A NEW HYBRID END-USE ENERGY AND EMISSIONS MODEL OF THE CANADIAN HOUSING STOCK

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ABSTRACT

The structure and development of a new state-of-the-art hybrid energy end-use and greenhouse gas (GHG) emissions model of the Canadian housing stock (CHS), with the capability of accurately determining the effects of renewable energy technologies, is presented. The model incorporates a 17,000 house database developed using the latest data available from the EnerGuide for Houses database, Statistics Canada housing surveys, and other available housing databases. The geometry and thermal envelope of each house is defined in detail, making it suitable for energy simulation based on engineering methods (thermodynamics and heat transfer). The model utilizes the ESP-r building energy simulation program as its simulation engine.

To account for effects due to occupant behaviour, a new neural network methodology is utilized to estimate the demographic dependencies of the annual energy consumption of discretionary end-uses such as appliances, lighting and domestic hot water. A new approach is used to allot the annual energy consumption of discretionary end-uses to hourly or sub-hourly intervals based on occupancy, appliance, lighting and domestic hot water load profiles. Each house's profiles are incorporated into the model as loads, a portion of which becomes internal heat gain for inclusion in the space heating/cooling simulation conducted using ESP-r.

A new method is used to calculate the GHG emissions from electricity consumption used in the residential sector based on the actual electrical generation fuel mix and the marginal fuel used in each province as a function of the time of year.

The developing hybrid model will predict energy consumption and GHG emissions of the CHS based on the latest available stock databases and surveys and uses multiple simulation methods to account for envelope losses and occupant behaviour. When complete, the model may be used to assess the impacts of envelope upgrades or the addition of renewable energy technologies based on high resolution, targeted application.

INTRODUCTION

The residential sector in Canada is responsible for approximately 17% of the national end-use energy consumption and 16% of the greenhouse gas (GHG) emissions (OEE 2006a). Consequently, any national strategy to reduce energy consumption and the associated GHG emissions must address the residential sector energy consumption to be effective.

A reduction of energy consumption and the associated GHG emissions in the residential sector can be achieved by a combination of strategies that include increasing the use of renewable energy resources, improving end-use energy efficiency, and introducing alternative energy conversion technologies, such cogeneration systems, that have higher efficiencies and produce lower GHG emissions compared to conventional technologies. To identify economically and environmentally feasible strategies, a large number of scenarios need to be considered. Such scenarios include improving envelope characteristics, replacing existing standard efficiency heating equipment, use of higher efficiency household appliances and lighting, switching to less carbon-intensive fuels, and renewable energy sources and cogeneration systems. However, such improvements have complex interrelated effects on the end-use energy consumption of houses and the associated pollutant emissions. For example, improving the efficiency of lighting reduces the internal heat gain from lights, but increases the space heating energy consumption. Owing to such interrelations, detailed computer models are necessary to evaluate the effect of various energy efficiency improvement scenarios on residential end-use energy consumption and associated emissions. Such models are useful for policy makers and analysts in government agencies, energy suppliers and utilities to evaluate the impact of a wide range of energy efficiency measures, such as integrated solar technologies, and strategies on the energy consumption and emissions in the residential sector.

Two approaches are used for this purpose, namely: Top-down and Bottom-up. Top-down approaches utilize econometric, macro-economic and/or statistical methods to forecast the energy consumption based on formulations that take into consideration parameters such as historical trends, fuel prices, economic activity, income levels and input-output matrices representing the economy. 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 (DOE 2005), the residential energy demand system for Spain (Labandeira et al. 2005) and the energy demand model of the residential sector of Delhi, India (Kadian et al. 2007). While top-down approaches are useful to predict the effects of changes in fuel prices, demographics, and the like, they are not suitable to estimate the impact of specific energy efficiency measures and applications of cogeneration and alternative energy options on residential energy consumption. On the other hand, bottom-up approaches use information on the housing stock and predict the energy consumption based on the current and predicted characteristics of the housing stock itself. Thus, they can be used to assess the impact of a wide range of technologies on energy consumption.

For the bottom-up modeling of the residential energy consumption, three methods are suitable: the engineering method (EM), the conditional demand analysis (CDA) method and the neural network (NN) method (Aydinalp et al. 2003). The EM involves developing a housing database representative of the national housing stock and estimating the energy consumption of the dwellings in the database using a building energy simulation program, then extrapolating the energy consumption of the dwellings in the database to the entire residential sector (Farahbakhsh et al. 1998, Guler et al. 2007, Ugursal and Fung 1998). CDA is a regression-based method in which the regression attributes consumption to end-uses on the basis of the total household energy consumption (Aydinalp and Ugursal 2008). The NN method models the residential energy consumption as a neural network, which is an information-processing model inspired by the way the densely interconnected, parallel structure of the brain processes information (Aydinalp et al. 2002, 2004).

Due to the limited availability of detailed data on the physical characteristics of houses required for the EM, many researchers develop and use house archetypes to represent the housing stock. One of the early reported applications of the archetype approach was by McGregor, et al. (1992) where a set of 27 archetype

buildings were developed to represent the single- and multi-family residential buildings in Nova Scotia to study the feasibility of using small scale fluidized bed boilers. More recently, Kohler et al. (1997) used a reference population of 160 archetype buildings to study the mass, energy and monetary flows of the German building stock. In Japan, Shimoda et al. (2003) classified all households in Osaka City into 460 archetype buildings to estimate the city-level energy consumption in the residential sector. In Canada, Parekh (2005) reported on the development of archetype libraries based on geometric configuration, thermal characteristics and operating parameters for simplified energy use evaluation of houses in the Canadian residential sector. Petersdorf, et al. (2006) used five standard archetype buildings with eight insulation standards assigned to building age and renovation status to study the impact of insulation level on heating demand and carbon dioxide emissions from space heating energy use in the European building stock. To conduct nationwide and regional analyses of ventilation and indoor air quality issues in residential buildings, a "suite" of homes consisting of 209 archetypes was developed to represent the U.S. housing stock (Persily et al. 2006). While the results of these studies provide safe indicators for the magnitude of energy-saving potentials, the simplification associated with the reduction of the building stock to few archetypes needs to be taken into account when evaluating the accuracy of the results. In an effort to address this problem, the archetype approach was advanced by augmenting archetype data from large scale databases to model the energy consumption in the Canadian single-family housing stock (Farahbakhsh et al. 1998, Ugursal and Fung 1998). The resulting model called the Canadian Residential Energy End-use Model (CREEM) was used to predict the energy and GHG emission reductions due to a wide range of energy efficiency measures (Guler et al. 2001, 2007)

Each modeling approach has unique advantages and limitations, unique data requirements, and is suitable for different purposes. For example, the EM based model requires detailed data on each household, while the NN and CDA models require less detailed data on each household, but data from a larger set of households. On the other hand, the EM based model can evaluate a large variety of energy saving scenarios, but has limitations in modeling the effects of socio-economic factors. In contrast, the NN models have limitations in evaluating energy saving scenarios, but can deal with socio-economic factors more easily.

Considering the capabilities of the existing models and the need for a comprehensive energy modeling tool for the CHS that can be used to study the impacts of

various energy and GHG emission reduction scenarios, it was concluded that there is a need to develop a new residential end-use energy and emissions model that combines the advantages and versatility of the EM and NN modeling approaches, and is based on the latest data available on the Canadian residential sector. Focus is placed on an appropriate assessment technique for renewable energy technologies. Renewable energy sources vary considerably in short periods of time and therefore simulation must be conducted using a sub-hourly timestep interval to capture these transient effects. Furthermore, they are only applicable to buildings with an appropriate location, orientation and load profile (e.g. domestic hot water use). In the remainder of this paper, the new Canadian hybrid residential end-use energy and emissions model (CHREM) is presented.

OVERVIEW OF THE CHREM

The CHREM consists of six components that work together to provide predictions of the end-use energy consumption and GHG emissions of the CHS. These components are:

- The Canadian Single-Detached & Double/Row Housing Database (CSDDRD)

- A neural network model of the appliances and lighting (AL) and domestic hot water (DHW) energy consumption of Canadian households

- A set of AL and DHW load profiles representing the usage profiles in Canadian households

- A high-resolution building energy simulation software (ESP-r) that is capable of accurately predicting the energy consumption of each house file in CSDDRD

- A model to estimate GHG emissions from marginal electricity generation in each province of Canada and for each month of the year

- A model to estimate GHG emissions from fossil fuels consumed in households.

The structure and flow diagram of the CHREM is shown in Figure 1.

Canadian Single-Detached & Double/Row Housing Database

The backbone of the CHREM is the CSDDRD, which is a comprehensive housing database representative of the CHS and contains detailed data on house characteristics of each house (Swan et al. 2008).
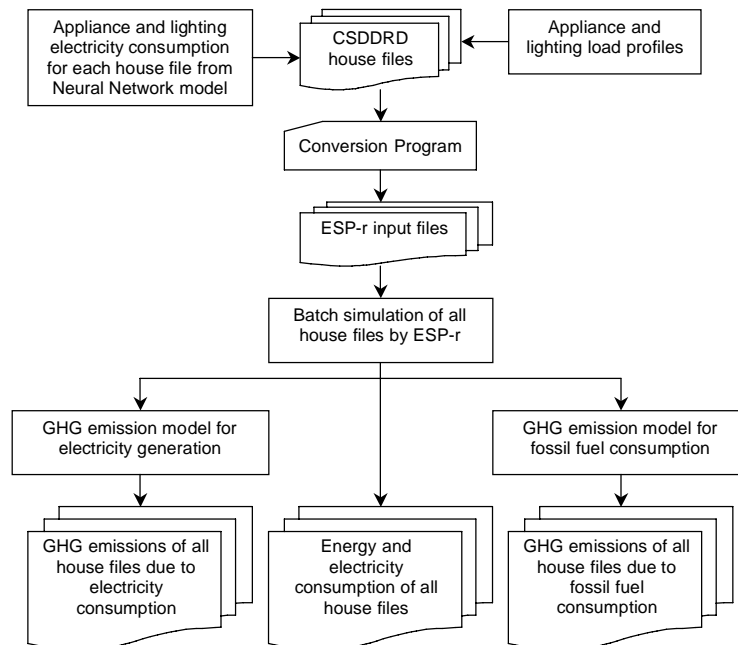

Figure 1. Structure and flowchart of CHREM

The CSDDRD is a subset of the EnerGuide for Houses Database (EGHD), which is the culmination of over 200,000 requested home energy audits collected from 1997 through 2006 (SBC 2006) by Natural Resources Canada (NRCan). The audits, conducted by professional auditors, measured and recorded the location, type, geometry, storeys, foundation, attic, construction materials including windows and doors,

blower door test results (air-tightness), and DHW and space heating systems. Blais et al. (2005) describes in detail the EnerGuide objectives and the development of the EGHD.

The basis for the audit was to estimate the house's annual energy consumption using NRCan's software HOT2XP (SBC 2008) to quantify the energy savings of retrofits for federal and provincial incentive purposes. The EGHD is unprecedented due to its size and parameter inclusion which provides far more details than most housing databases (e.g. the American Housing Survey of 2005 which includes 50,000 samples (US Census Bureau (2006)). A file composed of 187,821 complete house records from the EGHD, each with over 161 distinct data fields, was provided for this project by NRCan.

The EGHD does not include apartments or mobile home dwelling types. It does account for single-detached (SD) and double/row (D/R) houses, representing 80% of the CHS (OEE 2006b). SD is defined as an entirely separated stand-alone single unit. D/R is similar, but shares one or more walls with another house. From a national housing energy perspective, the SD and D/R house types represent more than 85% of the sector's energy consumption (OEE 2006b). This is because the other significant dwelling type, apartments, typically has fewer walls exposed to ambient conditions and less floor area per dwelling.

The selection of house files from the EGHD to form the CSDDRD was based on a comparison with the national and regional parameter distributions obtained from Survey of Household Energy Use 2003, also known as SHEU-03 (OEE 2006b). 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. SHEU was conducted in 1993, 1997, and 2003. Statistics Canada conducts this survey of randomly selected dwellings based on population distribution, and ensures that the dataset is representative of the CHS. The 2003 survey of over 4,500 participant dwellings included data on parameters such as dwelling type and floor area, but did not include detailed information on the building envelope or infiltration/ventilation values, which are desired for energy simulation.

To limit the number of house records in an effort to obtain a reasonable batch energy simulation computational time of less than one day using the building simulation program ESP-r (ESRU 2002) running on two dual-processor (1.86Ghz) quad-core computers, 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 house records.

Using an iterative selection process described in detail by Swan et al. (2008), a total of 14,036 SD and 3,205 D/R house records were selected from the EGHD, totalling 17,241 records which, based on the selection parameters, statistically represent the 8.9 million SD and D/R houses of the CHS. The parameters used for selection were:

- House type (SD or D/R)
- Region (Atlantic, Quebec, Ontario, Prairies, British Columbia)
- Vintage (1900-1945, 1946-1969, 1970-1979, 1980-1989, 1990-2003)
- Storeys (one through three, including half storeys)
- Living space floor area (25-56, 57-93, 94-139, 140-186, 187-232, 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)

Key characteristics of the CSDDRD are:

- Nationally and regionally representative of both the SD and D/R house types of the CHS based on the selection parameters
- Detailed information on geometry, construction fabric, infiltration/ventilation, and heating systems
- Individual records that allow the assessment of interrelated characteristics (e.g. insulation levels as a function of region or vintage).

These characteristics allow the CSDDRD to be used as the dataset for energy simulation or interrelation/uptake investigation. The latter two characteristics allow for each house record to be individually assessed for applicability of renewable energy technologies. House orientation, roof slope and direction, size and type of windows can significantly impact a dwelling's potential for renewable energy technologies.

Neural network models of appliances, lighting and DHW energy consumption

Neural network models were developed by Aydinalp et al. (2002, 2004) to predict the annual energy consumption by AL and DHW equipment of Canadian households. The AL models predict electricity consumption based on the AL inventory, usage (clothes washer, clothes dryer, dishwasher and air-conditioner), weather conditions (heating and cooling degree days), size and type of the dwelling (whether it is SD or D/R, and renter or owner occupied), and socioeconomic and demographic characteristics such as household income,

employment status and number of occupants, and population size of the city or town where the household is located. The DHW model predicts energy consumption based on water heating equipment, presence of low-consumption outlets (e.g. aerators), and similar socioeconomic and demographic characteristics. As socioeconomic and demographic characteristics are not included in the CSDDRD, the database was augmented with socioeconomic and demographic characteristics determined based on regional distributions sourced from recent census data (Statistics Canada 2007) and appliance penetration rates (OEE 2006b, 1994). Where correlations could be found, suitable socioeconomic and demographic data was applied to the CSDDRD. Otherwise, the socioeconomic and demographic distributions were randomly applied to the CSDDRD with respect to region and building type.

Using these models, the annual AL and DHW electricity consumption of each house in the CSDDRD can be estimated and provided as input for the building simulation program once the consumption is converted from annual values to hourly values using the representative load profiles.

Appliance, lighting and DHW load profiles

The conversion from annual energy consumption to sub-hourly profiles was accomplished using Canadian AL and DHW profiles generated from the International Energy Agency's (IEA) Energy Conservation in Buildings and Community Systems Program (Knight et al. 2007). The DHW profiles were originally developed as part of the IEA's Solar Heating and Cooling Program by Jordan and Vajen (2001). The AL profile is the aggregate of consumption for the following loads: dishwasher, range (cooking), clothes washer and dryer, refrigerator and freezer, lights, and small appliances (e.g. coffee maker, television). The AL and DHW profiles were generated based on experimentally determined probability of use and limiting conditions (e.g. clothes dryer follows clothes washer). Three sets of AL and DHW profiles corresponding to specific demand levels were utilized as shown in Table 1.

Table 1. AL and DHW demand levels

Demand Level	AL annual energy consumption range (kWh)	DHW average daily draw range (litres)
Low	<6,460	<150
Medium	6,460-10,605	150-250
High	>10,605	>250

These profiles were normalized by their annual energy consumption and then used for each house of the

CSDDRD by multiplying the appropriate demand profiles by each house's estimated AL and DHW annual energy consumption. This resulted in AL and DHW profiles with individual levels for each house, as shown in Figure 2.

The DHW profile was originally in units of LPM. This profile represents that of an instantaneous hot water appliance, but does not adequately represent a system that incorporates hot water storage. For systems with storage capacity the profile will be reorganized to represent the heating element's duty cycle.
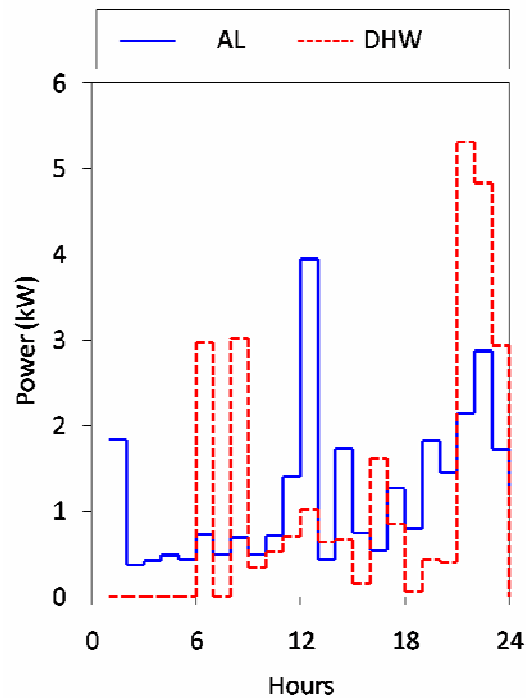

Figure 2. Example AL and DHW hourly profile

Building simulation program ESP-r

The energy consumption of each house in the CSDDRD will be predicted using ESP-r (ESRU 2002), which is an integrated modeling tool for the simulation of the thermal, visual and acoustic performance of buildings and the assessment of the energy use and gaseous emissions associated with environmental control systems and construction materials. It is available at no cost under an open source license and is capable of predicting the energy consumption of buildings at one-hour or smaller time increments. ESP-r has been extensively tested and verified, and was selected by NRCan as the basis for its residential simulation tool development (Haltrecht et al. 1999).

Simulations in ESP-r account for the detailed house envelope. Incident solar radiation is calculated for each exterior surface on a sub-hourly timestep and can be

used to properly account for the collection characteristics of solar thermal or photo-voltaic collectors or passive solar gains. This capability allows for the assessment of new glazing materials with integrated and automatics shading mechanisms, Trombe-Michel walls and foundations or flooring built with phase change materials.

Electrical systems can be modeled to account for the electrical energy needs of the AL and DHW demand which is offset through the use of solar collectors. Additionally, as mass flows are modeled, advanced thermal solar systems such as multiple series storage tanks, photo-voltaic driven solar thermal fluid loops and shell in coil in tank heat exchangers may be modeled.

As the above renewable energy technologies require certain characteristics of the host dwelling to function adequately, their applicability will be assessed. The 17,241 houses of the CSDDRD represent approximately 8.9 million houses of the CHS and therefore a high resolution representation ratio of 500:1 is achieved. This advantage allows renewable energy technologies to be applied to both todays and the future penetration rate levels.

Conversion Program

A conversion program is currently being developed to convert the detailed house description information on each household from the CSDDRD, as well as the AL and DHW energy consumption values and profiles, into the house input file format required by the ESP-r building simulation program. Once the conversion program is completed, it will be used to prepare an ESP-r input file for each one of the 17,241 households in the CSDDRD.

These files will be batch simulated on a sub-hourly timestep using a computer cluster. It is expected that simulation of the entire database will take less than one day. The results will provide the baseline energy consumption of the CHS.

The generated ESP-r input files are the entry point for the addition of upgrades or renewable energy technologies to the CHS. Technologies which are applicable to houses within the database will be added to the ESP-r input files and re-simulated to identify their impact.

GHG emission model for fossil fuel consumption

The GHG emissions due to on-site fossil fuel consumption using home heating equipment characteristic to Canada will be calculated using the GHG emission factors and will be converted to equivalent carbon dioxide emissions using global warming potentials (GWP) published by the IPCC (Forster et al. 2007), as shown in Table 2.

Table 2. GWP of fossil fuels consumed on-site

Residentially Consumed Fuel	GHG Emission Intensity Factor (grams of CO_2e per $kWh_{thermal}$)
Natural Gas	185
Light Fuel oil	264

GHG emission model for electricity generation

Using a similar methodology, the GWPs associated with electrical generation can be calculated, as shown in Table 3.

Table 3. GWP of fossil fuels consumed for electricity generation

Electricity Generation Fuel	GHG Emission Intensity Factor (grams of CO_2e per $kWh_{electrical}$)
Natural Gas	536
Heavy Fuel oil	838
Bituminous Coal	766

When there is a reduction in the electricity consumption as a result of energy efficiency measures undertaken in the CHS, the reduction will be reflected in the on-margin electricity generation (i.e. the electricity reductions will be from the last block of energy generation). Since fuel mix used for electricity generation varies by province and by month, a new method to predict the GHG emissions from on-margin electricity generation in each month of the year for each province of Canada is currently being developed.

CONCLUSION

The structure and development of a new state-of-the-art hybrid energy end-use and GHG emissions model of the CHS is presented. The model makes use of the latest data and methods available. It will be completed within a year, and results obtained using the model will be published shortly thereafter.

The strengths of the model lie in its high resolution of the CHS and flexible, advanced simulation technique. These characteristics allow for the introduction of renewable energy technologies to the applicable portion of the CHS for an accurate assessment of the impacts on energy consumption and GHG emissions.

The ESP-r engine is capable of simulating a wide variety of renewable energy technologies. Additional descriptions of new technologies are continually being developed and added to ESP-r. The CHREM will be used to assess construction materials, fenestration

systems and integrated thermal and photo-voltaic solar systems.

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