.
3) An algorithm for the application of windows and doors was developed.
    a) Doors and windows were inserted into walls, and consideration was given to walkout sides of a basement.
    b) Window area was amalgamated per side, and then distributed among thermal zones by side surface area. The aspect ratio of the window is similar to the wall.
    c) Windows were divided into two surfaces: a transparent aperture section and an opaque frame section. The area ratio of these two sections is 75% and 25%, respectively, in accordance with the ranges specified by Mitchell et al. (2003).
4) A database and algorithm were developed to define surface characteristics.

  a) A new database of typical Canadian construction surfaces (opaque and transparent) was created for ESP-r.
  b) A mapping method was developed to translate the CSDDRD construction codes into unique surface material layers.
  c) An algorithm was developed to modify material layers to account for framing.
    i) Thermal conductivity of all insulation layers was available for modification to account for thermal bridging.
    ii) Density and specific heat of cavity insulation were modified to account for the thermal mass characteristics of the framing material.
  d) The shared surfaces of a double/row house have an adiabatic condition imposed at the center of the shared surface layers. This accounts for thermal mass effects which store absorbed solar radiation.

5) A new method was developed for the handling of heat advection. This method relies on three distinct airflow modeling methods within ESP-r.
  a) If present in the house, mechanical ventilation is imposed under all circumstances.
  b) The AIM-2 air-leakage model (Walker and Wilson 1990, 1998) is only invoked for zones characterized by the blower door test. AIM-2 is only active when windows are closed. A conservative window opening algorithm was independently imposed on each zone which has windows.
  c) The air-flow-network functionality (Hensen 1991) is used to model zone-zone airflow exchange, as well as zone-ambient airflow when the windows are open.

6) Functionality was added to the ESP-r simulator to support internal gains due to DHW and AL. Special attention was paid to the internal gain interactions to preserve the spacial and temporal integrity of each end-use. For example, consider the DHW system. The statistical modeling method is employed to estimate the water draw, and this is imposed within the basement zone. The DHW tank has standby losses which are modeled using the engineering method. These standby losses are a function of basement zone temperature which varies throughout the year, and thus impacts the SH and SC energy consumption to different degrees. Other specific treatments of internal gains include:
  a) The AL-clothes-dryer is powered by electricity or natural gas, and exhaust outside the house.
  b) The AL-cook-stove is powered by electricity or natural gas, and becomes an internal gain in the first main level.
  c) The AL-other is powered by electricity, and becomes and internal gain which is distributed among all conditioned zones.

7) A zone conditioning control strategy was imposed with respect to the present equipment.
  a) Specific periods of system functionality and temperature setpoints were imposed to avoid under and overheating.

b) Master/slave controllers were specified for all systems with the exception of baseboards. Baseboard systems were controlled by zone specific controllers.

A method was developed to summarize the energy consumption results as a function of month. The summarization categories are:

- Total house energy consumption.
- Energy consumption by energy source.
- Energy consumption by end-use and sub-categorized by energy source.

The GHG emissions of each summarization category were calculated. The average GHG EIFs of electricity (Farhat and Ugursal 2010) were applied with consideration to province and month. The electricity consumption values were increased to account for transmission/distribution losses. During a new technology analysis, the marginal GHG EIFs are applied to the change in electricity consumption, including the avoided transmission/distribution losses.

8.2.3.2 Results

The CHREM engineering method was used to estimate the energy consumption and GHG emissions of the CHS by simulating each house of the database. This gives an independent bottom-up assessment using a unique database and hybrid modeling method. The estimates of the CHREM, SHEU-03 survey, and top-down REUM are shown in Table 8.3.

Table 8.3 Comparison of the national annual energy consumption estimates by end-use and energy source for the SD and DR house types

End-use or energy source		Energy (PJ)			GHG emissions (Mt of CO_2e)	
		CHREM	SHEU-03	REUM-00-04	CHREM	REUM-00-04
End-use	SH	860.6		714.4	39.20	34.50
	SC	13.0		16.2	0.68	1.00
	DHW	192.4		237.7	8.40	13.00
	AL	246.4		184.5	17.70	11.70
Energy source	Electricity	523.9	447.8	413.1	25.36	25.60
	Natural gas	627.6	600.0	533.5	31.74	25.30
	Oil	126.3		103.8	8.88	7.20
	Wood	34.6		91.2	0.00	1.00
	Total	1312.4	1182.9	1152.8	65.98	60.30

In general, there is reasonable agreement between the CHREM, SHEU-03, and REUM estimates. The CHREM estimates approximately 12% greater values of energy consumption and GHG emissions.

The commonality between the SHEU-03 and REUM is that they rely on billing data. One of the best attributes of billing data is that it is irrespective of the thermal envelope, active energy systems, and occupant control (e.g. DHW use, heating temperature setpoint). However, the use of billing data suffers from unreported energy deliveries and non-responsive suppliers. Thus, the national energy consumption values of the SHEU-03 and REUM are likely less than the actual CHS energy consumption. Neither the SHEU-03 nor the REUM have the capacity to investigate new technologies.

In contrast, the CHREM estimates are based on bottom-up methods and simulation which captures the wide variation in the CHS. Each end-use is specifically modeled based on its characteristics. This allows the CHREM to clearly differentiate between different end-uses and energy sources. It also allows the CHREM to assess the impact on energy consumption and GHG emissions due to new technologies.

The difference in estimates was principally attributed to the CHREM assumptions of specific heating temperature setpoints, operational periods, and occupancy, and to a lesser extent the energy accounting methods of the models. It should be noted that the CHREM was not calibrated against billing data as no suitable data exists.

8.3 Recommendations

As the title of this dissertation suggests, the CHREM is intended as an energy consumption and GHG emissions model of the CHS for the investigation of new technologies. This dissertation primarily presents on the research and development of the CHREM. It demonstrates the strengths and capabilities of the CHREM using the window analysis in Chapter 7. The recommendations are presented in two parts: i) further enhancements to the CHREM, and ii) suggested technology analysis to exercise the unique strengths and capabilities of the CHREM.

8.3.1 Further Enhancement of the CHREM

The CHREM has developed over a period of time. Throughout this period the CHS has continued to evolve. Other groups have also continued their research. Because of this, it is now possible to further enhance the CHREM.

8.3.1.1 Database Selection and Update Recommendations

The CSDDRD consists of 16,952 houses which were selected from 121,456 houses of the EGHD (CANMET 2006) using distributions of the Survey of Household Energy Use 2003 (SHEU-03, OEE 2006). The selection of houses presents three opportunities for enhancement:

1) Since the development of the CSDDRD, a new SHEU survey (2007) has been conducted (OEE 2010). SHEU-07 shows that the average heated area continues to increase, and that the penetration rate of condensing natural gas furnaces is high among new construction. It is recommended to re-select the CSDDRD based on these most recent distributions. This will allow for the CSDDRD to evolve with the building stock.
2) Although the SHEU-03 only gives distributions by region, a provincial representation was required for GHG emissions analysis. This lead to certain provinces being underrepresented, as shown in Table 6.10 on page 195. It is recommended to re-select the CSDDRD with consideration given to provinces based on the distribution of Census 2006, as shown in Table 6.9 on page 194. It should be noted that the latest SHEU-07 separates the province of Alberta from the Prairies region.
3) Figures 3.5 and 3.6 (see pages 74 and 75, respectively) show that the selected houses are close in distribution, but are not exact. This is a result of the consecutive selection algorithm. It is recommended to use an iterative algorithm to select the "best" representation, as opposed to the "first" representation. An iterative algorithm would have the capability of rejecting a previously selected house in favour of another.

8.3.1.2 Bottom-up Statistical Method Recommendations

The statistical method requires input information related to common appliances and demographics. These two characteristics are highly related and evolve more rapidly than building envelope changes. Because of this, there are two opportunities for enhancement:

1) The CSDDRD primarily contains information related to the house thermal envelope and energy conversion systems. Much of the occupant and appliance data of the statistical method was populated using a variety of data sources, including distributions. This populating process by distribution reduces the ability of the NN to distinguish interrelated functions. If new data becomes available, it is recommended to select a representative house of occupant and appliance data for each house of the CSDDRD. The selection process could be based on comparable information between the CSDDRD and the new data. By applying a specific house of occupant and appliance data, the interrelation between functions is preserved.
2) The NN used for the CHREM bottom-up statistical method was calibrated using the SHEU-93 database. This data is now almost two decades old. Many changes in electronic items have occurred since then (e.g. penetration rate of home computers). Additionally, recent appliances have focused on energy efficiency (e.g. front loading washing machines). It is recommended to re-calibrate the NN should new data

become available. Such data exists in SHEU-07; however, the database is not presently available to the public. If sufficient differentiation in "high-efficiency" appliances exists, then the CHREM could be used to investigate the impacts of new appliance penetration on the end-use energy consumption and GHG emissions of the CHS.

8.3.1.3 Bottom-up Engineering Method Recommendations

Section 6.3.3 discussed the significant impacts that control and temperature setpoints have on energy consumption. A number of assumptions were made for the control strategies of the engineering method. Due to lack of suitable data, the CHREM was not calibrated, and these assumptions stand. There is an opportunity to further examine their effect and increase their appropriateness:

1) The two major control assumptions are the heating/cooling temperature setpoints and the heating/cooling periods of use throughout the year. The heating/cooling temperature setpoints were set to specific values of 21 °C and 25 °C, respectively. The heating/cooling periods were extended and overlapped throughout the spring/fall seasons to avoid over and under heating the house. It is recommended to consider alternative control strategies, setpoints, and periods of operation, especially if examining the use of setback thermostats.
2) A conservative algorithm was imposed on the use of windows for natural SC, in an effort to avoid simulation issues. The easing of window control restrictions should be considered.
3) The CSDDRD includes detailed window information such as the vertical and horizontal distance of the awning above windows; however, it is unreliable. Because of this, awnings which block summertime sunlight from entering the house were not modeled in the CHREM. This likely resulted in the SC energy consumption being overestimated. It is suggested to examine the impact due to shading caused by occupant use of windows coverings, eaves, and other external obstructions.

As noted in section 6.2.4.2 on page 188, the electricity generation GHG emission intensity factors are subject to the electricity generation energy sources. It is expected that these will reduce significantly over the next decade as a transition is made from coal to less carbon intensive energy sources, and significant non-dispatchable renewable energy is integrated to the electricity grid. The GHG emission intensity factors should be updated to reflect these changes.

8.3.2 Suggested Technology Analysis to Exercise the Strengths and Capabilities of the CHREM

The CHREM provides a unique capability for the evaluation of new technologies applied to the housing stock. It primarily derives this quality from the CSDDRD, and the bottom-up engineering method which employs the ESP-r simulator. The CSDDRD can be used to assess potential penetration levels of technologies based on the existing thermal envelope and energy conversion systems. The CHREM statistical method estimates can be used to determine suitability of a new technology with DHW and AL use. The bottom-up engineering modeling method can simulate nearly any technology and estimate its impact on energy consumption and GHG emissions. A study is ongoing which is examining an array of technologies using the CHREM (Nikoofard et al. 2009, Nikoofard 2010). The following subsections introduce a selection of technologies which can be evaluated for the CHS because of the advancements of the CHREM.

8.3.2.1 Alternative Energy Technologies for the Reduction of Conventional Energy Use: Heat Pumps and Co-generation Systems

Heat pumps are an alternative energy technology that utilizes the ambient conditions (air, water, soil) outside the house as an energy source for SH. This utilization gives a heat pump a coefficient of performance, the ratio of output heat to input electricity, typically ranging from 2 to 4. Because of the reliance on ambient conditions, heat pump performance varies significantly throughout the heating season, primarily as a function of source temperature. Furthermore, during much of the heating season, air-source heat pumps require a defrost cycle. The CHREM can be used to assess the performance of heat pumps applied to the CHS.

Such an assessment of heat pumps would begin with the CSDDRD. Houses with conventional air or hydronic SH distribution systems are candidates for this technology. Houses that presently rely on distributed electric baseboards may be of less interest, as a complete new distribution system would be required for the house. Houses that are located in very cold regions may not be suitable for single-stage air-source heat pumps.

The performance of heat pumps would then be evaluated using the CHREM engineering method. The CWEC weather data would be employed, which includes both ambient air temperature and relative humidity. During the timestep simulation, the ESP-r simulator is capable of determining electrical power and the delivery heat rate of the heat pump, including the effects of defrost cycles. The CHREM would then assess the change in electrical energy consumption and the provincially dependent impact upon GHG emissions. All performance metrics of the heat pump may be examined to determine suitability to the CHS: compressor runtime, defrost cycle rate, auxiliary heat use, and the change in energy consumption and GHG emissions.

A second alternative energy technology is co-generation systems: heat engines which produce electricity and use the exhaust heat to offset SH energy consumption. The assessment begins using the CSDDRD. Houses with long heating seasons that require significant electricity for AL are candidates. Houses located in regions serviced by hydroelectricity are likely not candidates due to the resultant increase in GHG emissions by using co-generation technologies.

The performance of such a co-generation system could be evaluated using the CHREM engineering method. During the heating season, the co-generation system would be controlled so as to meet the imposed AL electricity use profile. The exhaust heat of the co-generation system would offset all or a portion of the SH energy consumption. The CHREM engineering method is fully capable of capturing the interrelations between the energy flows. The electricity generated by the co-generation system would offset that required from the electricity grid. This electricity use would primarily become heat and offset the SH needs, along with the co-generation exhaust heat. The change in consumption of each energy type could be identified using the CHREM, and the resultant change in GHG emissions would also be estimated.

8.3.2.2 Renewable Energy Use: Active Solar Energy Systems

There are a variety of active solar energy systems that can be investigated using the CHREM. Solar thermal systems that offset conventional DHW energy consumption are one type. Solar photovoltaic systems that offset electricity consumption from the grid are another type.

The assessment of both technologies using the CHREM would begin with the CSDDRD. Houses with a sloped roof and a ridgeline running east-west are likely candidates for both systems due to the integration directly with the roof. It would be preferred to install solar thermal systems on houses in warmer regions to avoid thermal losses. In contrast, it would be preferred to install solar photovoltaic systems in colder regions to increase electricity conversion efficiency.

The performance of both systems would be evaluated using the CHREM engineering method. The solar thermal system would be compared with the DHW use profile. The solar photovoltaic system would be compared to the electricity consumption profile. While this would be primarily aimed at offsetting AL grid electricity consumption, it is likely to also offset SC grid electricity consumption. The solar thermal system would likely involve an energy storage tank. The ESP-r simulator is capable of assessing the temperature and energy level of the solar thermal storage tank in any of the variety of configurations found in commercial or research systems (see Nikoofard 2010 for examples).

8.3.2.3 Electricity Demand Analysis

Electricity demand analysis has become a principal concern for utilities as they further integrate non-dispatchable renewable energy. Periods of peak demand may be mitigated by the use of thermal or electrical energy storage, or specific system deactivation (e.g. SC). Each of these may be modeled using the CHREM to assess the impact on demand.

The CSDDRD could be used to examine and identify houses with significant electricity consumption during peak periods. For certain provinces, this will be related to wintertime SH using electricity, and for other provinces summertime SC.

The impact of storage or control systems could be evaluated using the CHREM engineering method. For demand peaking related to wintertime SH, high-temperature heat storage units may be employed. Control can be imposed within the ESP-r simulator to charge this sensible or latent thermal energy storage unit during off-peak periods. Alternatively, an electrical energy storage unit (e.g. batteries) could be investigated. This system would also be charged during off-peak periods, and would power a heat pump.

For demand peaking related to summertime SC, control could be implemented to utilize the “weather forecast” to “pre-cool” a house prior to an expected demand peak. Alternatively, an electrical energy storage unit could again be employed. Such an electrical energy storage unit might be combined with a solar photovoltaic system. If demand peaking was found to occur in the late afternoon, the electrical energy storage system could be used to shift the noontime solar electricity generation for later use.

It should be noted that a limited number of AL and DHW use profiles were incorporated into the present CHREM. Although 27 variations of these profile groups were created, they are repetitively used among many houses. Therefore, an hourly demand analysis at the housing stock level will show significantly overstated extremes. It is possible to institute unique use profiles into the CHREM by either utilizing the profile generator (Armstrong et al. 2009) or using a temporal shifting technique.

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Appendix A Climatic Summary of the Canadian Weather for Energy Calculations (CWEC)

Province	City	Latitude (deg.)	Longitude (deg.)	Elevation (m)	HDD (18 °C base)	CDD (24 °C base)
AB	Calgary	51.1	-114.0	1084	5108	0.2
AB	Edmonton	53.3	-113.6	723	5708	0.0
AB	Fort McMurray	56.7	-111.2	369	6346	0.8
AB	Medicine Hat	50.0	-110.7	717	4632	10.0
BC	Fort St. John	56.2	-120.7	695	5847	0.0
BC	Abbotsford	49.0	-122.4	59	2981	0.9
BC	Summerland	49.6	-119.7	454	3525	18.4
BC	Victoria	48.6	-123.4	19	3041	0.0
BC	Prince George	54.1	-122.7	691	5132	0.0
BC	Kamloops	50.7	-120.4	345	3571	19.5
BC	Port Hardy	50.7	-127.4	22	3552	0.0
BC	Prince Rupert	54.3	-130.4	35	3967	0.0
BC	Vancouver	49.2	-123.2	4	2927	0.1
MB	Winnipeg	49.9	-97.2	238	5778	10.8
MB	Churchill	58.7	-94.1	29	9068	0.6
MB	Le Pas	54.0	-101.1	270	6598	2.3
NB	Saint John	45.3	-65.9	109	4755	0.2
NB	Fredericton	45.9	-66.5	21	4751	4.3
NL	St. John's	47.6	-52.7	141	4882	0.0
NL	Goose Bay	53.3	-60.4	49	6787	1.8
NL	Stephenville	48.5	-58.6	24	4899	0.0
QC	Schefferville	54.8	-66.8	522	8476	0.2
NT	Yellowknife	62.5	-114.4	206	8256	0.4
NT	Inuvik	68.3	-133.5	68	9767	0.3
NS	Halifax	44.7	-63.6	70	4031	0.7
NS	Sydney	46.2	-60.0	62	4618	0.9
NU	Resolute	74.7	-95.0	65	12526	0.0
ON	Thunder Bay	48.4	-89.3	199	5718	1.2
ON	Trenton	44.1	-77.5	86	4223	9.0
ON	London	43.0	-81.2	278	4058	12.3
ON	Muskoka	45.0	-79.3	282	4883	1.7
ON	North Bay	46.4	-79.4	370	5295	2.1
ON	Ottawa	45.3	-75.7	114	4602	14.0
ON	Sault Ste. Marie	46.5	-84.5	192	5057	1.5
ON	Toronto	43.7	-79.4	113	3570	30.2
ON	Windsor	42.3	-83.0	190	3525	43.4
PE	Charlottetown	46.3	-63.1	49	4715	0.6
QC	Quebec	46.8	-71.4	74	5202	3.0
QC	Montreal	45.5	-73.8	36	4519	11.9
SK	Estevan	49.2	-103.0	581	5361	13.1
SK	Regina	50.4	-104.7	577	5661	7.9
SK	North Battleford	52.8	-108.3	548	5930	3.1

Province	City	Latitude (deg.)	Longitude (deg.)	Elevation (m)	HDD (18 ℃ base)	CDD (24 ℃ base)
SK	Swift Current	50.3	-107.7	818	5251	5.9
YT	Whitehorse	60.7	-135.1	706	6811	0.0

Appendix B BASESIMP Foundation Types used in the CHREM

BASESIMP			Insulation placement			
number	BASESIMP label	Foundation type	Wall	Slab	Edge break	Skirt
1	BCIN_1	Basement - concrete	Interior full			
2	BCIN_2	Basement - concrete	Interior partial			
4	BCIN_4	Basement - concrete	Interior partial			
6	BCEN_2	Basement - concrete	Exterior full			
8	BCEN_4	Basement - concrete	Exterior below grade			
10	BCNN_2	Basement - concrete				
12	BCCN_2	Basement - concrete	Overlapped Exterior and Interior			
14	BWIN_1	Basement - wood	Interior full			
15	BWIN_2	Basement - wood	Interior partial			
18	BWEN_2	Basement - wood	Exterior below grade			
19	BCIB_1	Basement - concrete	Interior full	Bottom full		
20	BCIB_2	Basement - concrete	Interior full	Bottom perimeter		
28	SCN_1	Crawl space or slab on grade				
34	SCB_1	Crawl space or slab on grade		Bottom perimeter		
38	SCB_5	Crawl space or slab on grade			Exists	
40	SCB_9	Crawl space or slab on grade		Bottom perimeter	Exists	
52	SCB_25	Crawl space or slab on grade		Bottom full		
54	SCB_29	Crawl space or slab on grade		Bottom full	Exists	
56	SCB_33	Crawl space or slab on grade		Bottom full	Exists	Exists
60	SCA_17	Crawl space or slab on grade		Top full		
62	SCA_19	Crawl space or slab on grade		Top full	Exists	
64	SCA_21	Crawl space or slab on grade		Top full	Exists	Exists
68	BCCN_3	Basement - concrete	Both full		Exists	
69	BCCN_4	Basement - concrete	Interior full, exterior partial			
71	BCEA_4	Basement - concrete	Exterior full	Top full		
72	BCIA_1	Basement - concrete	Interior full	Top full		
73	BCIA_4	Basement - concrete	Interior partial	Top full		
89	BBEN_2	Basement - wood walls and concrete floor	Exterior partial			

BASESIMP number	BASESIMP label	Foundation type	Insulation placement			
			Wall	Slab	Edge break	Skirt
92	BCCB_8	Basement - concrete	Interior full, exterior full	Bottom perimeter		
93	BCCA_7	Basement - concrete	Interior full, exterior partial	Top full		
94	BCCA_8	Basement - concrete	Interior partial, exterior full	Top full		
98	BCEA_6	Basement - concrete	Exterior partial	Top full		
99	BCEB_4	Basement - concrete	Exterior full	Bottom full		
103	BWIA_2	Basement - wood	Interior full	Top full		
108	BBIN_1	Basement - wood walls and concrete floor	Interior full			
110	BCEN_6	Basement - concrete	Exterior partial			
111	BBIA_1	Basement - wood walls and concrete floor	Interior full	Top full		
112	BBIB_1	Basement - wood walls and concrete floor	Interior full	Bottom perimeter		
113	BBIB_2	Basement - wood walls and concrete floor	Interior full	Bottom full		
114	BCCB_9	Basement - concrete	Interior full, exterior partial	Bottom full		
115	BCCB_10	Basement - concrete	Interior full, exterior partial	Bottom perimeter		
119	BCIB_8	Basement - concrete	Interior full	Bottom full	Exists	
121	BCIA_3	Basement - concrete	Interior full	Top perimeter		
129	BCEA_9	Basement - concrete	Exterior full	Top perimeter		
133	BWIB_2	Basement - wood	Interior full	Bottom full		

Appendix C CHREM Estimates of Annual Energy Consumption and GHG Emissions by House Type, Province, End-use, and Energy Source

House type,	Energy (PJ)					GHG emissions (Mt of CO_2e)			
prov., end-use	Elec.	Nat. gas	Oil	Wood	Total	Elec.	Nat. gas	Oil	Total
Single detached	**432.4**	**522.2**	**108.9**	**34.6**	**1098.1**	**21.87**	**26.44**	**7.68**	**55.99**
NF	**12.9**	**0.0**	**7.7**	**3.1**	**23.7**	**0.04**	**0.00**	**0.51**	**0.55**
SH	5.7	0.0	7.4	3.1	16.2	0.04	0.00	0.51	0.55
DHW	2.4	0.0	0.3	0.0	2.7	0.00	0.00	0.00	0.00
AL	4.8	0.0	0.0	0.0	4.8	0.00	0.00	0.00	0.00
NS	**15.8**	**0.0**	**21.2**	**6.1**	**43.1**	**3.32**	**0.00**	**1.54**	**4.86**
SH	3.8	0.0	18.6	6.1	28.5	0.79	0.00	1.33	2.12
SC	0.0	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
DHW	3.1	0.0	2.6	0.0	5.7	0.64	0.00	0.21	0.85
AL	8.9	0.0	0.0	0.0	8.9	1.89	0.00	0.00	1.89
PE	**1.2**	**0.0**	**4.1**	**1.7**	**7.0**	**0.12**	**0.00**	**0.23**	**0.35**
SH	0.0	0.0	2.9	1.7	4.6	0.00	0.00	0.20	0.20
DHW	0.0	0.0	1.2	0.0	1.2	0.00	0.00	0.03	0.03
AL	1.2	0.0	0.0	0.0	1.2	0.12	0.00	0.00	0.12
NB	**17.6**	**0.0**	**8.1**	**10.9**	**36.6**	**2.26**	**0.00**	**0.59**	**2.85**
SH	7.2	0.0	8.1	10.9	26.2	0.92	0.00	0.59	1.51
SC	0.0	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
DHW	4.1	0.0	0.0	0.0	4.1	0.51	0.00	0.00	0.51
AL	6.3	0.0	0.0	0.0	6.3	0.83	0.00	0.00	0.83
QC	**160.3**	**0.9**	**22.3**	**10.6**	**194.1**	**0.29**	**0.05**	**1.58**	**1.92**
SH	91.5	0.9	22.3	10.6	125.3	0.16	0.05	1.58	1.79
SC	1.4	0.0	0.0	0.0	1.4	0.00	0.00	0.00	0.00
DHW	30.2	0.0	0.0	0.0	30.2	0.01	0.00	0.00	0.01
AL	37.2	0.0	0.0	0.0	37.2	0.12	0.00	0.00	0.12
OT	**118.0**	**277.4**	**45.5**	**0.0**	**440.9**	**6.95**	**14.00**	**3.23**	**24.18**
SH	26.4	228.5	45.5	0.0	300.4	1.57	11.58	3.23	16.38
SC	8.4	0.0	0.0	0.0	8.4	0.48	0.00	0.00	0.48
DHW	14.2	47.7	0.0	0.0	61.9	0.84	2.42	0.00	3.26
AL	69.0	1.2	0.0	0.0	70.2	4.06	0.00	0.00	4.06

House type, prov., end-use	Energy (PJ) Elec.	Nat. gas	Oil	Wood	Total	GHG emissions (Mt of CO_2e) Elec.	Nat. gas	Oil	Total
MB	**18.8**	**29.7**	**0.0**	**0.0**	**48.5**	**0.03**	**1.54**	**0.00**	**1.57**
SH	8.3	26.1	0.0	0.0	34.4	0.03	1.33	0.00	1.36
SC	0.2	0.0	0.0	0.0	0.2	0.00	0.00	0.00	0.00
DHW	3.3	3.6	0.0	0.0	6.9	0.00	0.21	0.00	0.21
AL	7.0	0.0	0.0	0.0	7.0	0.00	0.00	0.00	0.00
SK	**10.4**	**37.4**	**0.0**	**0.0**	**47.8**	**2.31**	**1.90**	**0.00**	**4.21**
SH	1.8	30.8	0.0	0.0	32.6	0.42	1.56	0.00	1.98
SC	0.3	0.0	0.0	0.0	0.3	0.08	0.00	0.00	0.08
DHW	1.2	6.6	0.0	0.0	7.8	0.20	0.34	0.00	0.54
AL	7.1	0.0	0.0	0.0	7.1	1.61	0.00	0.00	1.61
AB	**22.7**	**103.0**	**0.0**	**0.0**	**125.7**	**6.26**	**5.22**	**0.00**	**11.48**
SH	0.0	82.9	0.0	0.0	82.9	0.00	4.21	0.00	4.21
SC	0.0	0.0	0.0	0.0	0.0	0.03	0.00	0.00	0.03
DHW	0.0	20.1	0.0	0.0	20.1	0.12	1.01	0.00	1.13
AL	22.7	0.0	0.0	0.0	22.7	6.11	0.00	0.00	6.11
BC	**54.7**	**73.8**	**0.0**	**2.2**	**130.7**	**0.29**	**3.73**	**0.00**	**4.02**
SH	9.0	62.5	0.0	2.2	73.7	0.05	3.16	0.00	3.21
SC	0.6	0.0	0.0	0.0	0.6	0.00	0.00	0.00	0.00
DHW	7.0	11.3	0.0	0.0	18.3	0.00	0.57	0.00	0.57
AL	38.1	0.0	0.0	0.0	38.1	0.24	0.00	0.00	0.24
Double/row	**91.5**	**105.4**	**17.4**	**0.0**	**214.3**	**3.49**	**5.30**	**1.20**	**9.99**
NF	**1.9**	**0.0**	**1.8**	**0.0**	**3.7**	**0.00**	**0.00**	**0.12**	**0.12**
SH	0.7	0.0	1.8	0.0	2.5	0.00	0.00	0.12	0.12
DHW	0.0	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
AL	1.2	0.0	0.0	0.0	1.2	0.00	0.00	0.00	0.00
NS	**2.1**	**0.0**	**1.9**	**0.0**	**4.0**	**0.55**	**0.00**	**0.12**	**0.67**
SH	0.9	0.0	1.9	0.0	2.8	0.19	0.00	0.12	0.31
SC	0.0	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
DHW	0.0	0.0	0.0	0.0	0.0	0.12	0.00	0.00	0.12
AL	1.2	0.0	0.0	0.0	1.2	0.24	0.00	0.00	0.24

House type,	Energy (PJ)					GHG emissions (Mt of CO_2e)			
prov., end-use	Elec.	Nat. gas	Oil	Wood	Total	Elec.	Nat. gas	Oil	Total
PE	**0.0**	**0.0**	**0.1**	**0.0**	**0.1**	**0.00**	**0.00**	**0.00**	**0.00**
SH	0.0	0.0	0.1	0.0	0.1	0.00	0.00	0.00	0.00
DHW	0.0	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
AL	0.0	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
NB	**0.1**	**0.0**	**1.7**	**0.0**	**1.8**	**0.12**	**0.00**	**0.12**	**0.24**
SH	0.0	0.0	1.7	0.0	1.7	0.00	0.00	0.12	0.12
DHW	0.0	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
AL	0.1	0.0	0.0	0.0	0.1	0.12	0.00	0.00	0.12
QC	**46.8**	**0.3**	**8.6**	**0.0**	**55.7**	**0.05**	**0.01**	**0.61**	**0.67**
SH	28.4	0.3	8.6	0.0	37.3	0.05	0.01	0.61	0.67
SC	0.4	0.0	0.0	0.0	0.4	0.00	0.00	0.00	0.00
DHW	8.1	0.0	0.0	0.0	8.1	0.00	0.00	0.00	0.00
AL	9.9	0.0	0.0	0.0	9.9	0.00	0.00	0.00	0.00
OT	**23.1**	**67.5**	**3.3**	**0.0**	**93.9**	**1.33**	**3.45**	**0.23**	**5.01**
SH	3.7	54.3	3.3	0.0	61.3	0.20	2.76	0.23	3.19
SC	1.7	0.0	0.0	0.0	1.7	0.09	0.00	0.00	0.09
DHW	2.1	13.2	0.0	0.0	15.3	0.12	0.69	0.00	0.81
AL	15.6	0.0	0.0	0.0	15.6	0.92	0.00	0.00	0.92
MB	**1.3**	**2.8**	**0.0**	**0.0**	**4.1**	**0.00**	**0.14**	**0.00**	**0.14**
SH	0.1	2.5	0.0	0.0	2.6	0.00	0.14	0.00	0.14
SC	0.0	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
DHW	0.0	0.3	0.0	0.0	0.3	0.00	0.00	0.00	0.00
AL	1.2	0.0	0.0	0.0	1.2	0.00	0.00	0.00	0.00
SK	**1.2**	**4.1**	**0.0**	**0.0**	**5.3**	**0.12**	**0.16**	**0.00**	**0.28**
SH	0.0	2.9	0.0	0.0	2.9	0.00	0.16	0.00	0.16
SC	0.0	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
DHW	0.0	1.2	0.0	0.0	1.2	0.00	0.00	0.00	0.00
AL	1.2	0.0	0.0	0.0	1.2	0.12	0.00	0.00	0.12
AB	**4.8**	**18.9**	**0.0**	**0.0**	**23.7**	**1.32**	**0.97**	**0.00**	**2.29**
SH	0.0	14.4	0.0	0.0	14.4	0.00	0.73	0.00	0.73
SC	0.0	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
DHW	0.0	4.5	0.0	0.0	4.5	0.00	0.24	0.00	0.24
AL	4.8	0.0	0.0	0.0	4.8	1.32	0.00	0.00	1.32

House type, prov., end-use	Energy (PJ)					GHG emissions (Mt of CO_2e)			
	Elec.	Nat. gas	Oil	Wood	Total	Elec.	Nat. gas	Oil	Total
BC	**10.2**	**11.8**	**0.0**	**0.0**	**22.0**	**0.00**	**0.57**	**0.00**	**0.57**
SH	1.3	8.9	0.0	0.0	10.2	0.00	0.45	0.00	0.45
SC	0.0	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
DHW	1.2	2.9	0.0	0.0	4.1	0.00	0.12	0.00	0.12
AL	7.7	0.0	0.0	0.0	7.7	0.00	0.00	0.00	0.00
Canada total (SD and DR)	**523.9**	**627.6**	**126.3**	**34.6**	**1312.4**	**25.36**	**31.74**	**8.88**	**65.98**

Appendix D CHREM Estimates of Monthly Energy Consumption and GHG Emissions for SD and DR House Types as a function of Province and End-use

Province and month	Energy (PJ)					GHG emissions (Mt of CO_2e)				
	SH	SC	DHW	AL	Total	SH	SC	DHW	AL	Total
NF	**18.7**	**0.0**	**2.7**	**6.0**	**0.67**	**0.00**	**0.00**	**0.00**	**27.4**	**0.67**
Jan	3.3	0.0	0.2	0.5	0.12	0.00	0.00	0.00	4.0	0.12
Feb	3.0	0.0	0.2	0.5	0.12	0.00	0.00	0.00	3.7	0.12
Mar	2.6	0.0	0.3	0.5	0.10	0.00	0.00	0.00	3.4	0.10
Apr	2.0	0.0	0.3	0.5	0.06	0.00	0.00	0.00	2.8	0.06
May	1.2	0.0	0.2	0.5	0.04	0.00	0.00	0.00	1.9	0.04
Jun	0.0	0.0	0.2	0.5	0.00	0.00	0.00	0.00	0.7	0.00
Jul	0.0	0.0	0.2	0.5	0.00	0.00	0.00	0.00	0.7	0.00
Aug	0.0	0.0	0.2	0.5	0.00	0.00	0.00	0.00	0.7	0.00
Sep	0.3	0.0	0.2	0.5	0.01	0.00	0.00	0.00	1.0	0.01
Oct	1.3	0.0	0.2	0.5	0.04	0.00	0.00	0.00	2.0	0.04
Nov	2.0	0.0	0.2	0.5	0.07	0.00	0.00	0.00	2.7	0.07
Dec	3.0	0.0	0.3	0.5	0.11	0.00	0.00	0.00	3.8	0.11
NS	**31.3**	**0.0**	**5.7**	**10.1**	**2.43**	**0.00**	**0.97**	**2.13**	**47.1**	**5.53**
Jan	6.1	0.0	0.5	0.9	0.48	0.00	0.09	0.19	7.5	0.76
Feb	5.6	0.0	0.5	0.8	0.42	0.00	0.08	0.17	6.9	0.67
Mar	4.7	0.0	0.6	0.9	0.37	0.00	0.09	0.18	6.2	0.64
Apr	3.1	0.0	0.6	0.8	0.24	0.00	0.09	0.18	4.5	0.51
May	1.6	0.0	0.5	0.9	0.13	0.00	0.08	0.18	3.0	0.39
Jun	0.1	0.0	0.4	0.8	0.01	0.00	0.07	0.17	1.3	0.25
Jul	0.0	0.0	0.4	0.8	0.00	0.00	0.07	0.17	1.2	0.24
Aug	0.0	0.0	0.4	0.8	0.00	0.00	0.06	0.17	1.2	0.23
Sep	0.2	0.0	0.4	0.8	0.01	0.00	0.08	0.17	1.4	0.26
Oct	1.5	0.0	0.4	0.9	0.13	0.00	0.08	0.18	2.8	0.39
Nov	3.2	0.0	0.5	0.8	0.24	0.00	0.09	0.18	4.5	0.51
Dec	5.2	0.0	0.5	0.9	0.40	0.00	0.09	0.19	6.6	0.68

Province and month	Energy (PJ)					GHG emissions (Mt of CO_2e)				
	SH	SC	DHW	AL	Total	SH	SC	DHW	AL	Total
PE	**4.7**	**0.0**	**1.2**	**1.2**	**0.20**	**0.00**	**0.03**	**0.12**	**7.1**	**0.35**
Jan	1.0	0.0	0.1	0.1	0.04	0.00	0.00	0.01	1.2	0.05
Feb	0.8	0.0	0.1	0.1	0.03	0.00	0.00	0.01	1.0	0.04
Mar	0.6	0.0	0.1	0.1	0.03	0.00	0.01	0.01	0.8	0.05
Apr	0.5	0.0	0.1	0.1	0.02	0.00	0.01	0.01	0.7	0.04
May	0.2	0.0	0.1	0.1	0.01	0.00	0.00	0.01	0.4	0.02
Jun	0.0	0.0	0.1	0.1	0.00	0.00	0.00	0.01	0.2	0.01
Jul	0.0	0.0	0.1	0.1	0.00	0.00	0.00	0.01	0.2	0.01
Aug	0.0	0.0	0.1	0.1	0.00	0.00	0.00	0.01	0.2	0.01
Sep	0.0	0.0	0.1	0.1	0.00	0.00	0.00	0.01	0.2	0.01
Oct	0.3	0.0	0.1	0.1	0.01	0.00	0.00	0.01	0.5	0.02
Nov	0.5	0.0	0.1	0.1	0.02	0.00	0.00	0.01	0.7	0.03
Dec	0.8	0.0	0.1	0.1	0.04	0.00	0.01	0.01	1.0	0.06
NB	**27.9**	**0.0**	**4.1**	**6.4**	**1.63**	**0.00**	**0.51**	**0.95**	**38.4**	**3.09**
Jan	5.9	0.0	0.4	0.7	0.34	0.00	0.05	0.08	7.0	0.47
Feb	4.8	0.0	0.3	0.5	0.28	0.00	0.04	0.08	5.6	0.40
Mar	3.8	0.0	0.4	0.5	0.23	0.00	0.05	0.08	4.7	0.36
Apr	2.3	0.0	0.4	0.5	0.14	0.00	0.05	0.08	3.2	0.27
May	1.1	0.0	0.3	0.6	0.05	0.00	0.04	0.08	2.0	0.17
Jun	0.0	0.0	0.3	0.5	0.00	0.00	0.04	0.07	0.8	0.11
Jul	0.0	0.0	0.3	0.5	0.00	0.00	0.04	0.08	0.8	0.12
Aug	0.0	0.0	0.3	0.5	0.00	0.00	0.03	0.08	0.8	0.11
Sep	0.3	0.0	0.3	0.5	0.02	0.00	0.04	0.08	1.1	0.14
Oct	1.5	0.0	0.3	0.5	0.09	0.00	0.04	0.08	2.3	0.21
Nov	3.1	0.0	0.4	0.5	0.18	0.00	0.04	0.08	4.0	0.30
Dec	5.1	0.0	0.4	0.6	0.30	0.00	0.05	0.08	6.1	0.43

Province and month	Energy (PJ)					GHG emissions (Mt of CO_2e)				
	SH	SC	DHW	AL	Total	SH	SC	DHW	AL	Total
QC	**162.6**	**1.8**	**38.3**	**47.1**	**2.46**	**0.00**	**0.01**	**0.12**	**249.8**	**2.59**
Jan	36.5	0.0	3.3	4.2	0.57	0.00	0.00	0.01	44.0	0.58
Feb	30.2	0.0	3.2	3.8	0.45	0.00	0.00	0.01	37.2	0.46
Mar	23.6	0.0	3.7	4.0	0.36	0.00	0.01	0.01	31.3	0.38
Apr	10.8	0.0	3.4	3.8	0.16	0.00	0.00	0.01	18.0	0.17
May	3.5	0.1	3.3	4.1	0.04	0.00	0.00	0.01	11.0	0.05
Jun	0.0	0.4	2.9	3.7	0.00	0.00	0.00	0.01	7.0	0.01
Jul	0.0	0.7	2.8	3.8	0.00	0.00	0.00	0.01	7.3	0.01
Aug	0.0	0.5	2.5	3.8	0.00	0.00	0.00	0.01	6.8	0.01
Sep	1.1	0.1	3.2	3.8	0.01	0.00	0.00	0.01	8.2	0.02
Oct	8.4	0.0	3.2	4.0	0.13	0.00	0.00	0.01	15.6	0.14
Nov	18.0	0.0	3.3	3.9	0.28	0.00	0.00	0.01	25.2	0.29
Dec	30.5	0.0	3.5	4.2	0.46	0.00	0.00	0.01	38.2	0.47
OT	**361.7**	**10.1**	**77.2**	**85.8**	**19.57**	**0.57**	**4.07**	**4.98**	**534.8**	**29.19**
Jan	82.4	0.0	6.8	7.6	4.48	0.00	0.35	0.44	96.8	5.27
Feb	65.9	0.0	6.3	7.0	3.55	0.00	0.33	0.41	79.2	4.29
Mar	50.6	0.0	7.2	7.2	2.73	0.00	0.37	0.42	65.0	3.52
Apr	25.7	0.1	7.0	7.1	1.39	0.00	0.37	0.41	39.9	2.17
May	8.1	0.5	6.6	7.4	0.44	0.02	0.35	0.43	22.6	1.24
Jun	0.1	1.9	5.9	6.7	0.00	0.11	0.31	0.39	14.6	0.81
Jul	0.0	3.6	5.6	6.8	0.00	0.21	0.30	0.39	16.0	0.90
Aug	0.0	3.0	5.3	7.0	0.00	0.17	0.29	0.40	15.3	0.86
Sep	2.7	1.0	6.5	7.0	0.15	0.06	0.34	0.40	17.2	0.95
Oct	18.9	0.0	6.4	7.3	1.02	0.00	0.34	0.43	32.6	1.79
Nov	40.2	0.0	6.6	7.1	2.18	0.00	0.35	0.42	53.9	2.95
Dec	67.1	0.0	7.0	7.6	3.63	0.00	0.37	0.44	81.7	4.44

Province and month	Energy (PJ)					GHG emissions (Mt of CO_2e)				
	SH	SC	DHW	AL	Total	SH	SC	DHW	AL	Total
MB	**37.0**	**0.2**	**7.2**	**8.2**	**1.50**	**0.00**	**0.21**	**0.00**	**52.6**	**1.71**
Jan	8.5	0.0	0.6	0.7	0.34	0.00	0.02	0.00	9.8	0.36
Feb	6.6	0.0	0.6	0.7	0.26	0.00	0.02	0.00	7.9	0.28
Mar	4.9	0.0	0.7	0.7	0.19	0.00	0.02	0.00	6.3	0.21
Apr	2.1	0.0	0.7	0.7	0.09	0.00	0.02	0.00	3.5	0.11
May	0.7	0.0	0.6	0.7	0.03	0.00	0.02	0.00	2.0	0.05
Jun	0.0	0.0	0.5	0.6	0.00	0.00	0.01	0.00	1.1	0.01
Jul	0.0	0.1	0.5	0.6	0.00	0.00	0.01	0.00	1.2	0.01
Aug	0.0	0.1	0.5	0.7	0.00	0.00	0.01	0.00	1.3	0.01
Sep	0.4	0.0	0.6	0.7	0.02	0.00	0.02	0.00	1.7	0.04
Oct	1.9	0.0	0.6	0.7	0.08	0.00	0.02	0.00	3.2	0.10
Nov	4.6	0.0	0.6	0.7	0.19	0.00	0.02	0.00	5.9	0.21
Dec	7.3	0.0	0.7	0.7	0.30	0.00	0.02	0.00	8.7	0.32
SK	**35.5**	**0.3**	**9.0**	**8.3**	**2.14**	**0.08**	**0.54**	**1.73**	**53.1**	**4.49**
Jan	7.9	0.0	0.8	0.7	0.48	0.00	0.05	0.15	9.4	0.68
Feb	6.0	0.0	0.7	0.7	0.36	0.00	0.05	0.14	7.4	0.55
Mar	5.0	0.0	0.8	0.7	0.30	0.00	0.05	0.15	6.5	0.50
Apr	2.1	0.0	0.8	0.7	0.13	0.00	0.05	0.14	3.6	0.32
May	0.7	0.0	0.8	0.7	0.04	0.01	0.05	0.15	2.2	0.25
Jun	0.0	0.1	0.7	0.6	0.00	0.01	0.04	0.14	1.4	0.19
Jul	0.0	0.1	0.7	0.7	0.00	0.03	0.03	0.14	1.5	0.20
Aug	0.0	0.1	0.7	0.7	0.00	0.02	0.03	0.14	1.5	0.19
Sep	0.5	0.0	0.7	0.7	0.03	0.01	0.04	0.14	1.9	0.22
Oct	1.9	0.0	0.7	0.7	0.12	0.00	0.05	0.15	3.3	0.32
Nov	4.6	0.0	0.8	0.7	0.27	0.00	0.05	0.14	6.1	0.46
Dec	6.8	0.0	0.8	0.7	0.41	0.00	0.05	0.15	8.3	0.61

Province and month	Energy (PJ)					GHG emissions (Mt of CO_2e)				
	SH	SC	DHW	AL	Total	SH	SC	DHW	AL	Total
AB	**97.3**	**0.0**	**24.6**	**27.5**	**4.94**	**0.03**	**1.37**	**7.43**	**149.4**	**13.77**
Jan	20.1	0.0	2.2	2.4	1.02	0.00	0.12	0.66	24.7	1.80
Feb	15.3	0.0	2.0	2.2	0.78	0.00	0.11	0.60	19.5	1.49
Mar	11.8	0.0	2.3	2.3	0.60	0.00	0.12	0.63	16.4	1.35
Apr	6.1	0.0	2.2	2.3	0.30	0.00	0.12	0.61	10.6	1.03
May	2.2	0.0	2.1	2.4	0.12	0.00	0.12	0.64	6.7	0.88
Jun	0.0	0.0	1.8	2.2	0.00	0.01	0.11	0.58	4.0	0.70
Jul	0.0	0.0	1.8	2.2	0.00	0.01	0.11	0.59	4.0	0.71
Aug	0.0	0.0	1.7	2.2	0.00	0.01	0.10	0.60	3.9	0.71
Sep	1.8	0.0	2.1	2.2	0.09	0.00	0.11	0.60	6.1	0.80
Oct	6.0	0.0	2.1	2.4	0.30	0.00	0.11	0.64	10.5	1.05
Nov	14.8	0.0	2.1	2.3	0.75	0.00	0.12	0.62	19.2	1.49
Dec	19.2	0.0	2.2	2.4	0.98	0.00	0.12	0.66	23.8	1.76
BC	**83.9**	**0.6**	**22.4**	**45.8**	**3.66**	**0.00**	**0.69**	**0.24**	**152.7**	**4.59**
Jan	18.1	0.0	2.0	4.1	0.78	0.00	0.06	0.02	24.2	0.86
Feb	12.3	0.0	1.8	3.6	0.54	0.00	0.06	0.02	17.7	0.62
Mar	10.0	0.0	2.2	4.0	0.44	0.00	0.06	0.02	16.2	0.52
Apr	4.8	0.0	2.0	3.8	0.20	0.00	0.06	0.02	10.6	0.28
May	1.8	0.1	1.9	4.0	0.08	0.00	0.06	0.02	7.8	0.16
Jun	0.0	0.1	1.7	3.6	0.00	0.00	0.05	0.02	5.4	0.07
Jul	0.0	0.2	1.6	3.6	0.00	0.00	0.05	0.02	5.4	0.07
Aug	0.0	0.1	1.6	3.7	0.00	0.00	0.05	0.02	5.4	0.07
Sep	1.2	0.1	1.8	3.6	0.06	0.00	0.06	0.02	6.7	0.14
Oct	6.0	0.0	1.8	3.9	0.26	0.00	0.06	0.02	11.7	0.34
Nov	12.6	0.0	2.0	3.8	0.56	0.00	0.06	0.02	18.4	0.64
Dec	17.1	0.0	2.0	4.1	0.74	0.00	0.06	0.02	23.2	0.82

Province and month	Energy (PJ)					GHG emissions (Mt of CO_2e)				
	SH	SC	DHW	AL	Total	SH	SC	DHW	AL	Total
Canada	**860.6**	**13.0**	**192.4**	**246.4**	**39.20**	**0.68**	**8.40**	**17.70**	**1312.4**	**65.98**
Jan	189.8	0.0	16.9	21.9	8.65	0.00	0.74	1.56	228.6	10.95
Feb	150.5	0.0	15.7	19.9	6.79	0.00	0.69	1.44	186.1	8.92
Mar	117.6	0.0	18.3	20.9	5.35	0.00	0.78	1.50	156.8	7.63
Apr	59.5	0.1	17.5	20.3	2.73	0.00	0.77	1.46	97.4	4.96
May	21.1	0.7	16.4	21.4	0.98	0.03	0.72	1.52	59.6	3.25
Jun	0.2	2.5	14.5	19.3	0.01	0.13	0.63	1.39	36.5	2.16
Jul	0.0	4.7	14.0	19.6	0.00	0.25	0.61	1.41	38.3	2.27
Aug	0.0	3.8	13.3	20.0	0.00	0.20	0.57	1.43	37.1	2.20
Sep	8.5	1.2	15.9	19.9	0.40	0.07	0.69	1.43	45.5	2.59
Oct	47.7	0.0	15.8	21.0	2.18	0.00	0.70	1.52	84.5	4.40
Nov	103.6	0.0	16.6	20.4	4.74	0.00	0.73	1.48	140.6	6.95
Dec	162.1	0.0	17.5	21.8	7.37	0.00	0.77	1.56	201.4	9.70

Appendix E CHREM Estimates of Monthly Energy Consumption and GHG Emissions for SD and DR House Types as a function of Province and Energy Source

Province	Energy (PJ)					GHG emissions (Mt of CO_2e)			
and month	**Elec.**	**Nat. gas**	**Oil**	**Wood**	**Total**	**Elec.**	**Nat. gas**	**Oil**	**Total**
NF	**14.8**	**0.0**	**9.5**	**3.1**	**27.4**	**0.04**	**0.00**	**0.63**	**0.67**
Jan	1.8	0.0	1.6	0.6	4.0	0.01	0.00	0.11	0.12
Feb	1.7	0.0	1.5	0.5	3.7	0.01	0.00	0.11	0.12
Mar	1.6	0.0	1.4	0.4	3.4	0.01	0.00	0.09	0.10
Apr	1.4	0.0	1.1	0.3	2.8	0.00	0.00	0.06	0.06
May	1.1	0.0	0.6	0.2	1.9	0.00	0.00	0.04	0.04
Jun	0.7	0.0	0.0	0.0	0.7	0.00	0.00	0.00	0.00
Jul	0.7	0.0	0.0	0.0	0.7	0.00	0.00	0.00	0.00
Aug	0.7	0.0	0.0	0.0	0.7	0.00	0.00	0.00	0.00
Sep	0.8	0.0	0.1	0.1	1.0	0.00	0.00	0.01	0.01
Oct	1.2	0.0	0.6	0.2	2.0	0.00	0.00	0.04	0.04
Nov	1.4	0.0	1.0	0.3	2.7	0.00	0.00	0.07	0.07
Dec	1.7	0.0	1.6	0.5	3.8	0.01	0.00	0.10	0.11
NS	**17.9**	**0.0**	**23.1**	**6.1**	**47.1**	**3.87**	**0.00**	**1.66**	**5.53**
Jan	2.1	0.0	4.3	1.1	7.5	0.46	0.00	0.30	0.76
Feb	2.0	0.0	3.8	1.1	6.9	0.40	0.00	0.27	0.67
Mar	1.9	0.0	3.4	0.9	6.2	0.40	0.00	0.24	0.64
Apr	1.6	0.0	2.3	0.6	4.5	0.35	0.00	0.16	0.51
May	1.4	0.0	1.2	0.4	3.0	0.29	0.00	0.10	0.39
Jun	1.0	0.0	0.3	0.0	1.3	0.23	0.00	0.02	0.25
Jul	1.0	0.0	0.2	0.0	1.2	0.23	0.00	0.01	0.24
Aug	1.0	0.0	0.2	0.0	1.2	0.22	0.00	0.01	0.23
Sep	1.0	0.0	0.3	0.1	1.4	0.23	0.00	0.03	0.26
Oct	1.3	0.0	1.2	0.3	2.8	0.29	0.00	0.10	0.39
Nov	1.6	0.0	2.3	0.6	4.5	0.35	0.00	0.16	0.51
Dec	2.0	0.0	3.6	1.0	6.6	0.42	0.00	0.26	0.68

Province	Energy (PJ)					GHG emissions (Mt of CO_2e)			
and month	Elec.	Nat. gas	Oil	Wood	Total	Elec.	Nat. gas	Oil	Total
PE	**1.2**	**0.0**	**4.2**	**1.7**	**7.1**	**0.12**	**0.00**	**0.23**	**0.35**
Jan	0.1	0.0	0.8	0.3	1.2	0.01	0.00	0.04	0.05
Feb	0.1	0.0	0.6	0.3	1.0	0.01	0.00	0.03	0.04
Mar	0.1	0.0	0.5	0.2	0.8	0.01	0.00	0.04	0.05
Apr	0.1	0.0	0.4	0.2	0.7	0.01	0.00	0.03	0.04
May	0.1	0.0	0.2	0.1	0.4	0.01	0.00	0.01	0.02
Jun	0.1	0.0	0.1	0.0	0.2	0.01	0.00	0.00	0.01
Jul	0.1	0.0	0.1	0.0	0.2	0.01	0.00	0.00	0.01
Aug	0.1	0.0	0.1	0.0	0.2	0.01	0.00	0.00	0.01
Sep	0.1	0.0	0.1	0.0	0.2	0.01	0.00	0.00	0.01
Oct	0.1	0.0	0.3	0.1	0.5	0.01	0.00	0.01	0.02
Nov	0.1	0.0	0.4	0.2	0.7	0.01	0.00	0.02	0.03
Dec	0.1	0.0	0.6	0.3	1.0	0.01	0.00	0.05	0.06
NB	**17.7**	**0.0**	**9.8**	**10.9**	**38.4**	**2.38**	**0.00**	**0.71**	**3.09**
Jan	2.6	0.0	2.1	2.3	7.0	0.32	0.00	0.15	0.47
Feb	2.0	0.0	1.7	1.9	5.6	0.28	0.00	0.12	0.40
Mar	1.9	0.0	1.3	1.5	4.7	0.26	0.00	0.10	0.36
Apr	1.5	0.0	0.8	0.9	3.2	0.21	0.00	0.06	0.27
May	1.2	0.0	0.4	0.4	2.0	0.15	0.00	0.02	0.17
Jun	0.8	0.0	0.0	0.0	0.8	0.11	0.00	0.00	0.11
Jul	0.8	0.0	0.0	0.0	0.8	0.12	0.00	0.00	0.12
Aug	0.8	0.0	0.0	0.0	0.8	0.11	0.00	0.00	0.11
Sep	0.9	0.0	0.1	0.1	1.1	0.13	0.00	0.01	0.14
Oct	1.2	0.0	0.5	0.6	2.3	0.17	0.00	0.04	0.21
Nov	1.7	0.0	1.1	1.2	4.0	0.22	0.00	0.08	0.30
Dec	2.3	0.0	1.8	2.0	6.1	0.30	0.00	0.13	0.43

Province and month	Energy (PJ)					GHG emissions (Mt of CO_2e)			
	Elec.	Nat. gas	Oil	Wood	Total	Elec.	Nat. gas	Oil	Total
QC	**207.1**	**1.2**	**30.9**	**10.6**	**249.8**	**0.34**	**0.06**	**2.19**	**2.59**
Jan	34.4	0.4	6.9	2.3	44.0	0.06	0.03	0.49	0.58
Feb	29.3	0.3	5.7	1.9	37.2	0.05	0.01	0.40	0.46
Mar	25.2	0.1	4.4	1.6	31.3	0.05	0.01	0.32	0.38
Apr	15.2	0.0	2.1	0.7	18.0	0.02	0.00	0.15	0.17
May	10.0	0.0	0.7	0.3	11.0	0.01	0.00	0.04	0.05
Jun	7.0	0.0	0.0	0.0	7.0	0.01	0.00	0.00	0.01
Jul	7.3	0.0	0.0	0.0	7.3	0.01	0.00	0.00	0.01
Aug	6.8	0.0	0.0	0.0	6.8	0.01	0.00	0.00	0.01
Sep	7.8	0.0	0.3	0.1	8.2	0.01	0.00	0.01	0.02
Oct	13.3	0.0	1.7	0.6	15.6	0.02	0.00	0.12	0.14
Nov	20.5	0.1	3.4	1.2	25.2	0.04	0.00	0.25	0.29
Dec	30.3	0.3	5.7	1.9	38.2	0.05	0.01	0.41	0.47
OT	**141.1**	**344.9**	**48.8**	**0.0**	**534.8**	**8.28**	**17.45**	**3.46**	**29.19**
Jan	17.6	68.4	10.8	0.0	96.8	1.04	3.46	0.77	5.27
Feb	13.4	57.0	8.8	0.0	79.2	0.79	2.88	0.62	4.29
Mar	12.5	45.7	6.8	0.0	65.0	0.74	2.30	0.48	3.52
Apr	10.6	25.8	3.5	0.0	39.9	0.61	1.31	0.25	2.17
May	9.8	11.6	1.2	0.0	22.6	0.56	0.59	0.09	1.24
Jun	9.7	4.9	0.0	0.0	14.6	0.57	0.24	0.00	0.81
Jul	11.4	4.6	0.0	0.0	16.0	0.67	0.23	0.00	0.90
Aug	10.9	4.4	0.0	0.0	15.3	0.64	0.22	0.00	0.86
Sep	9.5	7.3	0.4	0.0	17.2	0.55	0.37	0.03	0.95
Oct	10.0	19.9	2.7	0.0	32.6	0.59	1.01	0.19	1.79
Nov	11.4	37.0	5.5	0.0	53.9	0.68	1.88	0.39	2.95
Dec	14.3	58.3	9.1	0.0	81.7	0.84	2.96	0.64	4.44

Province	Energy (PJ)					GHG emissions (Mt of CO_2e)			
and month	Elec.	Nat. gas	Oil	Wood	Total	Elec.	Nat. gas	Oil	Total
MB	**20.1**	**32.5**	**0.0**	**0.0**	**52.6**	**0.03**	**1.68**	**0.00**	**1.71**
Jan	3.0	6.8	0.0	0.0	9.8	0.01	0.35	0.00	0.36
Feb	2.5	5.4	0.0	0.0	7.9	0.01	0.27	0.00	0.28
Mar	2.1	4.2	0.0	0.0	6.3	0.00	0.21	0.00	0.21
Apr	1.5	2.0	0.0	0.0	3.5	0.00	0.11	0.00	0.11
May	1.2	0.8	0.0	0.0	2.0	0.00	0.05	0.00	0.05
Jun	0.8	0.3	0.0	0.0	1.1	0.00	0.01	0.00	0.01
Jul	0.9	0.3	0.0	0.0	1.2	0.00	0.01	0.00	0.01
Aug	1.0	0.3	0.0	0.0	1.3	0.00	0.01	0.00	0.01
Sep	1.1	0.6	0.0	0.0	1.7	0.00	0.04	0.00	0.04
Oct	1.4	1.8	0.0	0.0	3.2	0.00	0.10	0.00	0.10
Nov	2.0	3.9	0.0	0.0	5.9	0.00	0.21	0.00	0.21
Dec	2.6	6.1	0.0	0.0	8.7	0.01	0.31	0.00	0.32
SK	**11.6**	**41.5**	**0.0**	**0.0**	**53.1**	**2.43**	**2.06**	**0.00**	**4.49**
Jan	1.2	8.2	0.0	0.0	9.4	0.26	0.42	0.00	0.68
Feb	1.1	6.3	0.0	0.0	7.4	0.23	0.32	0.00	0.55
Mar	1.1	5.4	0.0	0.0	6.5	0.23	0.27	0.00	0.50
Apr	0.9	2.7	0.0	0.0	3.6	0.19	0.13	0.00	0.32
May	0.9	1.3	0.0	0.0	2.2	0.19	0.06	0.00	0.25
Jun	0.8	0.6	0.0	0.0	1.4	0.16	0.03	0.00	0.19
Jul	0.9	0.6	0.0	0.0	1.5	0.18	0.02	0.00	0.20
Aug	0.9	0.6	0.0	0.0	1.5	0.17	0.02	0.00	0.19
Sep	0.8	1.1	0.0	0.0	1.9	0.17	0.05	0.00	0.22
Oct	0.9	2.4	0.0	0.0	3.3	0.19	0.13	0.00	0.32
Nov	1.0	5.1	0.0	0.0	6.1	0.21	0.25	0.00	0.46
Dec	1.1	7.2	0.0	0.0	8.3	0.25	0.36	0.00	0.61

Province and month	Energy (PJ)					GHG emissions (Mt of CO_2e)			
	Elec.	Nat. gas	Oil	Wood	Total	Elec.	Nat. gas	Oil	Total
AB	**27.5**	**121.9**	**0.0**	**0.0**	**149.4**	**7.58**	**6.19**	**0.00**	**13.77**
Jan	2.4	22.3	0.0	0.0	24.7	0.67	1.13	0.00	1.80
Feb	2.2	17.3	0.0	0.0	19.5	0.61	0.88	0.00	1.49
Mar	2.3	14.1	0.0	0.0	16.4	0.64	0.71	0.00	1.35
Apr	2.3	8.3	0.0	0.0	10.6	0.62	0.41	0.00	1.03
May	2.4	4.3	0.0	0.0	6.7	0.65	0.23	0.00	0.88
Jun	2.2	1.8	0.0	0.0	4.0	0.60	0.10	0.00	0.70
Jul	2.2	1.8	0.0	0.0	4.0	0.61	0.10	0.00	0.71
Aug	2.2	1.7	0.0	0.0	3.9	0.62	0.09	0.00	0.71
Sep	2.2	3.9	0.0	0.0	6.1	0.61	0.19	0.00	0.80
Oct	2.4	8.1	0.0	0.0	10.5	0.65	0.40	0.00	1.05
Nov	2.3	16.9	0.0	0.0	19.2	0.63	0.86	0.00	1.49
Dec	2.4	21.4	0.0	0.0	23.8	0.67	1.09	0.00	1.76
BC	**64.9**	**85.6**	**0.0**	**2.2**	**152.7**	**0.29**	**4.30**	**0.00**	**4.59**
Jan	7.1	16.6	0.0	0.5	24.2	0.03	0.83	0.00	0.86
Feb	5.9	11.5	0.0	0.3	17.7	0.03	0.59	0.00	0.62
Mar	6.0	9.9	0.0	0.3	16.2	0.03	0.49	0.00	0.52
Apr	5.1	5.4	0.0	0.1	10.6	0.02	0.26	0.00	0.28
May	5.0	2.7	0.0	0.1	7.8	0.02	0.14	0.00	0.16
Jun	4.3	1.1	0.0	0.0	5.4	0.02	0.05	0.00	0.07
Jul	4.4	1.0	0.0	0.0	5.4	0.02	0.05	0.00	0.07
Aug	4.4	1.0	0.0	0.0	5.4	0.02	0.05	0.00	0.07
Sep	4.5	2.2	0.0	0.0	6.7	0.02	0.12	0.00	0.14
Oct	5.3	6.2	0.0	0.2	11.7	0.02	0.32	0.00	0.34
Nov	6.0	12.1	0.0	0.3	18.4	0.03	0.61	0.00	0.64
Dec	6.9	15.9	0.0	0.4	23.2	0.03	0.79	0.00	0.82

Province and month	Energy (PJ)					GHG emissions (Mt of CO_2e)			
	Elec.	Nat. gas	Oil	Wood	Total	Elec.	Nat. gas	Oil	Total
Canada	**523.9**	**627.6**	**126.3**	**34.6**	**1312.4**	**25.36**	**31.74**	**8.88**	**65.98**
Jan	72.3	122.7	26.5	7.1	228.6	2.87	6.22	1.86	10.95
Feb	60.2	97.8	22.1	6.0	186.1	2.42	4.95	1.55	8.92
Mar	54.7	79.4	17.8	4.9	156.8	2.37	3.99	1.27	7.63
Apr	40.2	44.2	10.2	2.8	97.4	2.03	2.22	0.71	4.96
May	33.1	20.7	4.3	1.5	59.6	1.88	1.07	0.30	3.25
Jun	27.4	8.7	0.4	0.0	36.5	1.71	0.43	0.02	2.16
Jul	29.7	8.3	0.3	0.0	38.3	1.85	0.41	0.01	2.27
Aug	28.8	8.0	0.3	0.0	37.1	1.80	0.39	0.01	2.20
Sep	28.7	15.1	1.3	0.4	45.5	1.73	0.77	0.09	2.59
Oct	37.1	38.4	7.0	2.0	84.5	1.94	1.96	0.50	4.40
Nov	48.0	75.1	13.7	3.8	140.6	2.17	3.81	0.97	6.95
Dec	63.7	109.2	22.4	6.1	201.4	2.59	5.52	1.59	9.70

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