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1 # Hybrid residential end-use energy and greenhouse gas ~~(GHG)~~ emissions model – development and verification for Canada

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2 This article presents the Canadian Hybrid Residential End-Use Energy and GHG Emissions Model (CHREM), a model based upon building performance simulation, and compares its estimates with residential sector energy consumption surveys and the estimates of other models. The CHREM advances the state of the art of residential sector energy consumption and green house gas (GHG) emissions modelling by three new contributions: (i) the use of 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' modelling approach that integrates the neural network and engineering modelling methods to estimate the energy consumption of the major end-uses, providing 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 consumption and GHG emissions results as a function of end-use and energy source.

Keywords: residential energy model; residential emissions model; building simulation; neural network; housing stock; housing database

1. Introduction

The residential sector constitutes approximately 30% of all end-use energy consumed worldwide (Saidur *et al.* 2007). This energy consumption, which is predominantly supplied by fossil fuels (IEA 2010), and thus results in the release of greenhouse gas (GHG) emissions, has come under pressure to reduce and be provided by renewable energy sources. Because 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. Two distinct approaches exist for modelling residential energy consumption: *top-down* and *bottom-up*.

The top-down approach treats the residential sector as an energy-sink, utilizing historic gross energy supply data and regressing this as a function of top-level variables such as macroeconomic indicators, energy price, and climate. Historic gross energy supply data are typically published by governments and are based upon values submitted by energy suppliers (e.g. USDOE 2006, UK 2007a). Top-down modelling methods used to regress energy consumption can be broadly grouped as either: *econometric* which is based primarily on price and household income (e.g. Bentzen and Engsted 2001, Labandeira *et al.* 2006), or *technological* which is based on general advances such as appliance ownership and building codes (e.g. USDOE 2005, Siller *et al.* 2007). The top-down modelling approach is appropriate for predicting variance in energy consumption caused by macro changes such as population growth and housing construction/demolition rates. However, this reliance on historical energy consumption data renders the top-down approach incapable of capturing the effects of new technologies that cause discontinuous change in energy consumption.

The bottom-up approach estimates the energy consumption of a representative set of individual houses and extrapolates the values to regional or national levels. Representative housing datasets are obtained from surveys which determine specific building and occupant characteristics, and appliance penetration levels (e.g. OEE 2006a, UK 2007b). Extrapolation of values to the national level is completed using estimates of total houses provided by recent census. Bottom-up modelling methods can broadly be grouped as either: *statistical* which regresses individual house energy consumption as a function of appliance ownership and certain building characteristics (e.g. Fung *et al.* 1999, Lins *et al.* 2002, Yang *et al.*

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2005), or *engineering* which explicitly accounts for the energy consumption of end-uses based on equipment power ratings and use, and/or heat transfer and thermodynamic relationships (e.g. Larsen and Nesbakken 2004, Petersdorff *et al*. 2006, Saidur *et al*. 2007). Because the bottom-up statistical method employs regression, it is capable of capturing effects such as occupant behaviour. However, as with the top-down approach, the bottom-up statistical method reliance on historic data inhibits the modelling of new technologies. In contrast, the bottom-up engineering method is capable of modelling new technologies by accounting for the specific heat transfer and thermodynamic relationships. Unfortunately, the treatment of occupant behaviour by the engineering method is rudimentary (e.g. an assumption may be made that lights are used only in morning and evening hours).

Complete descriptions of both the top-down and bottom-up modelling approaches, a survey of models utilizing them, and a critique of their strengths and weaknesses are given by Swan and Ugursal (2009) and Kavgic *et al*. (2010).

A series of residential end-use energy and GHG emissions models of increasing sophistication have been developed over the past two decades for the Canadian housing stock (CHS). The interested reader is referred to Aydinalp-Koksal and Ugursal (2008) for a description and comparison of these models. The latest contribution to this effort is the Canadian Hybrid Residential End-Use Energy and GHG Emissions Model (CHREM), which utilizes a bottom-up approach that employs both the statistical neural network (NN) and engineering methods (hence 'hybrid'). The hybrid approach takes advantage of the unique strengths of the NN and engineering modelling methods to estimate the end-use energy consumption and GHG emissions of the CHS. The statistical NN component of the CHREM is used to estimate the appliance and lighting (AL) end-use energy consumption and the domestic hot water (DHW) volume draw, taking into consideration the effect of occupant behaviour on these end-uses. The methodology used to develop the NN component of the CHREM and its results are presented by Swan *et al*. (2010). The engineering method-based component of the CHREM employs building performance simulation to estimate the space heating (SH) and space cooling (SC) end-use energy consumption based on physical and thermodynamic modelling of the building envelope and the SH and SC equipment, as well as the DHW end-use energy consumption in response to the volume draw and the performance of the DHW system.

In addition to its capability to estimate the end-use energy consumption and GHG emissions of the CHS at a national or regional level, the CHREM has the ability to assess the reduction in energy consumption and GHG emissions for each end-use and energy source due to the adoption of a wide variety of alternative and renewable energy technologies at various levels of penetration.

This article presents the overall structure of the CHREM, followed by a detailed discussion of the engineering method based component, and concludes with a verification of the CHREM by comparing its energy consumption and GHG emissions predictions with those of other models. A comprehensive presentation of the CHREM is given by Swan (2010). Results of several case studies conducted to demonstrate the capabilities and uses of the CHREM will be presented in a subsequent article.

2. Structure of the CHREM

As depicted in the left-hand side of Figure 1, CHREM consists of five interconnected components:

(1) The *Canadian Single-Detached and Double/Row House Database (CSDDRD)* is a statistically representative database of the CHS that includes single-detached (SD) and double/row (DR) house types. It contains detailed thermal envelope, equipment, occupancy, and air infiltration data collected by energy auditors from 16,952 actual and unique houses in Canada. The development of the CSDDRD and its characteristics are presented by Swan *et al*. (2009).

(2) *The Bottom-up NN Model* estimates the annual DHW volume draw and the AL energy consumption of each house in the CSDDRD based on the presence and use of common appliances (e.g. loads of laundry), occupancy, and demographic indicators such as population density, ownership, and household income. The NN model is presented by Swan *et al*. (2010), and employs the work of Aydinalp *et al*. (2002, 2004).

(3) *The Bottom-up Engineering Model* uses the results of the bottom-up NN model and the CSDDRD information, and develops the required set of house input data files to perform building energy performance simulation for each house of the CSDDRD. The building energy performance simulator ESP-r (Clarke 2001, ESRU 2002) is used to estimate the end-use energy (fuel and electricity) consumption of each house in a typical climatic year.

(4) *The GHG Emissions Estimator* calculates the GHG emissions from fossil fuels combusted at each house as well as the GHG emissions associated with average and marginal electricity

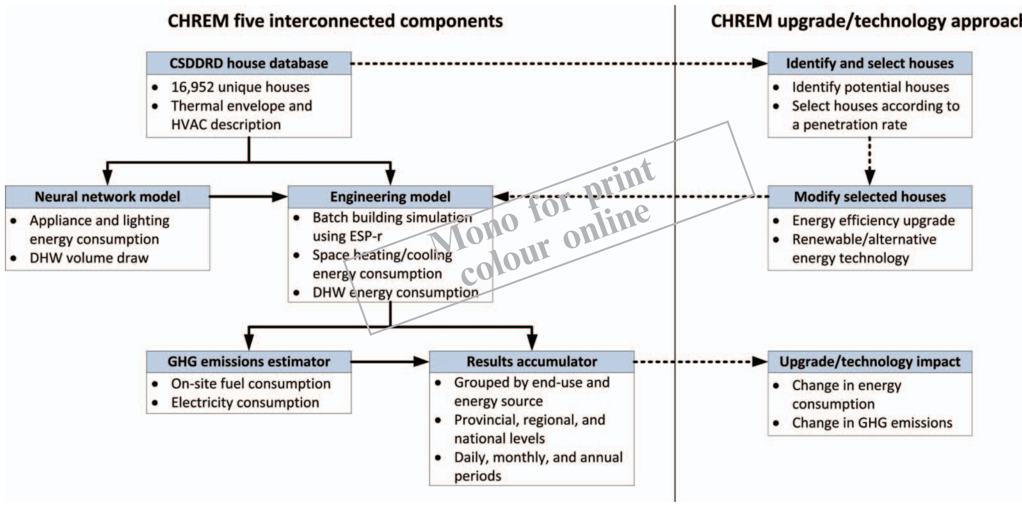

Figure 1. Flowchart of the CHREM five interconnected components and the CHREM upgrade/technology approach.

generation. The method proposed by Farhat and Ugursal (2010) is employed to estimate GHG emissions from marginal electricity generation in each province of Canada.

(5) *The Results Accumulator* processes the results obtained from the batch simulation of all houses, and summarizes the results in files that are suitable for the user. Also, the results accumulator extrapolates the results obtained from the simulations to be representative of the entire CHS.

The CHREM upgrade/technology approach, as depicted in the right-hand side of Figure 1, is used to assess the impact upon energy consumption and GHG emissions of the CHS due to the adoption of an energy efficiency upgrade or renewable/alternative energy technology. This is accomplished through the following steps:

- Identify houses suitable to receive the upgrade/technology: For example, only houses with the long roof peak axis in or close to east–west orientation would be suitable for roof mounted solar collectors. Therefore, a search has to be conducted in the CSDDRD to identify such houses.
- Assume or estimate a penetration rate and randomly select houses: It is unlikely that all suitable houses would adopt a given upgrade/technology. Therefore, a penetration rate has to be assumed or estimated. Once a penetration rate is determined, the houses to receive the upgrade/technology are randomly selected from the available candidates.
- Modify the input files of the selected houses to add the upgrade/technology for use in the ESP-r energy simulations.
- Estimate the energy consumption and GHG emissions reductions (or increases) of the CHS with the adopted upgrade/technology. The change in GHG emissions due to a change in electricity consumption is estimated using the marginal GHG emission intensity factors given by Farhat and Ugursal (2010).

3. Engineering model component of the CHREM

The engineering model component of CHREM builds the input data files required for building energy simulation using ESP-r. For each one of the 16,952 houses in the CSDDRD, an input data file is developed based on the detailed house description data and the results obtained from the CHREM NN model. After the simulation, the results are processed and scaled to the CHS. These processes, which correspond to numbers 3–5 in section 0, are discussed in the following sections.

3.1. *Building energy simulation of end-use energy consumption*

The estimation of the end-use energy consumption of the houses in the CSDDRD requires consideration of each end-use, as well as the interaction between end-uses. In this work, the end-uses within a dwelling are grouped as follows:

- *SH and SC end-uses* 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 (HA), 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 the ambient and thermal zone conditions. Solar radiation enters the thermal zones through windows. HA is a consequence of air exchange across the thermal envelope due to leakage and active ventilation.

- *DHW end-use* provides hot water at an 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 heating immediately exits the dwelling as hot water running down the drain and thermal energy in the flue gas. Depending upon the DHW system equipment, a small portion of the energy consumption may become heat gain to the thermal zone, and may offset SH or increase SC energy consumption.
- *AL end-use* energy consumption supports common appliances (e.g. refrigerator, television) and provides for adequate lighting. The majority of this energy becomes heat gain to the thermal zone, and may offset SH or increase SC energy consumption.

Building energy performance simulation is 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. Examples of such energy simulation engines include ESP-r (Clarke 2001, ESRU 2002), EnergyPlus (Crawley *et al*. 2004), and TRNSYS (Solar Energy Laboratory 2009). 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). The rationale for selecting ESP-r includes 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 simulation engines and their present technological status, ESP-r was selected as the building energy performance simulator that can meet the needs and objectives of CHREM.

The ESP-r simulator is based on numerical methods that employ finite volumes to represent 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. thermostat set-point and dead-band) are imposed upon the equations. A time-step is considered to occur from the present nodal condition state to a future state, during which the conservation equations allow for thermodynamic exchange between nodes. The solution of the conservation equations after the time-step represents the new nodal states. The selection of the length of the time-step is critical to capture the dynamic effects of the systems. For thermal envelopes, a time-step of 60 min or less is suitable for solar radiation considerations and the significance of thermal mass. For typical plant equipment (e.g. furnace and air distribution system) and solar technologies, a time-step of 10 min or less is suitable to capture the cycling effects. The interested reader is referred to Clarke (2001) for a comprehensive treatment of the methodologies employed by ESP-r.

3.2. *House description input file development for building energy simulation*

The CHREM engineering method relies on the detailed geometric, thermal envelope, and energy conversion equipment information contained in the CSDDRD to generate a unique house description input file for use with the building energy performance simulator ESP-r. Each house description file contains information regarding the climatic zone of the house, description of the house envelope components, air exchange with the ambient, energy conversion equipment and control strategies. The development and the contents of the house description input files are described in the following sections.

3.2.1. *Climatic data*

Canadian Weather for Energy Calculations (CWEC) weather data files available from Environment Canada

(2009) are used. The climatic data include the dry bulb temperature, relative humidity, direct and diffuse solar radiation on the horizontal, and wind speed and direction. Each weather file contains data for an entire year made up of 12 'Typical Meteorological Months' selected from a database of, in most cases, 30 years of data (Numerical Logistics 2010).

Out of the 65 cities represented in CSDDRD, only 35 cities have CWEC files. The remaining 31 cities are mapped to available weather data based on the indicator parameters of heating degree-days (HDD), used as a proxy for SH energy intensity, and longitude/latitude to account for regionally specific weather parameters such as solar radiation, clouds, and fog. This mapping process described in detail by Swan (2010) results in closely matched mapping of cities with CWEC files. With the exception of the few locations in the far north (above 53.5° latitude), the latitude differences range from −1.7 to +3.4°, the longitude differences range from −6.4 to +7.9°, and the ratio of the HDD of the CSDDRD city and selected CWEC city ranges from 0.98 to 1.21.

The majority of the CHS is located in climates ranging from 3500 to 5500 HDD (18°C base). In contrast, few houses require SC as most Canadian climates have less than 10 cooling degree days (24°C base).

3.2.2. Thermal zones

Three types of thermal zones are used to describe all houses in CHREM:

- *Foundation* may be a heated basement or a heated/unheated crawl space. Slab-on-grade structures and floors that are exposed to ambient conditions constitute structural foundations, but are not modelled as discrete thermal zones.
- *Main levels* are heated and consistently occupied. The number of levels ranges from one to three, and represent discrete storeys that are located vertically above the foundation zone (if present).
- *Attic* or *roof space* is unheated and located vertically above the highest main level. Flat, gable and hip type roofs are used.

An example of these zoning types and levels as employed by the CHREM is illustrated in Figure 2. The geometrical sizing of each zone is done through a

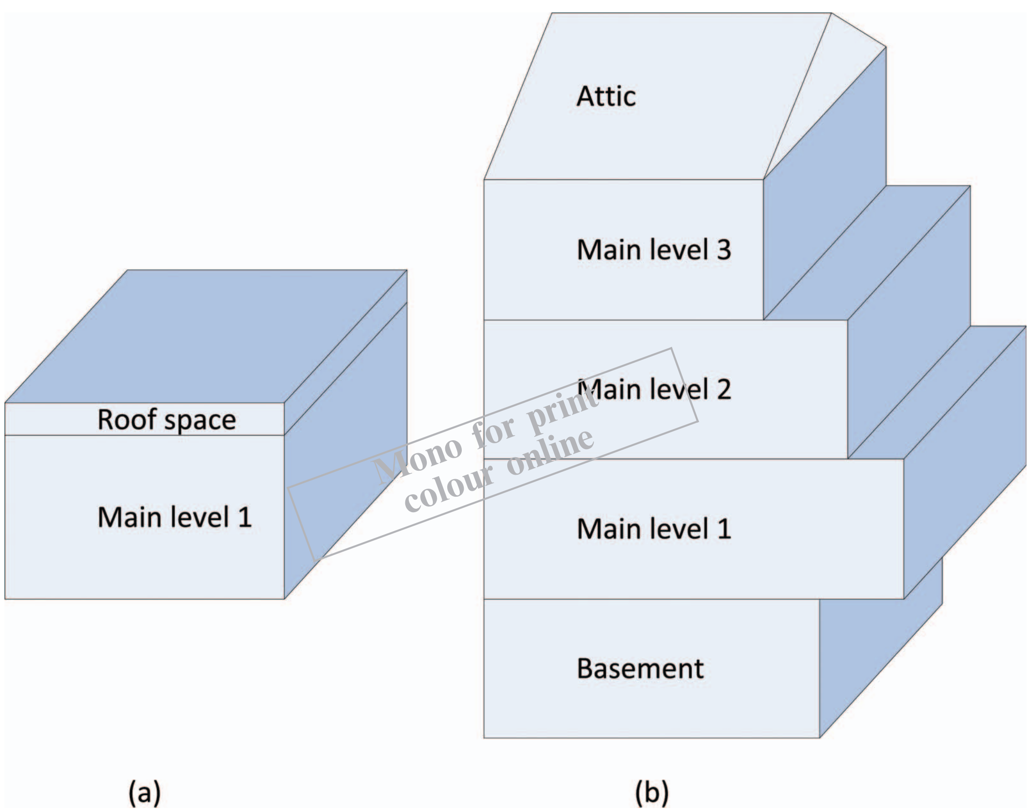

Figure 2. House zoning of the CHREM for (a) the most simple two-zone model consisting of a single main level and a flat roof space, and (b) the most complicated five-zone model consisting of three main levels supported by a basement and covered by an attic.

set of rectangularization processes that simplify the geometry while maintaining realistic similitude to the geometry of the house given in the CSDDRD. Figure 3 illustrates the result of the conversion process from the house description information given in the CSDDRD to a house file created in the CHREM. Details of the geometrical conversion process are given by Swan (2010). An analysis of the CSDDRD indicates that approximately 90% of houses have a basement foundation and that over the last three decades average house living space floor area has increased from 120 m^2 to 150 m^2.

3.2.3. *Zone surfaces*

Thermal zones are constructed from surfaces forming a thermal envelope. The surfaces must fully ~~bind~~ the zone, and the properties and thickness of each material layer of each surface must be defined. Providing such definition allows the ESP-r building simulator to calculate temperatures and the heat fluxes according to the energy conservation equations.

Due to rectangularization, each zone has a minimum of six surfaces: floor, ceiling and four sides (front, right, back and left). In the case of an attic the sides may be vertical or sloped. 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. To permit size variation between interfaced zones, portions of the floor and ceiling can be exposed to ambient conditions.

Each surface has two faces. The inward face is exposed to the zone interior conditions, typically the zone air-point and the inward faces of other surfaces. The outward face is exposed to the conditions exterior the zone, most commonly the ambient. But the outward face alternatively may be exposed to the condition of another zone or below-grade conditions, or be in an adiabatic state. Surfaces exposed to ambient conditions, i.e. above-grade-walls (including walkout basement walls), exposed floors and exposed ceilings, windows, doors and attic or roof-space sides and ceiling, have heat transfer modes of conduction/convection, solar radiation and long wave radiation exchange with the ground, other buildings, and the sky. The second common outward facing condition is the interface between two adjoined zones that 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. In the case of surfaces between consecutive houses of the double/row house type, the connected sides are of the same materials and size, and face the same space conditioning control strategies. 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 next consecutive double/row house, but does not inhibit the surface from acting as a thermal mass and transferring heat at the inward face.

Nearly all houses of the CSDDRD have a foundation that faces soil, the vast majority being full basements. The only exceptions are houses with floors exposed entirely to ambient conditions, such as open type crawl-spaces. Foundation heat transfer requires special consideration as it may have both

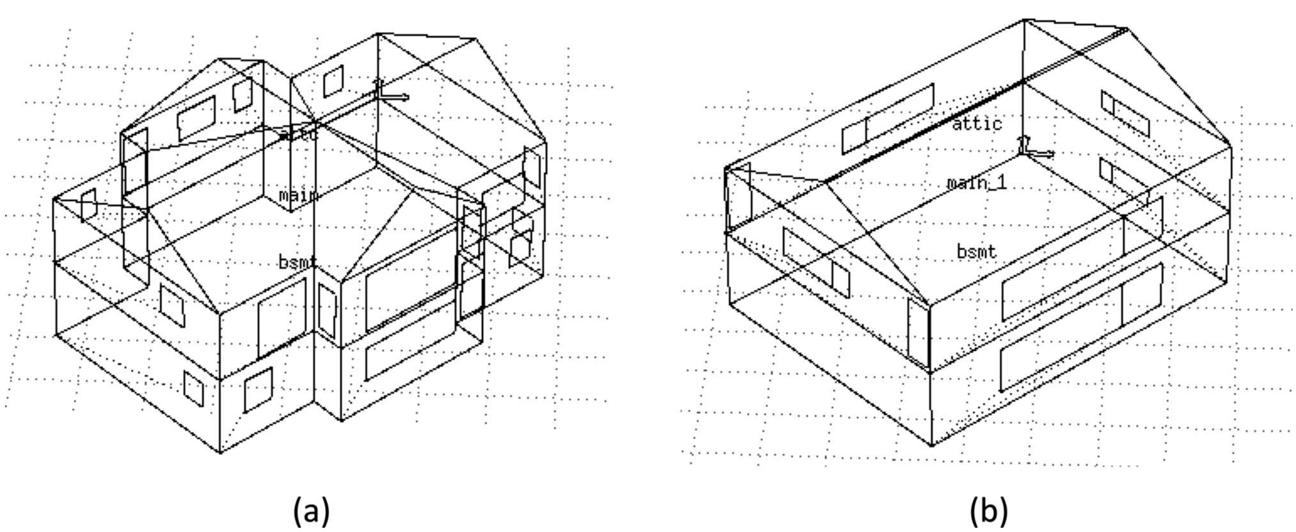

Figure 3. Three-dimensional building description renderings as (a) geometrically representative of each unique surface described in the CSDDRD, and (b) as converted and zoned by the CHREM.

above and below grade components, and is in contact with soil, which has significant thermal mass, and a temperature gradient caused by its thermal connections to both air (fluctuating temperature) and deep ground (static temperature). The energy modelling method BASESIMP (*simp*lified *base*ment model), developed by Beausoleil–Morrison and Mitalas (1997), is used by the CHREM to estimate the total foundation heat flux, including both above and below grade components. BASESIMP takes into consideration the insulating properties of the foundation, above/below grade surface areas, soil conductivity, and water table level information. While BASEIMP contains 145 unique foundation descriptions complete with correlation coefficients (Beausoleil-Morrison and Mitalas 1997, Beausoleil-Morrison 1999), only 45 of these appear in the CSDDRD due to standardized Canadian building design practice.

The information available on windows and doors in the CSDDRD includes the materials of construction and type of glazing, width, height, number present, and in the case of windows, direction, distance from eaves, and eave overhang width. As the information in the CSDDRD is converted into the CHREM, a maximum of one 'amalgamated' door and one 'amalgamated' window are created per surface, in an effort to simplify the ESP-r file description. An example of this is shown in Figure 2. Purdy and Beausoleil-Morrison (2001) examined the effect of amalgamating windows and found it to have an insignificant impact on predicting whole building energy consumption for typical Canadian houses.

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) state 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. In the CHREM, the aperture is considered to occupy 75% of the roughed-in area, and takes on the 'centre-of-glass' properties. The frame area is placed to the right-hand-side of the aperture area for modelling purposes. The representation of windows in the CHREM is shown in Figures 3 and 4. This amalgamation of frame and aperture areas has negligible impact on the energy simulation results as the heat transfer is treated as one dimensional within the wall, door, and window. Further details of the geometrical placement of windows and doors are discussed by Swan (2010). An analysis of the CSDDRD shows that on average windows occupy 15% of exterior wall area, and that marginally more window area faces south, presumably to capture sunlight and avoid heat loss.

3.2.4. Description of multilayer surfaces

The CSDDRD contains detailed information for each surface type including a multi-digit construction code with individual digits representing each material layer, and in most cases an effective thermal resistivity value. 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 layer for best representation, such as the presence of thermal bridging caused by structural framing. If no construction code is available, a representative Canadian multilayer surface is defined and the insulation layer is used to adjust for the best thermal resistance representation.

A materials database system was developed to supply material properties for describing each layer of

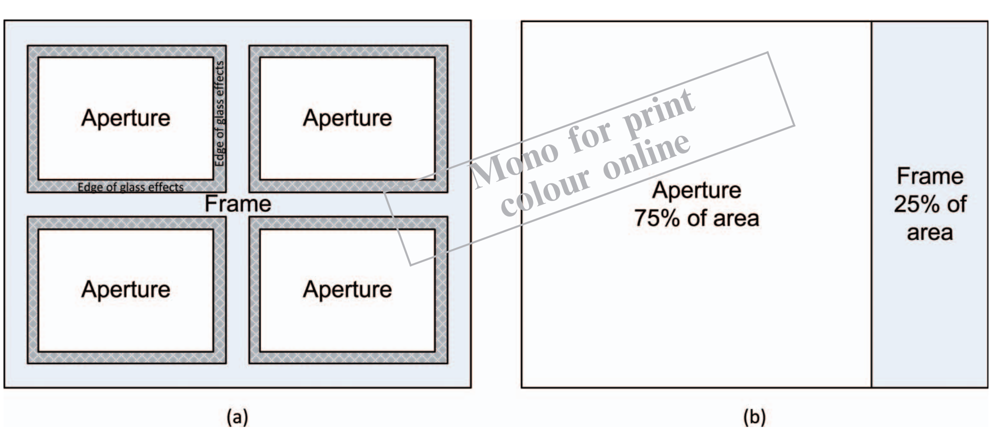

Figure 4. Window aperture and frame relationships for (a) the realistic layout showing the aperture, frame, and 'edge of glass effects' and (b) the CHREM modelling representation.

a multilayer surface. The database includes a variety of materials common in the CHS. Material properties were determined from ASHRAE (2005), McQuiston *et al*. (2005), Incropera *et al*. (2007).

There are two types of multilayer surfaces: opaque (such as walls) and transparent (such as windows). The opaque multilayer surface definitions vary considerably by zone type and surface type; for example, a foundation wall can be made of solid concrete, whereas a main level wall can consist of siding, sheathing, insulation, and interior gypsum. A complete mapping of construction codes was developed for the CHREM to support these different surface types. The mapping process translates the information provided for each layer in the CSDDRD, progressing from outside to inside, to the ESP-r input file specification.

The CSDDRD shows that effective thermal resistance of exterior walls of the CHS continues to climb with new construction. Houses constructed prior to 1946 average 1.6 RSI, whereas recent construction averages 2.9 RSI.

Windows consist of a transparent aperture area and an opaque frame area. Both the transparent aperture and the opaque frame are described layer by layer, progressing from outside to inside. Six different frame constructions are defined to encompass the variety of frame materials, such as wood, vinyl, and aluminium. 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 or triple-glazed, 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. The window construction code defines the type of window, the aperture properties, and the frame properties. 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. Based on this information, the solar transmittance and absorptance values, as well as other desired quantities such as gap resistance are determined using Window 5.2 (LBNL 2001). The CHREM maps the window construction codes of the CSDDRD to house model files suitable for the building energy simulator. A detailed discussion of the methods used in the mapping of information for multilayer surfaces from the CSDDRD to the CHREM is given by Swan (2010).

An analysis of the CSDDRD shows that approximately 90% of windows in the CHS are double glazed. This penetration level is only weakly related to vintage, indicating the majority of single-glazed windows have already been upgraded. However, single-glazed windows are still significant in certain regions such as Vancouver (3000 HDD), which has a notably warmer climate than the remainder of Canada.

3.2.5. *Heat advection*

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

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. Air also flows between conditioned zones due to open stairwells or the operation of circulation fans in the SH or SC systems. To account for this variety of airflows, the CHREM utilizes three unique airflow descriptions within ESP-r: mechanical ventilation, infiltration/exfiltration, and forced zone-zone and zone-ambient airflow through large openings such as stairwells, windows or attic vents.

Approximately 63% of houses in the CHS are equipped with basic washroom and kitchen exhaust fans, which cause air inflow through cracks and gaps in the building envelope due to house depressurization when they are operational. Close to 9% of houses have central ventilation systems that draw ambient air and supply it at registers distributed inside the house while exhausting the same amount outdoors. About two-thirds of these are equipped with heat recovery ventilators (HRV). The CSDDRD contains a description of the mechanical ventilation systems of each house, including intake and exhaust flow rates (annual average flow rate of intermittent basic exhaust fans), and HRV heat transfer effectiveness. The CHREM converts the CSDDRD data into ESP-r input data files for each house. It is assumed that all mechanical ventilation systems are operated continuously throughout the year.

Infiltration/exfiltration characteristics of all houses in the CSDDRD are known because a blower door test was conducted on each house. 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 10 pascal pressure difference. These values are industry-standard indicators of house airtightness based upon the blower door test. Using these data, the total zone-ambient airflow due to gaps, cracks and flues located in all conditioned zones (i.e. infiltration/exfiltration rate) for each house is estimated in the CHREM using the Alberta Air Infiltration Model, AIM-2 (Walker and Wilson 1990, 1998, Wang *et al.* 2009). AIM-2 calculates the zone-ambient airflow due wind-induced and stack effect pressure variations at each time-step, and the estimated total house-ambient airflow is apportioned to conditioned zones in relation to their volume.

A conservative window opening and closing control strategy was implemented to take advantage of natural SC. Three requirements must be met for the windows to open: (i) both the zone air temperature and ambient air temperature must be greater than the SH temperature set-point, (ii) the zone air temperature must be less than the SC temperature set-point if one exists, and (iii) the ambient air temperature must be less than the zone air temperature. These requirements were defined so as to avoid competing natural/active zone conditioning methods, as well as avoiding building simulation instability caused by a complete air mass replacement during a simulation time-step. The opening window area was set to one-quarter of the total window area, which represents one-half of the windows each opening halfway. The operable window area of each thermal zone is permitted to open independently.

3.2.6. *Internal gains and occupant related end-uses*

The CHREM NN model provides the estimated AL and end-use energy consumption and DHW volume draw values, as well as the number of adults and children, and employment ratio for each house in CSDDRD. The CHREM engineering method utilizes the DHW, AL, and occupant information, and imposes these as internal gains within the ESP-r building simulation.

The information on the adult and children occupant count and the employment ratio is used to populate the dwelling, resulting in the occupants rejecting heat that becomes an internal gain within the zone. Occupant heat gain values and sensible/latent ratios given by ASHRAE (2005) are used. For daytime 'seated, very light work' and for night time 'seated in a dark theatre' heat gain values are assumed. Since gender information is not provided by the CHREM NN model, the average of adult male and female values is used to represent adult occupants while children are assumed to produce 75% of the male values. 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 occupancy profile is used for both weekdays and weekends.

In modelling the DHW system energy consumption, the following assumptions are made: (i) distribution piping and standby tank losses result in internal gains whereas all heat carried with the DHW flow stream is immediately drained from the building and does not constitute an internal gain, (ii) the hot water ~~supply~~ temperature is 55°C, (iii) the DHW system is located in the basement if one exists, otherwise in the main level zone. The CSDDRD contains information on the energy source and tank type. If a tank exists, it is assumed to be 180 l capacity, a typical value for Canadian DHW heaters.

The AL energy consumption is modelled under three categories: clothes dryer, cook stove, and AL-other (e.g. plug loads, lighting, and other common appliances). All energy used by the clothes dryer is assumed to exhaust from the house whereas all energy used by the cook stove and AL-other uses is assumed to become sensible heat in the thermal zone. The sensible heat was assumed to be a mixed 50% convective, 50% radiative to account for the variety of appliances (e.g. personal air circulation fan is convective whereas lighting is primarily radiative). The cook-stove is located in the main level zone, while the AL-other use is 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 utilized, 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.

3.2.7. *Zone thermal conditioning strategy*

Crawl-spaces, attics, and roof-spaces are considered to be unconditioned, and as such have no thermal conditioning control strategy (i.e. free-floating). 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 short-wave radiation. Nearly all of this heat is then carried away by the significant air flow entering and exiting through the large vent openings.

In contrast, thermally conditioned zones, such as basements and main levels, have active SH, and in 26% of the houses, active SC systems. All SH and SC equipment types are considered to be centrally controlled, with the exception of electric baseboard systems. However, if central SC and an electric baseboard SH system is present, central control is specified due to limitations in the ESP-r ideal control strategies. The sensor for SH and SC activation measures the dry bulb air temperature of the zone in which it is placed. For central systems, the sensor is located in the first main level zone.

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 all use electricity. The capacity of the SH and SC system is apportioned to each conditioned zone based on volume. Based on findings of the Canadian Survey of Household Energy Use (OEE 2006a), the SH and SC temperature set-points are specified as 21°C and 25°C, respectively. The temperature controller varies the heat injection/extraction rate within the capacity limits of the system to maintain the zone temperature.

Reflecting common Canadian practice, a control strategy was adopted for periods of use for SH equipment and SC equipment (if available) as shown in Table 1. A time-of-day temperature setback strategy is not assumed for any of the houses as there is limited information on its use.

An analysis of the CSDDRD showed that air conditioners are found in approximately 25% of houses, and that they are concentrated in the province of Ontario where the penetration rate is 50%.

3.2.8. *Performance of SH and SC energy conversion systems*

The performance of SH and SC equipment in CHREM, i.e. furnace, boiler, stove, electric-baseboard, air-source heat pump (ASHP, heating and cooling), and ground-source heat pump (GSHP, heating and cooling), is modelled based on rated capacity, steady state efficiency and a part-load efficiency modifier as detailed by Haddad (2000) and Purdy and Haddad (2002). The so-called 'HVAC' equipment 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 time-step flux to calculate the end-use energy consumed during the time-step. 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 the AIM-2 model so as to affect the infiltration/exfiltration. As the ASHP capacity is affected by ambient temperature, its capacity is varied accordingly and used to modify the subsequent time-step 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 uses 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 2. The 'HVAC' functionality allows for multiple system descriptions of heating, cooling and auxiliary (back-up) heating systems. For example, a conventional furnace based SH system

Table 1. Annual use periods for space heating and space cooling control strategy.

Period	Dates	Space heating available	Space cooling available
1	1 January to 1 April	[illegible]	
2	2 April to 3 June	√	√
3	4 June to 16 September		√
4	17 September to 7 October	√	√
5	8 October to 31 December	√	

Table 2. Space heating and space cooling energy conversion system model input information.

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

requires a single system description while an air source heat pump requires all three, i.e. 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.

Because furnace fans and boiler pumps are identified in the AL end-use, they are 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 set to 250 W each, a typical value of ¼ horsepower fans used in units available in the Canadian marketplace (e.g. YORK 2011). The sensible heat ratio of SC equipment is set to 0.75 which is representative of residential applications (Langley 2000, e.g. YORK 2011). When an ASHP is specified in the CSDDRD, only the heating mode COP is given. Therefore, the cooling mode COP was assumed to the equal to the heating mode COP plus one. The justification for this is assumption is that the resultant ratio of cooling to heating COP is similar to the ratio of cooling seasonal energy efficiency ratio (SEER) to heating seasonal performance factor (HSPF) of units available in the Canadian marketplace (e.g. YORK 2011).

3.3. *Generation of house input files*

To conduct the data mapping processes summarized in the preceding sections, a computer code was written in the language of Perl (CPAN 2009). The files required by ESP-r vary according to model complexity and definition technique. Depending upon house characteristics, the number of files used to describe an individual house in ESP-r ranges from 18 to 31. An example of the set of files needed to describe a CHREM house for energy simulation in ESP-r is shown in Table 3.

As implemented, the CHREM generates 16,952 folders, one for each house in the CSDDRD. These are organized into 10 folders corresponding to house type and region as shown in Figure 5. In total, 402,506 files, totalling 1865 megabyte size were created. On average, each house is defined using 24 files.

Using an unbalanced multithreading method on a two-processor, four-core computer running at 1.86 GHz, the file generation process takes less than 10 min for all houses of the CSDDRD. Functionality is 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.

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 details of these processes are given by Swan (2010).

Table 3. Example files of a typical CHREM 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	Air flow network 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

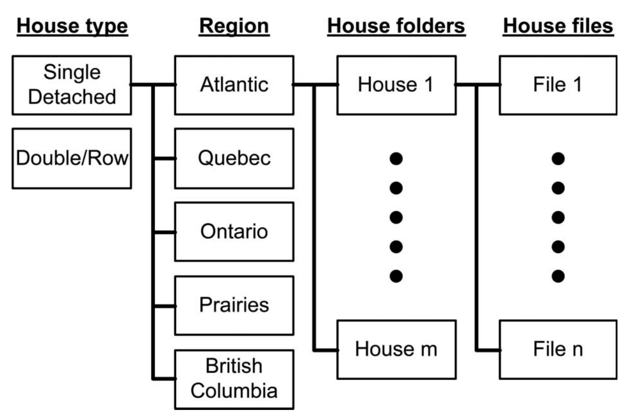

Figure 5. CHREM folder organization.

3.4. Simulation of CHREM houses

ESP-r simulation of each house of CHREM was conducted for a complete climatic year, from January 1 to December 31. 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 with a 60 minute time-step takes approximately 20 h, an average of 68 s per house.

ESP-r's Building and Plant Simulator (*bps*) and Insolation and Shading (*ish*) analysis modules were used to conduct the energy simulations. 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 zone air mass 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 *ish* component has the capability to model external obstructions that block short-wave 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 in the future for analysis of shading (e.g. trees or overhangs) and thermal energy storage surfaces (e.g. Michel–Trombe wall or high-mass flooring). The *ish* component is invoked prior to the *bps* simulator. Using climatic data and ray tracing techniques, *ish* provides *bps* with a time-series of short-wave solar radiation shading data for each external and internal surface.

A number of modifications were made to ESP-r to affect the handling of heat flows. In particular, HA due to simultaneous airflow mechanisms was allowed (see section ~~0~~) and logic was added for the separation of internal gains (e.g. heat exhausting outside the zone; see section ~~0~~). These additions extend the capability of ESP-r for more adequate treatment of heat flows in the CHS. To verify that new code additions do not negatively affect existing functionality or prediction, a series of automated simulation comparison tests supplied with the ESP-r source code were applied to the CHREM specific ESP-r code changes and no substantial differences were reported.

3.5. 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, as well as scaling to a national context. The XML 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 modelling 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 as shown in Table 4, and the second set ~~are~~ energy consumption results corresponding to the four end-use groups (SH, SC, DHW, and AL) and energy sources as shown in Table 5.

3.6. 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). GHGs are characterized by a global warming potential (GWP), which 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 (IPCC 2007). As combustion of fossil fuels results in all three important GHGs, the cumulative effect is quantified in terms of carbon dioxide equivalent (CO_2e). This is equal to the sum of the product of each GHG emission mass and its GWP, as shown in Equation 1.

$$CO_2e = CO_2 + 25\,CH_4 + 298\,N_2O \tag{1}$$

Since 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 emissions reporting. These emissions include those due to on-site fuel combustion and the emissions directly attributable to electricity production, inclusive of transmission.

Table 4. 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	Conduction through envelope	−30.3	−30.1	−27.7	19.6
	Convection to air-point	8.5	9.5	24.8	−19.6
	Absorbed short wave radiation	21.1	21.4	0.0	0.0
	Absorbed long wave radiation from internal gains	5.9	4.9	2.9	0.0
	Long wave radiation exchange with other 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	Conduction through envelope	−9.4	−10.2	0.0	0.0
	Convection to air-point	2.6	2.9	0.0	0.0
	Absorbed short wave radiation	1.3	1.4	0.0	0.0
	Absorbed long wave radiation from internal gains	0.3	0.2	0.0	0.0
	Long wave radiation exchange with other 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
Air-point	Convection to inward facing surfaces	−11.0	−12.4	−24.8	19.6
	Convection from internal gains	5.5	4.4	9.3	0.0
	Heat advection via mechanical ventilation	−2.7	−2.0	−0.7	0.0
	Heat advection via infiltration (AIM-2) and open windows	−16.3	−17.0	−13.8	−19.6
	Heat advection via zone-zone air exchange	−2.4	−0.7	3.1	0.0
	Space cooling	−5.3	−5.4	−5.3	0.0
	Space heating	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

Table 5. 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
Space heating	Natural gas	106.5	2863 m^3
Space cooling	Electricity	7.7	2116 kWh
Appliances and lighting	Electricity and natural gas	20.5	
Domestic hot water	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	

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, shown in Table 6 are 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.

Calculation of GHG emissions from electricity used in the CHS is more complicated because Canadian electricity generation is supported by a wide variety of energy sources: hydro, coal, nuclear, natural gas, heavy fuel oil, and (to a very minor extent) biomass and wind as shown Figure 6. Of these, coal, natural gas, and heavy fuel oil are the major contributors to GHG emissions. Estimates of combustion products and combustion efficiencies of common electricity generation techniques are published by Environment Canada (2007). As shown in Table 7, these values are used to calculate typical GHG EIFs for electricity generation.

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

Table 6. GHG emissions due to the conversion of fuels using residential equipment (based on Environment Canada 2007 and Canadian National Energy Board 2008).

Residentially consumed fuel	CO_2 (g)	CH_4 (g)	N_2O (g)	CO_2e (g)	HHV 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

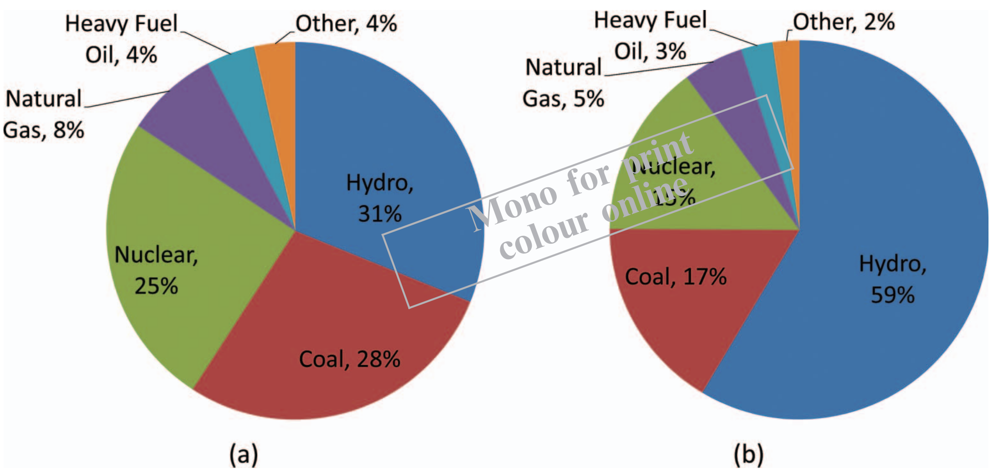

Figure 6. Canadian electricity generation sector by energy source (a) primary energy used to generate electricity, and (b) net generated electricity (OEE 2006b).

Table 7. Examples of GHG emissions due to the conversion of fuels to generate electricity (based on Environment Canada 2007).

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

Note: *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 CO_2e per kg of coal (Environment Canada 2007).

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 will cause an incremental change in the electricity consumption (increase or decrease). 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 8, are available for most provinces on an annual basis, and on a monthly basis for the provinces of Quebec, Ontario, and Alberta.

A baseline GHG emission value due to electricity consumption of the CHREM is calculated by increasing the energy consumption to account for provincially specific transmission/distribution losses (given in Table 8), 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 and upgraded cases) are increased to account for transmission/distribution savings, and are then multiplied by the marginal GHG EIF corresponding to the appropriate month.

3.7. *Scaling of results to the national context*

Each house in the CHREM is representative of a number of houses in the CHS. The number of houses represented by each CHREM house varies from region to region. Therefore, to extrapolate the energy consumption and GHG emission estimates obtained from the CHREM to the CHS, scaling factors need to be applied to the energy and GHG emission estimates obtained for each house of CHREM. The scaling factors, that is, the ratio of the number of houses in the CHS to CHREM simulations, are shown in Table 9.

4. CHREM estimates of end-use energy and GHG emissions

The CHREM estimates of the end-use energy consumption and GHG emissions of the CHS as a function of end-use and energy source are shown in Tables 10 and 11. The CHREM estimates annual total end-use energy consumption for the SD and DR house

Table 8. Average and marginal GHG emission intensity factors and transmission/distribution losses for Canadian provinces (Farhat and Ugursal 2010).

		GHG EIF by Canadian province (g of CO_2e per kW·h)									
Electrical generation characteristic		NF	NS	PE	NB	QC	ON	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 $EIF_{Marginal}$	January					23	395			591	
	February					0	352			591	
	March					0	329			785	
	April					0	463			785	
	May					0	501			785	
	June					0	514			769	
	July					0	489			769	
	August					0	491			769	
	September					0	455			769	
	October					0	458			785	
	November					0	379			591	
	December					4	371			591	
Transmission and distribution losses		9%	4%	6%	6%	4%	6%	12%	6%	4%	3%

Table 9. CHREM scaling factors calculated individually by house type and region as the ratio of target houses to successful simulations.

	Successful simulations		Targets		Scaling factors	
Region or province	Single-detached	Double/row	Single-detached	Double/row	Single-detached	Double/row
Newfoundland	179	22	148,879	26,098	831.7	1186.3
Nova Scotia	629	84	259,392	38,778	412.4	461.6
Prince Edward Island	65	14	38,980	6014	599.7	429.6
New Brunswick	396	17	215,084	23,260	543.1	1368.2
Quebec	2874	796	1,513,497	469,193	526.6	589.4
Ontario	5389	1231	2,724,438	707,777	505.6	575.0
Manitoba	858	78	305,111	34,609	355.6	443.7
Saskatchewan	188	13	285,601	29,494	1519.2	2268.8
Alberta	1655	347	790,508	182,745	477.6	526.6
British Columbia	1770	314	910,051	203,449	514.2	647.9
Canada	14,003	2916				

Table 10. 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)				
		Space heating	Space cooling	DHW	Appliances and lighting	Total	Space heating	Space cooling	DHW	Appliances and lighting	Total
House type	Single-detached	724.8	10.9	158.9	203.5	1098.1					
	Double/row	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
	ON	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 11. 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	Natural gas	Oil	Wood	Total	Electricity	Natural gas	Oil	Total
House type	Single-detached	432.4	522.2	108.9	34.6	1098.1				
	Double/row	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
	ON	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

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 separated by house type alone, as they are principally influenced by the specific energy sources used within a given province. As these results indicate, 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. 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 warm in comparison with most other Canadian locations.

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 (ON, MB, SK, AB, BC) use natural gas in place of heating oil. QC, a province which has ample access to inexpensive hydro powered electricity, predominantly uses electricity.

The GHG emission distributions as a function of end-use show substantial differences due to 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. 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.

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 8.

The Prairies provinces (MB, SK, AB) and BC exhibit energy source GHG emission distribution behaviour similar to Atlantic provinces, again based on electricity generation. 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.

Figure 7 shows that energy consumption and GHG emissions of the CHS vary significantly with season, and are principally a function of SH requirements. SC is only present between May and September. 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 fuel use and GHG emission estimates of the CHS shown in Figure 8 indicate that natural gas consumption 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.

5. Comparison of CHREM estimates with other assessments

To validate the end-use energy and GHG emissions estimates of CHREM, they are compared with recent Canadian estimates provided in the 2003 Survey of Household Energy Use (OEE 2006a) and the Canadian Residential End-Use Model (OEE 2006b).

The 2003 Survey of Household Energy Use (SHEU) 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 2006a). 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 4551 dwellings. Of the 4551 participating households, energy-supplier billing data was only acquired from approximately half due to a combination of consent rate and data received rate (OEE 2006a). The survey results of SHEU were extrapolated to the entire CHS of 11.1 million dwellings. The SHUE-03 reports estimates of energy consumption by both house type and region, and accumulates these by total site, electricity, and natural gas (OEE 2006a). Therefore, the energy consumption and GHG emission estimates of SHEU require careful consideration due to the regional nature of the selection of the households, as well as the small size of the energy billing dataset. Also, 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.

A comparison of the CHREM and the SHEU estimates for both house type and region is shown in Table 12. The CHREM estimate of total end-use energy consumption of the CHS is 11% greater than the SHEU. 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 for the Atlantic region. This is likely due to the significant use of wood as an energy source in the provinces of NF, NS, PE, and NB. Wood energy is particularly difficult for surveys to quantify due to the imprecise volumetric delivery format (subject to splitting/stacking technique) and moisture content.

The CHREM and SHEU estimates of natural gas consumption shown in Table 12 are in reasonable agreement. In certain cases, the electricity consumption estimates of the CHREM are considerably more than the SHEU (e.g. 33%). This difference may be attributed in part to the different scoping of the CHREM and SHEU. The CHREM examines houses on a provincial level, and is capable of identifying differences in the energy source distributions of provinces within a particular region, whereas the SHEU reports results on a regional level while surveying houses on a provincial level (OEE 2006a). However, the provincial distribution of SHEU samples

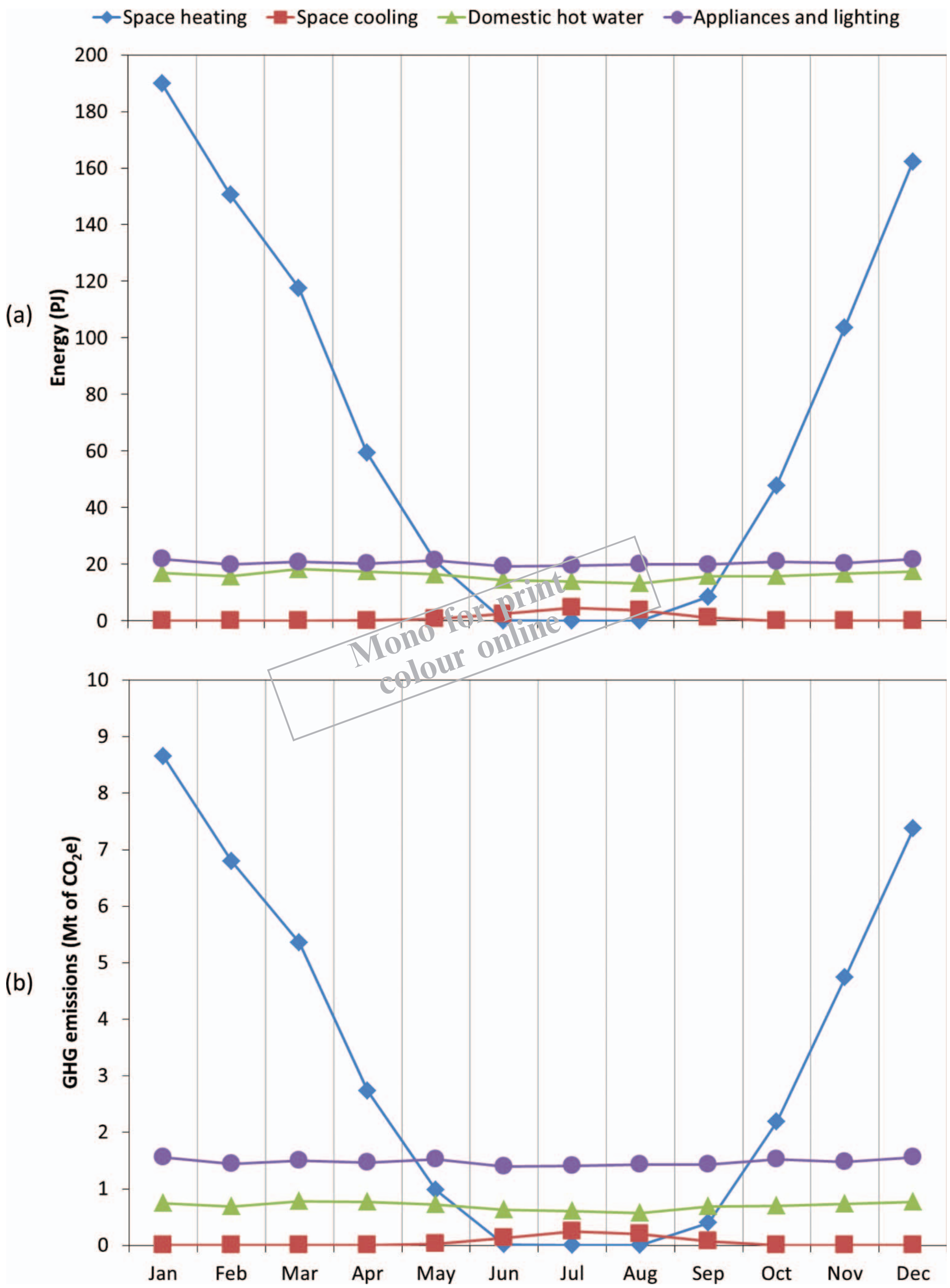

Figure 7. CHREM estimates of monthly national (a) energy consumption and (b) GHG emissions by end-use.

was not equivalent to provincial house distributions (Statistics Canada 2006).

The Canadian Residential End-Use Model (REUM) estimates 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, and allocates this consumption to end-uses based on housing stock characteristics and estimated unit energy consumption. The REUM reports national estimates of both energy consumption and GHG emissions as a function of end-use and energy type. The REUM estimates for DHW and AL from 2000 through 2004 were averaged to account for weather variations, and then adjusted to represent only the SD and DR house types. This facilitates comparison with CHREM. The

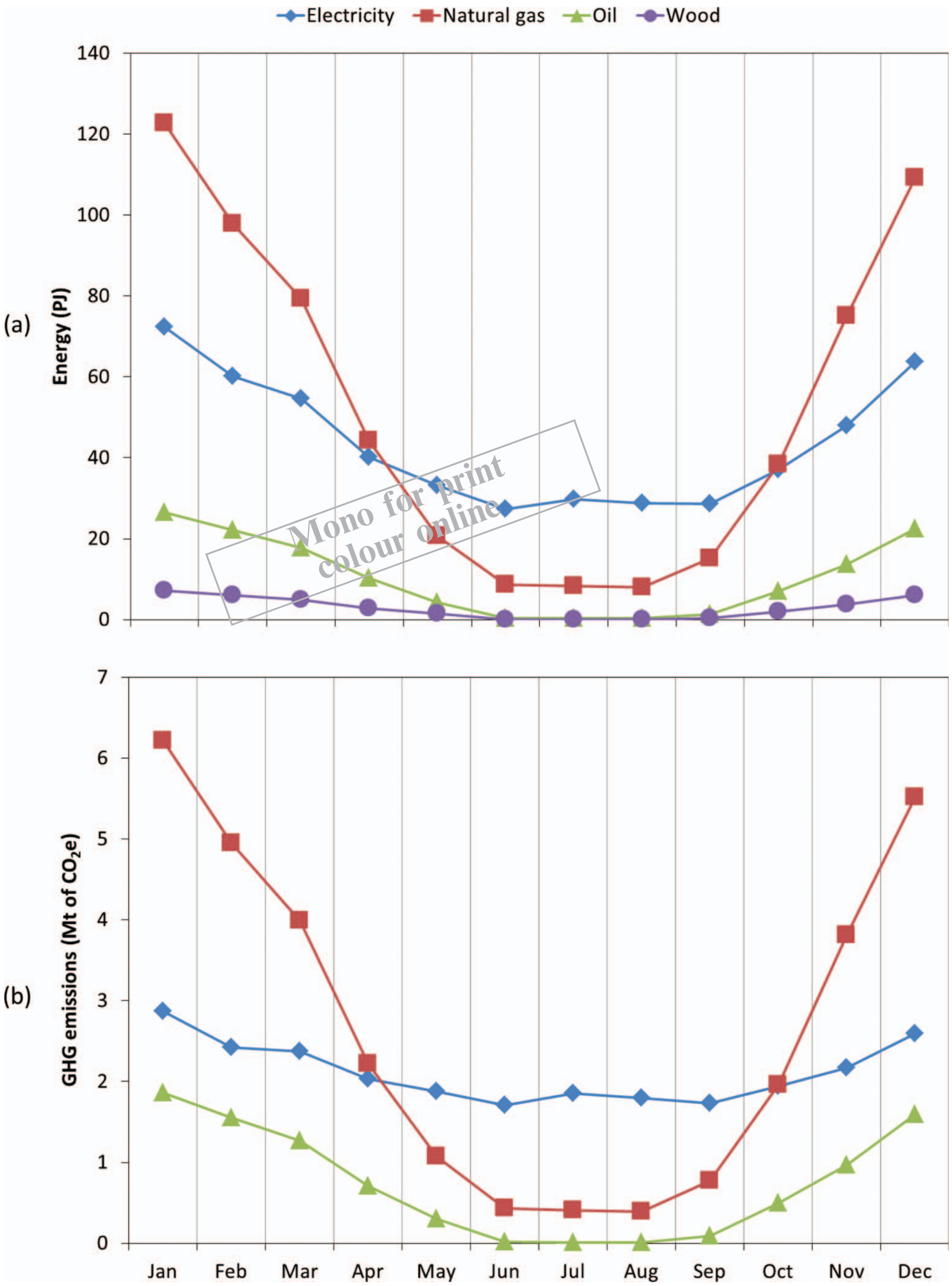

Figure 8. CHREM estimates of monthly national (a) energy consumption and (b) GHG emissions by energy source.

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.

A comparison of the CHREM and REUM estimates for both end-uses and energy sources as a function of energy consumption and GHG emissions is shown in Table 13. Overall, the CHREM estimates 14% greater energy consumption and 9% greater GHG emissions than the REUM. With regard to the

Table 12. Comparison of the CHREM and the SHEU annual energy consumption estimates by house type and region for the single-detached and double/row house types.

House type or region		Energy type	CHREM (PJ)	SHEU (PJ)	CHREM/SHEU ratio
House type	Single detached	Total	1098.1	989.5	1.11
		Electricity	432.4	372.4	1.16
		Natural gas	522.2	494.6	1.06
	Double/row	Total	214.3	193.4	1.11
		Electricity	91.5	75.4	1.21
		Natural gas	105.4	105.4	1.00
Region or province	Atlantic	Total	120.0	87.1	1.38
		Electricity	51.6	41.3	1.25
		Natural gas	0.0		–
	Quebec	Total	249.8	217.5	1.15
		Electricity	207.1	156.1	1.33
		Natural gas	1.2		–
	Ontario	Total	534.8	493.4	1.08
		Electricity	141.1	144.0	0.98
		Natural gas	344.9	311.1	1.11
	Prairies	Total	255.1	251.2	1.02
		Electricity	59.2	56.3	1.05
		Natural gas	195.9	192.8	1.02
	British Columbia	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

Table 13. Comparison of the CHREM and the REUM national annual energy consumption estimates by end-use and energy source for the single-detached and double/row house types.

		Energy			GHG emissions (CO_2e)		
End-use or energy source		CHREM (PJ)	REUM (PJ)	CHREM/REUM ratio	CHREM (Mt)	REUM (Mt)	CHREM/REUM ratio
End-use	Space heating	860.6	714.4	1.20	39.20	34.50	1.14
	Space cooling	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
	Appliances and lighting	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

DHW and AL end-uses, the totals are similar, but the individual contributions are different between the models. 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 modelled by the CHREM.

The comparisons of CHREM estimates with those of SHEU and REUM indicate that CHREM consistently estimates greater values of energy consumption and GHG emissions for the significant end-uses and energy sources. This is likely due to a combination of reasons, including the accuracy of the SHEU and REUM estimates, and the fixed indoor heating season temperature set-point assumption (21°C during the period of 17 September to 3 June) used in CHREM. Since a segment of CHS occupants use temperature setback during nights and unoccupied periods, the actual SH energy consumption is likely lower than the CHREM estimate. However, it is not possible to incorporate temperature setback in CHREM at this point in time due to a lack of data on the percentage of houses that implement temperature setback and the nature of temperature setback (number of hours and setback magnitude). Furthermore, CHREM assumes continuous occupancy of the housing stock. Periods of non-occupancy, such as vacations and seasonal use of houses, tend to reduce energy consumption. If new data becomes available to incorporate temperature setback and non-occupancy periods into CHREM, the estimates will become more accurate.[1]

Based on the above comparisons and analyses of the results, it can be concluded that there is a reasonable agreement between the national estimates of CHREM, and those of SHEU and REUM.

6. Conclusion

A new end-use energy consumption and GHG emissions model of the CHS called the Canadian Hybrid Residential End-Use Energy and GHG Emissions Model was developed. The CHREM 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 implementation of a wide variety of energy conservation measures, alternative energy technologies, and renewable energy technologies in the CHS.

CHREM advances the state of the art of residential sector energy consumption and GHG emissions modelling by three new contributions: (i) the use of a database of 16,952 unique house descriptions of thermal envelope and energy conversion system information that statistically represent the CHS; (ii) a 'hybrid' modelling approach that integrates the NN and engineering modelling methods to estimate the energy consumption of the major end-uses, providing 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 consumption and GHG emissions results as a function of end-use and energy source.

To verify the end-use energy and GHG emissions estimated by CHREM, it is compared with the estimates of two other available models of the CHS. The CHREM estimates are in reasonable agreement with those of the other models. Thus, the CHREM can confidently be used to study the impact of implementing energy conservation measures and alternative/renewable energy technologies within the CHS.

The CHREM is presently being employed to examine several case studies. Such studies begin with a statistical analysis of the CSDDRD to identify classes of houses (e.g. by region or vintage) suitable for an energy efficiency upgrade or new technology. This upgrade or technology, such as increased insulation or the addition of solar thermal collectors, is then imposed upon the houses of interest using the bottom-up modelling component. Finally, the results of these modified houses are compared with the base case and are scaled to be representative of the complete housing stock.

Examples of energy efficiency upgrades include increasing insulation levels in empty or under-filled cavities; replacing single-glazed windows with multi-glazed, coated, gas filled versions; improving airtightness levels; and implementing set-back temperature control strategies. Examples of new technologies that can be modelled using CHREM include co-generation units; the use of thermal or electricity energy storage; imposing integrated controllable blinds within window glazing layers (e.g. Lomanowski and Wright 2009), and building integrated photovoltaic-thermal roofing materials (e.g. Liao *et al*. 2007).

In addition to the ability to estimate annual energy consumption changes due to these upgrades and technologies, the CHREM provides detailed estimates of changes in GHG emissions. These are reported by energy source and account for marginal generation in the case of electricity. As such, the reports capture the effects of fuel switching and interrelation of different end-uses (e.g. lighting which offsets SH energy consumption). This is especially important given the present focus on reducing national GHG emissions by implementing new technologies.

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Note

1. To examine the effect of the temperature set-point, a heating set-point 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 the magnitude of the impact that temperature set-point has on energy consumption.

Nomenclature

AB	Province of Alberta
AC/h	air changes per hour (with subscript pressure rating in pascals)
AL	appliances and lighting
ASHP	air source heat pump
BC	Province of British Columbia
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
CWEC	Canadian weather for energy calculations
DHW	domestic hot water
DR	double row house type
EIF	emission intensity factor
ELA	effective leakage area (with subscript pressure rating in pascals)
GHG	greenhouse gas
GSHP	ground source heat pump
HA	heat advection
HDD	heating degree days
HRV	heat recovery ventilator
HSPF	heating seasonal performance factor
MB	Province of Manitoba
NB	Province of New Brunswick
NF	Province of Newfoundland and Labrador
NN	neural network
NS	Province of Nova Scotia
ON	Province of Ontario
PE	Province of Prince Edward Island
QC	Province of Quebec
REUM	Residential energy use model
SC	space cooling
SD	single detached house type
SEER	cooling seasonal energy efficiency ratio
SH	space heating
SHEU	Survey of household energy consumption
SK	Province of Saskatchewan

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