Analysis of the Renewable Energy Potentials in the Residential Sector of the Province of Quebec using the Building Energy Simulation Software ESP-r

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ABSTRACT

The Canadian residential sector contributes approximately 80 megatonnes (Mt) of greenhouse gases (GHG) to the environment each year. With the ratification of Kyoto protocol, Canada has committed to reduce its GHG emissions by at least five percent between 2008 and 2012 on the basis of its 1990 emission levels. To meet this target Canada has to evaluate and exploit all feasible means to reduce the fossil fuel energy consumption and the consequent GHG emissions. In this work, test-case houses for the province of Quebec were modeled in the building energy simulation software ESP-r. Requisite housing stock data was extracted from Canada's most comprehensive residential end-use energy surveys. As a source of alternate energy, photovoltaic (PV) and wind-turbine energy systems were assessed for their potential contribution to the energy and GHG savings. The results show that with the use of hybrid PV and wind-turbine energy systems, there is a huge potential of GHG reduction (about 16 %) and economic saving (about 16 %) due to reduced electricity bills and selling renewable electricity to the local grid.

KEYWORDS

Greenhouse gases (GHG), Kyoto Protocol, Photovoltaic systems, Wind-turbine energy systems, ESP-r

INTRODUCTION

Owing to its cold climate and the prevalence of single-family dwellings the total end-use energy consumption of Canada is very high. Figure 1 shows the trend of Canadian GHG emissions between years 1990 to 2003 for residential, commercial and institutional sector. In year 2004 a total of 8543 Petajoules (PJ) of energy was consumed, with 1421 PJ used in residential sector. The GHG emissions for the residential sector in 2004 were 77 Mt (NRCan 2006).

Addressing the worldwide concern over the potential undesirable climatic changes across the globe an international treaty known as the Kyoto Protocol was signed. Under the commitment of this protocol, Canada promised to reduce its GHG emissions by six percent by the year 2012 based on its emission levels of 1990.

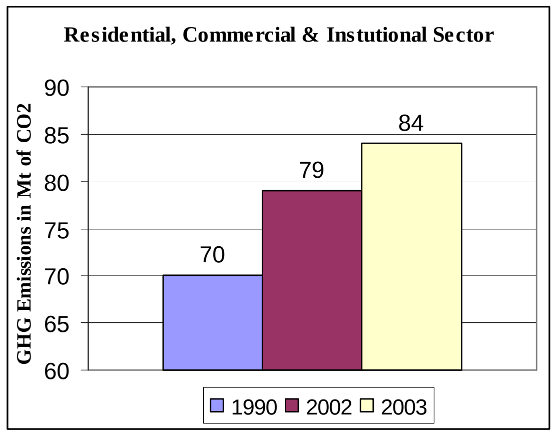

Figure 1 Trend of the Canadian GHG emission from 1990 to 2003 (Source: Environment Canada, 2005)

In this paper the results of a study done to assess the potential of using building integrated PV and roof mounted wind-turbine energy systems in the test-case residential models for province of Quebec have been presented. The test-case house models were developed and simulated with PV and wind-turbine energy systems in the state of the art building energy simulation tool ESP-r.

SELECTING TYPICAL TEST-CASE HOUSES FROM THE PROVINCE OF QUEBEC

The typical test-cases houses were generated using three Canadian housing stock databases, namely SHEU (Statistics Canada 1993), EnerGuide (NRCan 2005-ii) and New Housing Survey (NRCan 1997), respectively.

The data in SHEU contains associated weights of all houses it represents. For the present study only single detached houses were considered. All single detached houses in SHEU database falling in province of Quebec were segregated. Then the database of this province was classified based on the vintage groups its houses fell under. Four vintage groups were defined, which were the houses built ‘before 1941’, ‘between 1941-1960’, ‘between 1961-1977’ and ‘after 1977’, respectively. Houses falling in each vintage group were further classified based on the principal fuels used for their space heating. The principal space heating fuels considered in this study were oil, natural gas and electricity, respectively.

Once the SHEU database was classified in the categories stated above, three of the most representative test-case houses were chosen. The sole criterion of selection was the weighting factors the test-case houses carried, and the houses carrying highest weight compared to others were chosen. The selected test-case houses were simulated with the weather file of two most densely populated cities of Quebec, i.e. Montreal and Quebec City.

Based on the weighting factor carried by each test-case house, it was estimated that the test-case house 1 represents 12.8 %, test-case house 2 represents 23.9 % while test-case house 3 represents 33.1 % of all single-detached houses in the province of Quebec. Hence the selected sample size of three houses accurately represents 69.8 % of all single detached dwellings in province of Quebec. Some characteristics of the test-case houses are presented here:

TEST-CASE HOUSES 1:

- 1.5 storey house with living area of 116 m^2 (excluding basement).
- Built between 1941-1960.
- Uses electric baseboards with efficiency of 100 percent.
- DHW plant is electric, having efficiency of 82 percent.
- Construction details:
    - Main Wall RSI: 1.74
    - Foundation RSI: 1.26
    - Ceiling RSI: 3.431
- Has a full heated basement.
- It has 2 occupants.
- Infiltration: 8.1 @ 50Pa
- Total glazed area of 8.69m^2 with double glazed windows.
- Has an annual ‘appliance and lighting’ electric consumption of 6,907 kWh.

TEST-CASE HOUSES 2:

- 1.5 storey house with living area of 116 m^2 (excluding basement).
- Built between 1961-1977.
- Uses electric baseboards with efficiency of 100 percent.
- DHW plant is electric, having efficiency of 82 percent.
- Construction details:
    - Main Wall RSI: 2.034
    - Foundation RSI: 1.383
    - Ceiling RSI: 3.891
- Has a full heated basement.
- It has 2 occupants.
- Infiltration: 6.2 @ 50Pa
- Total glazed area of 9.486m^2 with double glazed windows.
- Has an annual ‘appliance and lighting’ electric consumption of 7,957 kWh.

TEST-CASE HOUSES 3:

- 1.5 storey with living area of 116 m^2 (excluding basement).
- Built after 1977.
- Uses electric baseboards with efficiency of 100 percent.
- DHW plant is electric, having efficiency of 82 percent.
- Construction details:
    - Main Wall RSI: 2.643
    - Foundation RSI: 1.854
    - Ceiling RSI: 4.935
- Has a heated full basement.
- It has 3 occupants.
- Infiltration: 5.2 @ 50Pa
- Total glazed area of 7.116m^2 with double glazed windows.
- Has an annual ‘appliance and lighting’ electric consumption of 8,411 kWh.

TEST-CASE HOUSE MODELING IN ESP-r

After test-case houses were selected, different constructional and thermal characteristic and attributes, like floor areas, wall insulations, heating set-points, space heating equipment efficiencies, domestic hot water (DHW) systems, window types, orientation etc. for each house were found. Most of the required information was available in SHEU database, while remaining information was supplemented from EnerGuide and New Housing Survey. Once the information was obtained, the houses were modeled in ESP-r. For building envelope, ESP-r default material database was used and detailed multi-layer construction of all building surfaces was defined. Event profiles specific to each test-case house and were developed using 'PRO' facility of ESP-r. Basement foundations were defined using BASESIMP model in ESP-r. The annual averaged soil temperature and the amplitude of the ground-temperature's annual sine wave for the simulation cities as required by BASESIMP was taken from BASECALC™ (BASECALC, 2006). Typical occupancy schedules were deduced from the CCHT Simulated Occupancy Schedule (CCHT, 2002). Existing ESP-r one diode equivalent PV modules, TRNSYS TYPE 75 power conditioning unit and wind-turbine models based on Twidell and Weir (1986) were used for this study. The temperature control scheme adopted for modeling these houses in ESP-r was 'basic control law'. Casual gains due to the consumption of electricity were included by manually adding 'type 5' casual gains to each test-case house operation file (.opr) in ESP-r models for all three test-case houses.

DEVELOPMENT OF ELECTRICAL LOAD PROFILES

The occupant driven appliance and lightning electricity demand plays a very important role in the electricity usage pattern of the house, having consequences on building thermal and on load factor of the PV and wind-turbine energy systems.

The typical Canadian residential electricity demand profiles developed by Good et al. (2004) were used to determine the shape of the electricity load curves for the selected test-case houses, while their magnitudes were taken from the Neural Network based residential appliance and lightning electricity demands by Aydinalp (2002). Complete detail of development of the electrical load profiles are presented in Syed (2007).

A PERL script was developed to generate the '.fcl' files to input the load profiles in the test-case house models. The electric load profiles were linked to the electric network of each house model in ESP-r. Figure 2 shows a typical seasonal averaged daily appliance and lighting electricity load profiles for the test-case house in Montreal. The seasons are defined as winter (December to February), spring (March to May), summer (June to August) and fall (September to November), respectively.

BASE-CASE SIMULATIONS

Once the models were developed in ESP-r and electrical load profiles properly linked to them, annual simulations were run to determine the required electric baseboard sizes for the test-case houses.

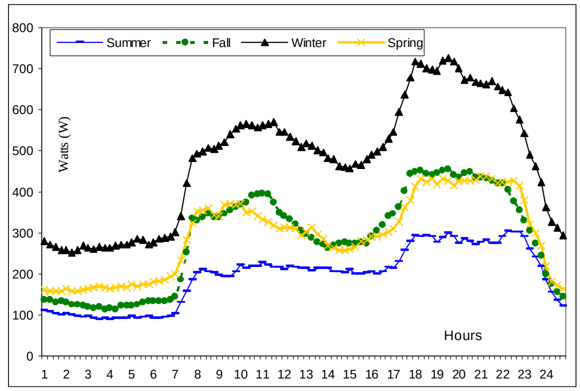

Figure 2 Daily electricity load profiles for test-case house model 1 for four seasons

Once the baseboard sizes were determined and the ESP-r models were updated with new sizes, the simulations were run again. These set of simulations were termed as 'base-case simulations'. These simulations assessed the thermal and electrical behaviour of the house at its current status, i.e. without any renewable energy component attached to it. The results of these simulations provided a basis for comparison of test-case houses behaviour with renewable energy components attached to it.

SELECTION OF SIZES OF PV AND WIND-TURBINE ENERGY SYSTEMS

After running base-case simulation for the selected test-case houses, the appropriate sizes of the PV and wind-turbine energy systems were determined. For this study the BP_saturn_36cell PV module and existing wind-turbine models in ESP-r were used. This PV module has an area of 0.621m^2 and has a power output of 85 Watts, rating its power-output to area ratio the highest among other PV models available in ESP-r.

For PV system, the size selection guidelines from NRCan (2002) were used. The total HVAC and non-HVAC electrical loads were summed up and divided by the average of the peak-sunshine hours of the simulation cities in the months of September and December, as shown in Table 1.

Table 1 The estimated PV array sizes for the selected test-case houses

Test-case houses	Daily average electrical demand (kWh)	Average Peak Sunlight Hours	Installed array size (kW)
1	125	3.5	8.1
2	128	3.5	8.1
3	136	3.5	8.1

The estimated required size in all the test-case houses resulted in the size of arrays that exceed the roof dimensions. Hence the allowable maximum number of modules was calculated based on the available roof area. This resulted in an array of capacity of 8.1 kWp for all test-case houses. If the roofs of selected test-case houses were facing east or west, both sides were tested for PV performance, and the orientation that gave maximum output was selected. In case when the roof of the test-case house was facing south, the array was installed on the south-facing roof. In this way the PV array sizes and orientations were finalized.

For the selection of roof-mounted wind-turbine energy systems, the turbine area and installation limitations outlined by Canadian Wind Energy Association (CanWEA 2006) led to the selection of two sizes of 600W and 1kW capacity respectively.

Hence each of the test-case houses was simulated for suitable PV array size with two wind-turbine sizes, resulting in two sets of simulations for each house. The set of simulations with PV and wind-turbine installed in the house models were called hybrid-case simulations.

SIMULATION RESULTS

The base case annual simulation results for the four test houses have been presented in Table 3. In Canada a substantial amount of residential energy is consumed in the form of electricity. In Canada, electricity production is primarily from three sources: fossil fuels, nuclear and hydro. Among fossil fuels, three most commonly used fuels are coal, oil and natural gas. The amount of GHG emissions from electricity generation can be calculated using the average GHG emission intensity. The average GHG emission intensity is the amount of GHG emissions produced as a result of generating one kWh of electricity. The average GHG emission intensity factors assume that the reduction in electricity consumption is uniformly distributed among all power plants and no transmission and distribution losses are considered (Syed, 2007). In real case, however, when electricity is saved it is not the average kWh but the marginal kWh, and in most parts of Canada the marginal kWh is more CO_2 intensive than the average kWh. Hence, it can be argued that the average GHG emission intensities are overly conservative and the impact of energy improvement scenarios on GHG emissions using national averages can likely underestimate the actual GHG emissions due to electricity consumption. Therefore, a second set of GHG emission intensities were derived to estimate upper limit of GHG reductions by assuming that all savings in electrical consumptions come from fossil fuel fired power plants (where possible), taking into account the distribution and transmission losses, based on Guler (In Press).

The average CO_2 equivalent emission factor for electricity generation in gCO_2eq/kWh for province of Quebec is 8 (Environment Canada 2006), while the high CO_2 equivalent emission factor for electricity generation in gCO_2eq/kWh for province of Quebec was assumed to be 549 (Guler, In Press). The high emission intensity factor assumes all of the savings in electrical consumptions from fossil fuel fired power plants (where applicable) and using province wide average transmission and distribution losses.

Table 3 The base-case annual simulation results for three test-case models

Test Case House	1		2		3	
	Montreal	Quebec	Montreal	Quebec	Montreal	Quebec
Electricity Consumption (kWh)	44421	45728	45364	46737	46304	47568
SH (GJ)	116.9	121.7	116.6	121.2	116.4	121.1
DHW GJ)	13.2	13.2	13.2	13.3	14.7	14.6
Flat Rate Cost (CAD)	2318	2387	2368	2439	2417	2483
GHG_{ai} (Tonnes)	0.4	0.4	0.4	0.4	0.4	0.4
GHG_{hi} (Tonnes)	24.4	25.1	24.9	25.7	25.4	26.1

The results of the hybrid case simulations (with PV and wind-turbines) for the four test-case houses have been presented in Tables 4 to 9.

The results presented here are assuming either battery storage or net-metering facility because there are mismatches in the occurrence of timings of the electricity demand of the house and the power production by the renewable energy systems. With the use of net-metering facility or on-site battery storage the excess can be sold to the grid or stored in the battery and imported when needed.

Table 4 The hybrid-case annual simulation results for Test-Case House 1 in Montreal

Test-Case House 1	8.1 kWp PV array	
	600W WT	1kW WT
PV output (kWh)	9213	9123
WT output (kWh)	847	1543
Total Energy (kWh)	9960	10401
Surplus energy produced (kWh)	3364	3423
Net Import (kWh)	37825	37444
Flat Rate Cost (CAD)	1974	1954
Credit (CAD)	175	178
GHG_{ai} (Tonnes)	0.3	0.3
GHG_{hi} (Tonnes)	20.8	20.6

Table 5 The hybrid-case annual simulation results for Test-Case House 1 in Quebec City

Test-Case House 1	8.1 kWp PV array	
	600W WT	1kW WT
PV output (kWh)	9539	9539
WT output (kWh)	917	1420
Total Energy (kWh)	10457	10960
Surplus energy produced (kWh)	3421	3514
Net Import (kWh)	38692	38282
Flat Rate Cost (CAD)	2019	1998
Credit (CAD)	178	183
GHG_{ai} (Tonnes)	0.3	0.3
GHG_{hi} (Tonnes)	21.2	21.0

Table 6 The hybrid-case annual simulation results for Test-Case House 2 in Montreal

Test-Case House 1	8.1 kWp PV array	
	600W WT	1kW WT
PV output (kWh)	9113	9113
WT output (kWh)	847	1287
Total Energy (kWh)	9960	10401
Surplus energy produced (kWh)	3247	3306
Net Import (kWh)	38651	38269
Flat Rate Cost (CAD)	2017	1997
Credit (CAD)	169	172
GHG_{ai} (Tonnes)	0.3	0.3
GHG_{hi} (Tonnes)	21.2	21.0

Table 7 The hybrid-case annual simulation results for Test-Case House 2 in Quebec City

Test-Case House 1	8.1 kWp PV array	
	600W WT	1kW WT
PV output (kWh)	9539	9539
WT output (kWh)	917	1420
Total Energy (kWh)	10457	10960
Surplus energy produced (kWh)	3312	3403
Net Import (kWh)	10457	10960
Flat Rate Cost (CAD)	2066	2045
Credit (CAD)	172	177
GHG_{ai} (Tonnes)	0.3	0.3
GHG_{hi} (Tonnes)	21.7	21.5

Table 8 The hybrid-case annual simulation results for Test-Case House 3 in Montreal

Test-Case House 1	8.1 kWp PV array	
	600W WT	1kW WT
PV output (kWh)	9113	9113
WT output (kWh)	847	1287
Total Energy (kWh)	9960	10401
Surplus energy produced (kWh)	3168	3225
Net Import (kWh)	39512	39128
Flat Rate Cost (CAD)	2062	2042
Credit (CAD)	165	168
GHG_{ai} (Tonnes)	0.3	0.3
GHG_{hi} (Tonnes)	21.7	21.5

Table 9 The hybrid-case annual simulation results for Test-Case House 3 in Quebec City

Test-Case House 1	8.1 kWp PV array	
	600W WT	1kW WT
PV output (kWh)	9539	9539
WT output (kWh)	917	1420
Total Energy (kWh)	10457	10960
Surplus energy produced (kWh)	3235	3324
Net Import (kWh)	10457	10960
Flat Rate Cost (CAD)	2106	2084
Credit (CAD)	168	173
GHG_{ai} (Tonnes)	0.3	0.3
GHG_{hi} (Tonnes)	22.1	21.9

DISCUSSIONS

For different hours of the day during different seasons, either the renewable energy exceeds the demand or it contributes to meet a part of total electric load. During the time of the day when the renewable power is contributing to the demand, the net import from the grid is lower, resulting in lesser load on the utility grid. During the times when the renewable power is more than the demand, the surplus power can be sold to the local grid using net metering facility. Net metering policy allows homeowners to receive the full value of the electricity that their hybrid renewable electric systems produce, without having to install a battery storage system (U. S. Department of Energy 2007). If more electricity is produced than the home needs, the extra kilowatts are fed to the utility grid and the customer earns the credit at the wholesale power rate system (U. S. Department of Energy 2007).

Tables 10 to 15 present the percentage of electricity demand that is met using the designed hybrid PV and wind energy sytems and the percentage reduction in GHG emissions and cost of electricity for the test-case houses.

The PV cluster with high penetration of PV power generation may affect the voltage profile of the interconnected distribution feeder by raising the voltage beyond the standard limit at light load and high solar irradiation conditions (Katiraei et al., 2007). Similarly, the presence of multiple PV-inverters in a distribution network can potentially increase the total amount of current harmonics injected to the grid (Katiraei et al., 2007).

The different PV and Wind-turbine energy system penetration levels cause non-linear effects in the grid network. High penetration levels of PV power generation may cause voltage problems in the electric network but also depends on the network type (Paatero and Lund, 2006), and it may not have an accumulated adverse impact on the grid voltage distortions for two reasons (Katirael et al., 2007):

1) Voltage distortion is highly dependent on the grid, determined by the series of impedance of the grid and existing background distortions
2) Geographical distribution of the multiple PV-inverters and the difference in the point of connections, generation intermittency, and randomness nature of the load demand lead to some degree of harmonic cancellations with in the PV network that reduce the overall harmonic pollution effects of the inverters.

Different network types can handle PV without significant problems both in a northern and southern climate with an amount of PV equaling up to the load (Paatero and Lund, 2006).

Table 10 Results summary for test-case house 1 in Montreal

Summary	PV and 600W	PV and 1kW
% Demand Met	14.8	15.7
% ΔGHG Elec $_{ai}$	14.8	15.7
% ΔGHG Elec $_{hi}$	14.8	15.7
% ΔCOST $_{FLAT}$	14.8	15.7

Table 11 Results summary for test-case house 1 in Quebec City

Summary	PV and 600W	PV and 1kW
% Demand Met	15.4	16.3
% ΔGHG Elec $_{ai}$	15.4	16.3
% ΔGHG Elec $_{hi}$	15.4	16.3
% ΔCOST $_{FLAT}$	15.4	16.3

Table 12 Results summary for test-case house 2 in Montreal

Summary	PV and 600W	PV and 1kW
% Demand Met	14.8	15.6
% ΔGHG Elec $_{ai}$	14.8	15.6
% ΔGHG Elec $_{hi}$	14.8	15.6
% ΔCOST $_{FLAT}$	14.8	15.6

Table 13 Results summary for test-case house 2 in Quebec City

Summary	PV and 600W	PV and 1kW
% Demand Met	15.3	16.2
% ΔGHG Elec $_{ai}$	15.3	16.2
% ΔGHG Elec $_{hi}$	15.3	16.2
% ΔCOST $_{FLAT}$	15.3	16.2

Table 14 Results summary for test-case house 3 in Montreal

Summary	PV and 600W	PV and 1kW
% Demand Met	14.7	15.5
% ΔGHG Elec $_{ai}$	14.7	15.5
% ΔGHG Elec $_{hi}$	14.7	15.5
% ΔCOST $_{FLAT}$	14.7	15.5

Table 15 Results summary for test-case house 3 in Quebec City

Summary	PV and 600W	PV and 1kW
% Demand Met	15.2	16.1
% ΔGHG Elec $_{ai}$	15.2	16.1
% ΔGHG Elec $_{hi}$	15.2	16.1
% ΔCOST $_{FLAT}$	15.2	16.1

Figures 3-4 show the GHG emissions in Megatons (Mt) for all the houses in both simulation cities for high and average emission intensities, respectively.

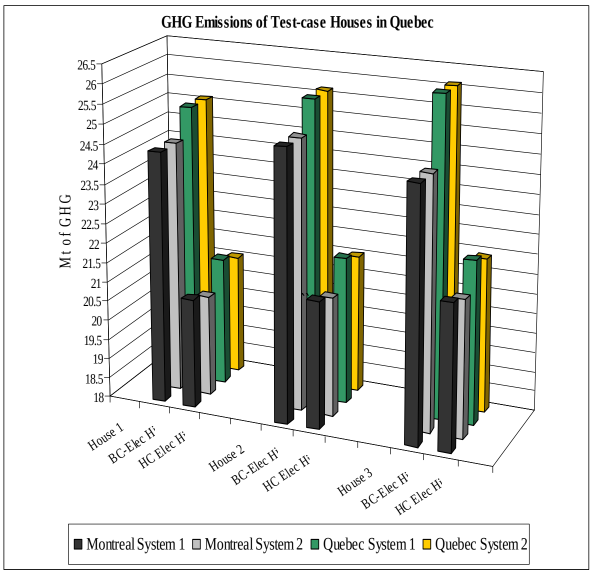

Figure 3 GHG emissions for test-case houses at high emission intensity factors

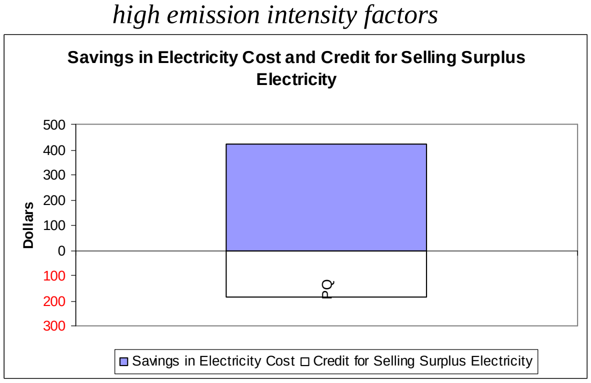

Figure 5 Economic savings and credit for selling surplus electricity to local grid in CAD

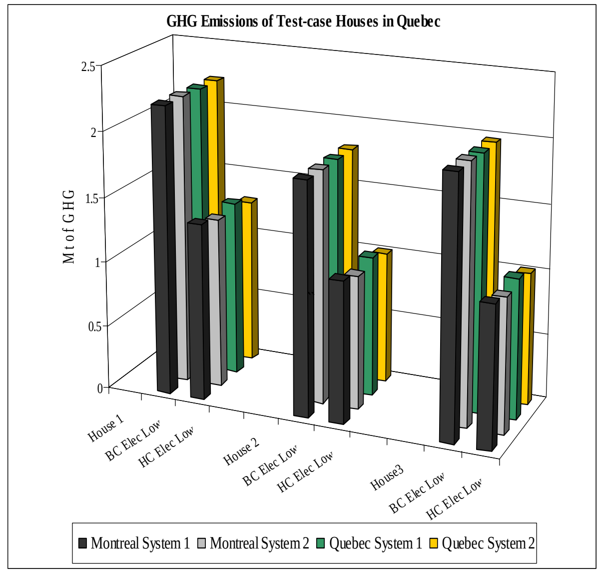

Figure 4 GHG emissions for test-case houses at average emission intensity factors

Figure 5 shows the average economic savings realized and the credit of selling surplus electricity to the local grid for the test-case houses.

CONCLUSIONS

The hybrid-case simulation results for test-case house 1, located in Montreal show that with 8.1 kWp PV array and 1kW wind turbine, 15.7 % of the annual electrical demands can be met, with a consequent 15.7 % reduction in GHG emissions. Similarly, for Quebec City, upto 16.3 % of annual electric demand can be met.

The results for test-case house 2 show that with the use PV and wind-turbine technologies up to 15.6 % and 16.2 % annual electricity requirements can be met for Montreal and Quebec City, respectively. This results in the same proportions of reduction in overall GHG emissions.

Test-case results for house 3 show the given hybrid energy system can meet upto 15.5 and 16.1 % of annual energy demands for Montreal and Quebec City, respectively.

Hence, it can be seen from the simulation results that there is a reasonable potential of electricity generation by using PV and wind-turbine systems for residential sector in province of Quebec. These renewable technologies not only result in production of onsite electricity but also have a pronounced effect on the GHG reduction.

NOMENCLATURE

Abbreviations	
CAD	Canadian dollars
DHW	domestic hot water
GHG_{av}	GHG emissions due to electricity generation at average intensity factor
GHG_{hi}	GHG emissions due to electricity generation at high intensity factor
GHG_{Total}	Total GHG emissions
SH	space heating
WT	Wind turbine

ACKNOWLEDGEMENTS

The authors acknowledge the financial support for this work provided by the Canadian Mortgage and Housing Corporation (CMHC), NSERC Discovery Grant and NSERC Solar Building Research Network (SBRN). Special thanks to Mr. Alex Ferguson and Ms. Maria Mottillo at Natural Resources Canada for their technical support.

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