A RESIDENTIAL END-USE ENERGY CONSUMPTION MODEL FOR CANADA

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ABSTRACT

The residential sector is the third largest end-use energy consumer in Canada. With the increasing pressure on Canada to reduce its energy consumption and the associated carbon dioxide emissions, reducing energy consumption in the residential sector is very important. To quantitatively assess the impact of the large number of measures that can be adopted to reduce the residential energy consumption, a residential energy model for Canada (Canadian Residential Energy End-use Model - CREEM) was developed. This paper presents the model, the characteristics of the residential energy consumption in Canada, and impact of various energy consumption reduction scenarios.

INTRODUCTION

There is an increasing pressure on Canada to reduce its energy consumption and the associated carbon dioxide emissions. One of the effective means of reducing emissions is through reducing energy consumption in the residential sector because this sector is responsible for close to 20% of the end-use energy consumption in Canada. Improving the end-use energy efficiency is one of the most effective ways to reduce energy consumption in the residential sector and the associated pollutant emissions. To identify strategies that would improve the energy efficiency in the residential sector in an economically and environmentally feasible manner, 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 heating. Energy efficiency 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, increasing 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 would help 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.

An accurate residential energy model is therefore required that can be used to study the characteristics of residential energy end-use, and to evaluate the impact of various energy efficiency measures, such as increasing envelope insulation and integrity, increasing appliance efficiencies, increasing heating/cooling system efficiencies, etc. on residential energy consumption. In this paper a new residential energy model for Canada and the results of several case studies are presented to illustrate the uses of the model. The Canadian Residential Energy End-use Model (CREEM) is the most comprehensive residential energy end-use model in Canada that integrates previous efforts (Ugursal and Fung, 1996) and existing data bases (Statistics Canada, 1993; NRCan, 1994; Scanada 1992). A more detailed description of CREEM and the results of case studies are presented elsewhere (Farahbakhsh et al., 1997, Farahbakhsh, 1997, Fung et al., 2000)

CONTRIBUTING FACTORS TO RESIDENTIAL ENERGY CONSUMPTION

The residential sector in Canada includes five major types of dwellings: single detached, single attached, apartments (less than 5 stories), high-rise apartments (5 stories and more), and mobile homes. Single attached houses include semi-detached houses (double), row or terrace houses, and duplex units. The distribution of these dwelling types in Canada is given in Table 1 (Statistics Canada, 1993).

As it is indicated in Table 1, single detached and single attached houses account for about 68 percent of the households in Canada, accounting for the largest share of residential energy use. As a result, most of the data collection efforts have been focused on these, with little data available on apartments and mobile homes. Therefore, only single-detached and single-attached dwellings are considered in this study.

Energy consumption in a house is due to four major categories of end-uses: space heating, water heating, appliances and lighting, and space cooling. In cold climates like that of Canada, space heating is the major contributor to the overall household energy consumption, accounting up to 62% of it (NRCan, 1996). Thus, reducing the energy consumed by space heating equipment, through upgrading of the thermal envelope and improving the efficiency of the heating system, is vital in reducing the energy consumption of a house.

Space heating energy consumption is influenced largely by house type since the amount of exposed surface area to the outside environment varies for different house types. Single detached houses have the largest surface area because all six sides are exposed to outside air and the ground. With semi-detached houses, at least one side is common with another dwelling, preventing heat loss through that side. The difference between row and semi detached houses is that the middle units of row houses have two walls common with adjoining units. Thus, space heating energy consumption for a row unit is lower compared to a semi-detached house with the same characteristics (thermal envelope, heating systems, life style, etc.). Duplex houses have either their main floor or ceiling common with another dwelling preventing heat loss from the common surface.

Water heating is another major contributor to the household energy consumption, accounting for up to 22 percent of the total, including the energy required for heating water for clothes washers and dishwashers (Wilson and Morrill, 1993). Energy consumed for water heating is the amount of heat required to bring the city water to about 50°C to 60°C for cleaning and other uses. Reducing the energy required for water heating by increasing insulation around the hot water tank, using more efficient systems, and by reducing the hot water usage reduces the overall residential energy demand.

Energy use by appliances and lighting represents about 20% of the residential end-use energy consumption. As such, improving the energy efficiency of household appliances and lighting present a valuable potential to reduce the overall energy consumption and carbon dioxide emissions of houses in Canada. Space cooling accounts for less than one half of one percent of the total residential energy use in Canada. Thus, it is not of any great significance in the overall residential energy consumption.

CANADIAN RESIDENTIAL ENERGY END-USE MODEL (CREEM)

To study and analyze the characteristics of the residential energy end-use in Canada, and to evaluate the impact of various energy efficiency measures on energy consumption and the associated carbon dioxide emissions, the Canadian Residential Energy End-use Model (CREEM) was developed. CREEM is an Engineering Method (EM) based model[1] of the Canadian residential sector.

To model the energy consumption in the residential sector using the EM, a database of dwellings that is representative of the residential sector is needed. In a representative database, each dwelling represents a certain number of dwellings in the residential sector, i.e.

$$NDRS = \sum_{i=1}^{n} M_i \qquad (1)$$

where,

NDRS = number of dwellings in the residential sector

M_i = multiplier for dwelling i in the database

n = number of dwellings in the database.

Thus, if the annual energy consumption of each dwelling in the database can be estimated, the total annual energy consumption of the residential sector can be calculated from:

$$AERS = \sum_{i=1}^{n} AED_i M_i \qquad (2)$$

where,

[1] Engineering Method refers to the bottom-up modeling of the residential energy consumption. A database of houses with detailed house description files representative of the national housing stock is used along with a building simulation program to estimate the annual energy consumption, and the results are extrapolated to the national housing stock using weighting factors. A detailed discussion of the EM as well as other methods used for residential energy modeling can be found in Aydinalp, et al. (2001)

AERS = annual energy consumption by the residential sector
AED_i = annual energy consumption of dwelling i

The EM involves the estimation of the annual energy consumption of each dwelling in the database using a building energy simulation program, and then extrapolating the energy consumption of the dwellings in the database to the entire residential sector using Eq. (2). Therefore, the available information on each dwelling in the database must be sufficiently detailed to develop an input data file to be used with a building energy simulation program.

CREEM was developed using data from the 1993 Survey of Household Energy Use (SHEU) (Statistics Canada, 1993), the Modified STAR-HOUSING database (STAtistically Representative HOUSING Stock) (Ugursal and Fung, 1996; Scanada, 1992), the 1993/94 "200-House Audit" project database (NRCan, 1994), HOT2000 building energy simulation program default values (NRCan, 1995), and minor contributions from other sources. Brief descriptions of the data sources and the building simulation program are given in Appendix A, and the structure of CREEM is shown in Figure 1.

The data from the Modified STAR-HOUSING database, the 1993/94 "200-House Audit" project database, and HOT2000 default values were used to develop 16 house archetypes to be used in CREEM. The archetypes are based on vintage (pre-1941, 1941-1960, 1961-1977, 1978 and later) and regional location (Western Canada, Prairies, Central Canada, Atlantic Canada). The rationale for this categorization of archetypes is given elsewhere (Farahbakhsh et al., 1997, Farahbakhsh, 1997, Fung et al., 2000). The archetype descriptions were augmented with the information from the SHEU database, and a HOT2000 input file was developed for each one of the 8767 houses in the SHEU database.

Actual energy billing data obtained from fuel suppliers and utility companies for a complete year are available for 2524 of the 8767 houses in the SHEU database. These billing data were used to verify the accuracy of the annual unit energy consumption (UEC) estimates obtained from the simulations of the 2524 house files. To do this, the UEC estimates were compared with the actual billing data, and some systemic errors in the input files were identified from these comparisons. After several cycles of simulation and input file improvement, an acceptable level of agreement was achieved between the actual billing data and the HOT2000 estimates. The refinements identified from the verification process were applied to the rest of the 8767 house files as necessary to improve the accuracy of the simulation results. To ensure the validity of the billing data, houses with auxiliary heating with other fuels (such as wood or propane) were excluded, and the UEC estimates were corrected for the actual weather using degree day ratios between the actual degree days and the typical year degree days for each region. The details of the verification and file improvement process, and its results are given elsewhere (Farahbakhsh et al., 1997, Farahbakhsh, 1997, Fung et al., 2000).

The refined HOT2000 house files were simulated using the HOT2000 simulation program (Batch version 7.14) to estimate the annual UEC of all of the 8767 houses in the SHEU database. HOT2000 simulations were done using weather files for the location of each house. The weather files represent long term (~30 year) averages of weather data obtained by Environment Canada. Thus, the simulation results are estimates of "typical" or "average" energy consumption that can be expected in an "average" year.

The unit energy consumption (UEC) by space heating fuel, by house type, by province, and by vintage were calculated from the simulation results. The refined HOT2000 house files and the results of simulations performed on these files using the HOT2000 simulation program form the Canadian Residential Energy End-use Model (CREEM). Since the SHEU database is representative of the Canadian housing stock, CREEM is also representative of the Canadian housing stock. Hence, the simulation results for UEC were extrapolated to estimate the energy consumption characteristics of the Canadian housing stock. These estimates are in agreement with those from other studies (Ugursal, V.I., Fung, A.S., 1994, Scanada, 1992)

CREEM was then used to assess the reductions in energy consumption and carbon dioxide emissions from the Canadian residential sector as a result of various energy efficiency measures.

As stated above, CREEM is largely based on the data in 1993 SHEU database. A new version of CREEM that will incorporate the data from the 1997 SHEU is currently under development. The 1997 SHEU database was made public by Statistics Canada in the beginning of 2001.

ENERGY CONSUMPTION CHARACTERISTICS OF THE CANADIAN HOUSING STOCK

Results of simulations conducted using CREEM indicate that the average annual heating energy requirement [2] of single detached houses in Canada is 65 GJ/year/house, while the average annual heating energy requirement of single attached houses is 46 GJ/year/house. Thus, the heating energy requirement of single attached houses are about 30 percent less than that of single detached houses. This is in accordance with the explanation given earlier regarding the difference in the exposed envelope surface area.

The average annual UEC (which includes the energy consumption for space heating and cooling, domestic hot water heating, appliances and lights, and heat recovery ventilators and fans) of single detached and single attached houses are found to be 144 and 113 GJ/year/house, respectively. The UEC of single attached houses are about 22 percent less than that of single detached houses due to their lower space heating requirement.

The breakdown of energy consumption by end use in Canadian houses is given in Table 2. Due to the colder climate of Canada, space heating is the major contributor to the overall energy consumption of Canadian houses, accounting for 56 percent of the total energy used.

The overall annual energy consumption of single detached and single attached Canadian housing stock is 1000 PJ/year in 1993. Single detached houses contribute 91% of this total, or 907 PJ/year. The overall annual energy consumption was determined by multiplying the average annual UEC of single attached and single detached houses by the projected number of houses in each house type in the Canadian housing stock.

The average annual space heating energy consumption and the average annual UEC of houses by province and for all of Canada are given in Figure 2. As it can be seen from Figure 2, Saskatchewan, Alberta and Prince Edward Island (PEI) have the highest UEC per house, while British Columbia (BC) has the lowest. The high UEC of houses in Saskatchewan and Alberta are largely due to the cold climate. In the case of PEI, the high UEC is due to the fact that space heating fuel is predominantly oil (77 percent) followed by wood (19 percent). Both of these fuels have lower end-use efficiency than electricity. On the other hand, BC has the warmest climate among all provinces. There are also a large number of electrically heated houses in BC resulting in a lower UEC.

The average annual UEC's of Canadian houses categorized by vintage are given in Table 3. It can be seen that newer houses have lower UEC. This is to be expected since newer houses are better built with higher insulation and lower infiltration rates.

IMPACT OF UPGRADING OF CANADIAN HOUSES ON RESIDENTIAL END-USE ENERGY CONSUMPTION

To demonstrate its capabilities, CREEM was used to study the impact of upgrading of Canadian houses on end-use energy consumption. To accomplish this, each HOT2000 house file in the CREEM database was modified to reflect the upgrade evaluated using a global editor developed for this purpose. Some results for upgrading houses to R-2000 standards (CHBA/NRCan, 1994) are summarized here. Detailed results and discussion of these and other energy saving measures, including upgrading houses to the National Energy Code for Housing (NECH) standards (NRC, 1996), and the impact of these upgrades on carbon dioxide emissions are presented elsewhere (Farahbakhsh, 1997, Ugursal and Fung, 1998, Guler et al., 1999, Guler et al., 2000)

The R-2000 standards provide homeowners and constructors the basis for the design and construction of energy efficient and healthy housing. Various aspects of the house structure are dealt with in the R-2000 standards to address energy efficiency and indoor air quality. Among these are higher envelope insulation, air tightness, orientation, heating, cooling, lighting, and ventilation.

The R-2000 standards specify the requirements for space and water heating in the form of an energy target. This target comprises of two components, i.e. space heating and DHW, each of which depends on certain

[2] "Space heating energy requirement" is the amount of energy required to maintain the temperature of a house at the required level. It does not include the efficiency of the space heating units. "Space heating energy consumption" is the total energy (fuel) consumed by the space heating equipment, taking into account the efficiency of the heating units.

characteristics of the house. The R-2000 energy target for space heating takes into account the climate condition, heated area of the house, and the type of space heating fuel, while the target value for water heating accounts for local water mains temperature, hot water temperature, and efficiency of water heating equipment.

As it was mentioned earlier, houses in CREEM are divided into four vintage categories: pre 1941, 1941-66, 1967-78, 1978 or later. It is unlikely that upgrading older houses to improve energy efficiency would be feasible due to their shorter remaining useful life. Furthermore, the amount of energy savings will not likely justify the cost of upgrading. Thus, only upgrading of houses built in 1967-78 and 1978 or later is considered here. Since it is unrealistic to assume that all houses would be upgraded, scenarios were evaluated which assumed that upgrading would be done by implementing the R-2000 standards to 10, 20, 30, 50, and 90 percent of the houses built in 1961 or later. Differences in energy consumption and pollutant generation levels were determined between the base case and upgrading scenarios in terms of the decrease in UEC and carbon dioxide emissions. These values were then projected to all houses in Canada using the number of houses in each province.

The reductions in the average UEC of single attached and single detached houses in Canada as a result of upgrading 10-90 percent of the housing stock to R-2000 standards are given in Figure 3. The resulting overall reduction in the energy consumption of houses in Canada is shown in Table 4 for each house type. It can be seen that the energy savings associated with the upgrading of single-detached houses are higher than the energy savings for single-attached units. This is because single-detached houses have larger heat losses through the building envelope as compared to single-attached units. Consequently, improving the house envelopes as part of R-2000 upgrade results in bigger savings.

The reductions in the average UEC of houses in each province and for all of Canada as a result of upgrading 10-90 percent of houses to R-2000 standards are given in Figure 4. As it can be seen from this figure, the impact of R-2000 upgrades is the highest in Newfoundland and the lowest in Ontario. This is partly due to the difference between the existing building practices in these two provinces. The other reason is that over 21 percent of houses in Newfoundland use wood for space heating, which results in the highest energy savings when upgraded to the R-2000 standards. The total energy savings resulting from the R-2000 upgrades for each province is shown in Figure 5. These values have been calculated by multiplying the energy savings per house by the total number of houses in each province in 1993.

As Figure 5 shows, Alberta has the highest potential for energy savings, followed by Ontario, Quebec, and British Colombia. On the other hand, the energy saving associated with the R-2000 upgrades is the lowest in PEI. This low energy saving reflect the low population and number of houses in this province, otherwise PEI has the second highest energy saving on a per house basis.

CONCLUSIONS

A residential energy model for Canada was developed using all available data on the Canadian residential sector. The Canadian Residential Energy End-use Model (CREEM) is representative of the Canadian housing stock.

Using CREEM, the characteristics of the Canadian housing stock was studied, and some results are presented in this paper. Also, the impact of two upgrading options on the residential energy consumption in Canada was assessed using the model. The upgrading options were applied to a fraction of newer houses in Canada, and it was found that significant energy savings can be achieved as a result of upgrading.

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APPENDIX A

A.1 Survey of Household Energy Use (SHEU)

The 1993 Survey of Household Energy Use (SHEU) was conducted by Statistics Canada on behalf of Natural Resources Canada, in cooperation with the provinces of Nova Scotia, New Brunswick, Ontario, Manitoba, Saskatchewan, and with SaskPower. SHEU was commissioned to enrich the residential sector data in Canada. The target population for this survey was composed of all the housing units in Canada (excluding Yukon and North Western Territories) occupied as primary residences, both owned and rented. It is based on a mail out survey that included 376 questions. The database includes detailed information on 8767 houses from all provinces of Canada.

A.2 Modified STAR-Housing Database

STAtistically Representative HOUSING Stock (STAR-HOUSING database) was first developed by Scanada Consultants Limited on behalf of Canada Mortgage and Housing Corporation (CMHC) in 1992. As its name implies, STAR-HOUSING database is a statistically representative database of housing characteristics and energy consumption data of the existing Canadian housing stock. The original STAR-HOUSING database was later improved and expanded by Thermal Engineering on behalf of CMHC in 1994. This revised version of STAR is called Modified STAR-HOUSING database.

A.3 200-House Audit Project Database

There are total of 197 house files in various versions of Audit2000 file formats. These house files contain detailed house envelope characteristic and energy usage pattern based on house energy audit conducted by NRCan in different province across Canada.

A.4 HOT2000 Building Energy Simulation program

HOT2000 was developed under the direction of the R-2000 Home Program of Natural Resources Canada. It is specifically written to simulate houses rather than large buildings. Its calculations are based on monthly average hourly weather data.

Table 1: Distribution of dwelling types in Canada

House Type	Number	Share (%)
Single Detached	5823176	56
Mobile Home	246970	2
Row or Terrace	489576	5
Apartment, Flat	2073859	20
High-Rise Apartment	936434	9
Semi-Detached	460305	4
Duplex	328896	3
Total	10359216	100

Table 2: Distribution of residential energy consumption by end use

End-uses	Space Heating	DHW Heating	Appliances Light	HRV Fans	Space Cooling
UEC (GJ/Year)	76.7	26.8	34.6	1.5	1.2
(%)	54.5	19.0	24.6	1.1	0.8

Table 3: Average annual UEC by vintage category

Vintage	Before 1941	1941-1960	1961-1977	1978 or Later
UEC (GJ/Year)	157.4	139.7	139.5	133.5

Table 4: Total annual energy savings with upgrading houses built in 1961 or later to R-2000 standards

Total Energy Saving Associated with the R-2000 Upgrade (PJ/Year)		
Penetration Level	Single-Detached	Single-Attached
10%	14.0	0.6
20%	26.9	1.5
30%	41.3	2.1
50%	67.3	3.3
90%	125.2	7.3
Basecase UEC	Single-Detached	Single-Attached
(PJ/Year)	906.7	92.8

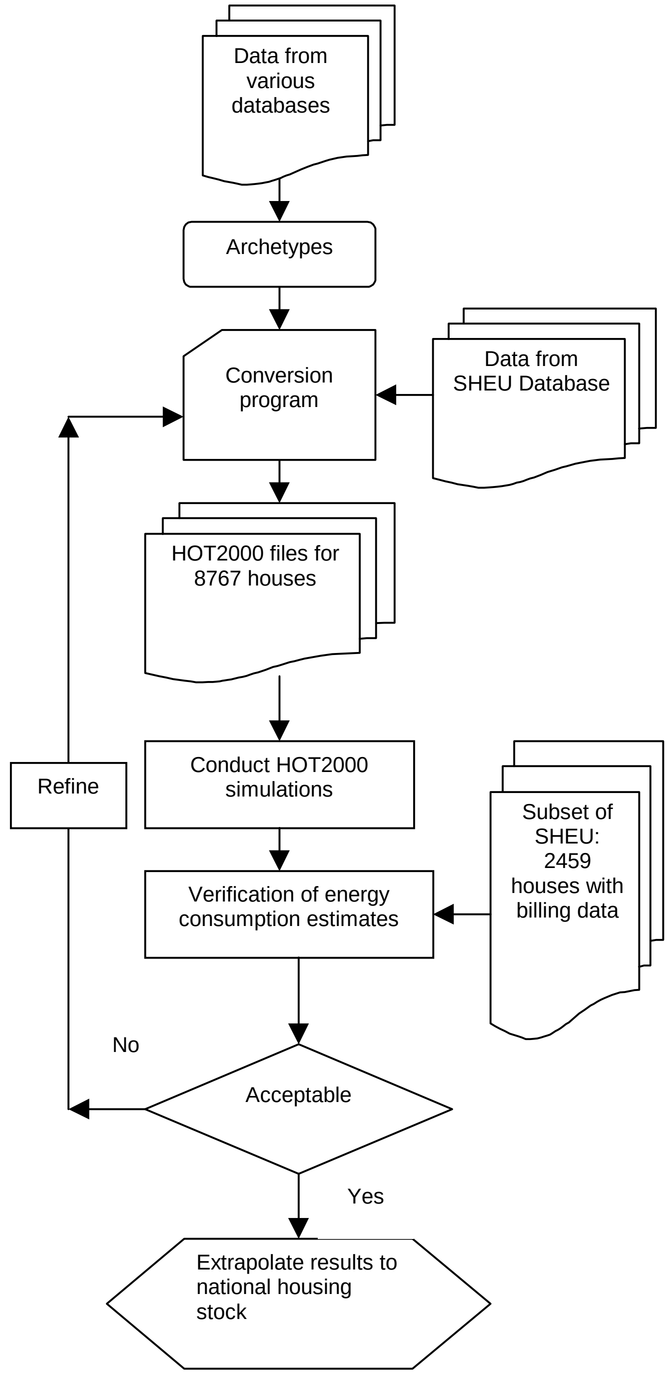

Figure 1: Structure of the CREEM Model

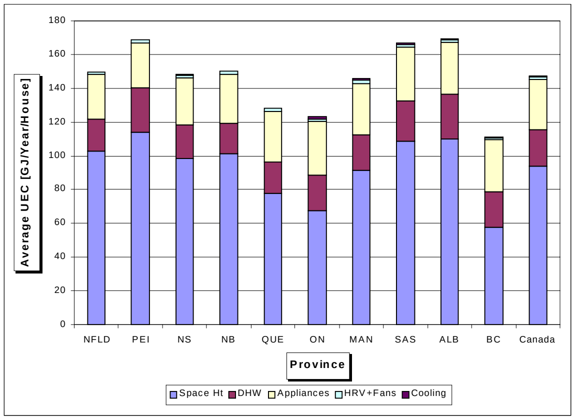

Figure 2: Average annual end-use energy consumption per house by province

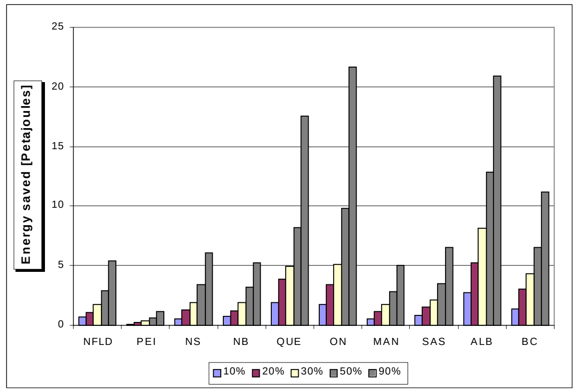

Figure 5: Total energy saving due to the R-2000 upgrades of 1961 or newer houses by province for different market penetration levels

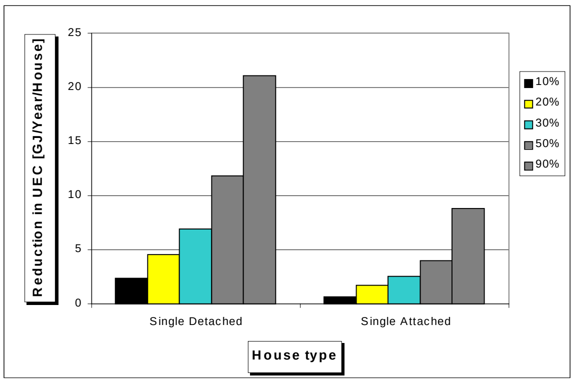

Figure 3: Effect of the R-2000 upgrades on the average UEC of Canadian houses by dwelling type

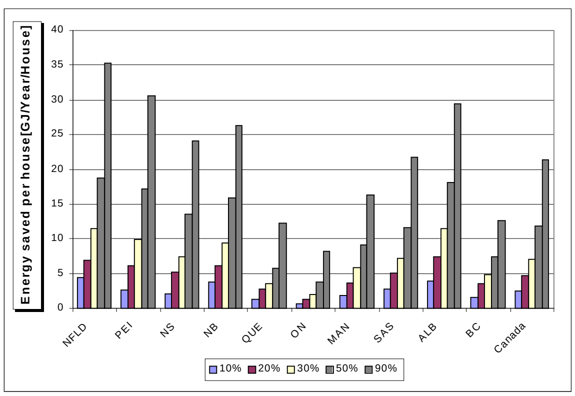

Figure 4: Effect of the R-2000 upgrades on the average UEC of houses by province for different market penetration levels