# [T11-03] A New Hybrid End-use Energy and Emissions Model of the Canadian Housing Stock

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## SUMMARY

The structure and development of a new state-of-the-art hybrid energy end-use and greenhouse gas (GHG) emissions model of the Canadian residential housing stock 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, and utilizes the ESP-r building energy simulation program as its simulation engine. A new neural network methodology is incorporated into the model to estimate the socio-economic and demographic dependencies of the energy consumption of discretionary end-uses such as appliances, lighting and domestic hot water, while a new approach is used to incorporate occupancy, appliance, lighting and domestic hot water load profiles into the model. 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 time of the year.

## 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, household appliances and lighting with higher efficiency units, and switching to less carbon-intensive fuels for space and domestic hot water (DHW) heating, 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 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 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 Canadian housing stock (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. 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 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 given in Figure 1.

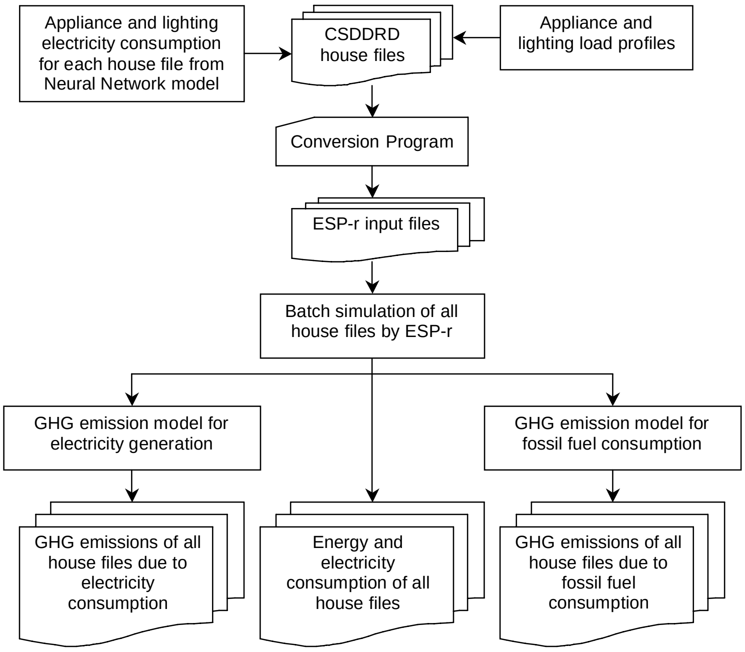


*Figure 1. Structure and flowchart of CHREM*

**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.

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 received for this project from 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.

**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 demand level were utilized representing low, medium and high demand levels (less than 6,460 kWh/yr and 150 L/day, between 6,460 and 10,605 kWh/year and 150 and 250 L/day, and more than 10,605 kWh/yr and 250 L/day, respectively). 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.

**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).

**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.

**GHG emission model for electricity generation**

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. This method uses the predicted magnitude and the mix of fuels used for on-margin electricity generation of each province for each month of the year provided by Environment Canada (2003).

**GHG emission model for fossil fuel consumption**

The GHG emissions due to fossil fuel consumption will be calculated using the GHG emission factors for each fuel used, and will be converted to equivalent carbon dioxide emissions using global warming potentials (GWP) published by Environment Canada (Matin et al. 2004).

## CONCLUSIONS

The structure and development of a new state-of-the-art hybrid energy end-use and GHG emissions model of the Canadian residential housing stock 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.

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## REFERENCES

Aydinalp M., Ugursal V.I. 2008. Comparison of Neural Network and Conditional Demand Analysis Approaches for Modeling End-use Energy Consumption in the Residential Sector. *Applied Energy*, 85, 271-296.

Aydinalp M., Ugursal V.I., Fung A.S. 2004. Modeling of the space and domestic hot water heating energy consumption in the residential sector using neural networks. *Applied Energy*, 79(2), 159-178.

Aydinalp M., Ugursal V.I., Fung A.S. 2003. Modeling of residential energy consumption at the national level, *Int. J. of Energy Research*, 27, 441-453.

Aydinalp M., Ugursal V.I., Fung A.S. 2002. Modeling of the Appliance, Lighting, and Space Cooling Energy Consumption in the Residential Sector using Neural Networks. *Applied Energy*, 71(2), 87-11.

DOE. 2005. Model documentation report: residential sector demand module of the national energy modeling system. U.S. Dept of Energy, DOE/EIA-M067(2005), Wash. DC.

Environment Canada. 2003. Analysis of Electricity Dispatch in Canada. Ottawa. Available from: http://www.ec.gc.ca/pdb/ghg/guidance/protocols/Electric2003/p1_e.cfm

ESRU. 2002. The ESP-r system for building energy simulation: user guide version 10 series. Energy Systems Research Unit, Univ. of Strathclyde, Glasgow, Scotland. Software available from: www.esru.strath.ac.uk

Farahbakhsh H., Ugursal V.I., Fung A.S. 1998. A Residential End-use Energy Consumption Model for Canada. *Int. J. of Energy Research*, 22, 1133-1143.

Guler B., Ugursal V.I., Fung A.S., Aydinalp-Koksal M. 2007. Impact of energy efficiency upgrade retrofits on the residential energy consumption and greenhouse gas emissions. *Int. J. Environmental Technology and Management*, in press.

Guler B., Fung A.S., Aydinalp M., Ugursal V.I. 2001. Impact of energy efficiency upgrade retrofits on the residential energy consumption in Canada. *Int. J. of Energy Research*, 25, 785-792.

Haltrecht D., Zmeureanu R., Beausoleil-Morrison I. 1999. Defining the Methodology for the Next-Generation HOT2000 Simulator. *Proc. Building Simulation '99*, 1, 61-68, IBPSA, Kyoto, Japan.

Jordan U., Vajen K. 2001. Realistic domestic hot-water profiles in different time scales. International Energy Agency, Annex 26- Solar Combisystems. Univ. Marburg, Germany.

Kadian R., Dahiya R.P., Garg H.P. 2007. Energy-related emissions and mitigation opportunities from the household sector in Delhi. *Energy Policy*, 35, 6195-6211.

Knight I., Kreutzer N., Maaning M., Swinton M., Ribberink H. 2007. European and Canadian non-HVAC electric and DHW load profiles for use in simulating the performance of residential cogeneration systems. IEA, Annex 42- FC+COGEN-SIM, Subtask A. (available from http://www.ecbcs.org/docs/Annex_42_Domestic_Energy_Profiles.pdf)

Kohler N., Barbel S., Barth B., Koch M. 1997. Mass flow, energy flow and costs of the German building stock, *CIB 2nd Int. Conf Buildings & the Environment*, Paris, June 9-12.

Labandeira X., Labeaga J.M., Rodriguez M. 2005. A residential energy demand system for Spain. *Center for En and Env Policy Res, MIT*, Rep no 05-001 WP, Cambridge, MA.

MacGregor W.A., Hamdullahpur F., Ugursal V.I. 1993. Space heating using small-scale fluidized beds: a technoeconomic evaluation. *Int J of Energy Research*, 17, 445-466.

Matin A., Collas P., Blain D., Ha C., Liang C., MacDonald L., McKibbon S, Palmer C., Rhoades K. 2004. Canada's Greenhouse Inventory 1990-2002. Environ. Canada, Ottawa.

OEE 2006a. Energy use data handbook- 1990 and 1998 to 2004. Office of Energy Efficiency, Natural Resources Canada. Ottawa.

OEE 2006b. 2003 Survey of household energy use- detailed statistical report. Ibid.

OEE. 1994. 1993 Survey of household energy use- provincial results. Ibid.

Parekh A. 2005. Development of archetypes of building characteristics libraries for simplified energy use evaluation of houses. *Proc. 9th Int IBPSA Conf*, Montreal, 921-928.

Persily A., Musser A., Leber D. 2006. A collection of homes to represent the U.S. housing stock. Nat Inst of Stand & Tech Rep No. NISTIR 7330 for US Dept of Housing and Urban Dev, Wash. DC.

Petersdorf C., Boermans T., Harnisch J. 2006. Mitigation of CO2 emissions from the EU-15 building stock. *Environ Sci Pollut Res*, 13/5, 350-358.

SBC. 2008. HOT2000 residential energy analysis and design software. Sustainable Buildings and Communities, CANMET Energy Technology Centre, Natural Resources Canada. Available from: www.sbc.nrcan.gc.ca/software_and_tools/hot2000_e

SBC. 2006. EnerGuide for Houses Database. Ibid.

Shimoda Y., Fujii T., Morikawa T., Mizuno M. 2003. Development of residential end-use simulation model at city scale. *Proc. 8th Int IBPSA Conf*, Eindhoven, 1201-1208.

Statistics Canada. 2007. Census 2006. Ottawa.

Swan, L., Ugursal, V.I., Beausoleil-Morrison I. 2008. Canadian housing stock database for energy simulation. To be published in the *Proceedings of eSim 2008*. Quebec.

Tooru M., Miyoko I., Zuo J., Hirofumi N. 2002. Energy demand model of residential and commercial sectors of Asian mega-cities, *Proc Ann Mtng of Env Syst Res*, 30, 25-33.

Ugursal V.I., Fung A.S. 1998. Residential carbon dioxide emissions in Canada: Impact of efficiency improvements and fuel substitution. *Global Env. Change*, 8(3), 263-273.

US Census Bureau. 2006. American Housing Survey for the United States: 2005. US Government Printing Office, Washington, DC.