RETROFIT MEASURES TO APPROACH NET ZERO ENERGY STATUS FOR THE CANADIAN HOUSING STOCK: AIR TO WATER HEAT PUMP + PV

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ABSTRACT

The aim of this paper is to present the impact of air to water heat pump (AWHP) and photovoltaic (PV) retrofit on the energy consumption and greenhouse gas (GHG) emissions of the Canadian housing stock. The study is conducted using the Canadian Hybrid Residential End-use Energy and Emission model (CHREM). CHREM is based on the Canadian Single-Detached and Double/Row Database (CSDDRD), and utilizes the high resolution building energy simulation program ESP-r as its simulation engine.

A suitable AWHP and PV system architecture for existing houses in the Canadian climate is selected. A numerical model for the selected architecture is developed using the available components in ESP-r. The model is applied to the houses eligible for AWHP and PV retrofit. The impact of AWHP and PV retrofit on electricity, oil, natural gas and wood consumption as well as the associated GHG emissions is estimated for each province. The results of this study will be used to develop strategies to convert existing Canadian houses into near/net zero energy buildings.

INTRODUCTION

The net zero energy building (NZEB) became a permanent part of the energy policy in many countries (Sartori *et al.*, 2012). Since the energy saving market is not reacting rationally on the classic market forces, legislations and government incentives are likely the key parameters to promote energy efficiency in buildings (Tommerup & Svendsen, 2006). Legislation, codes and incentives regarding the energy efficiency in buildings are primarily planned at the municipal and provincial levels in Canada (Tobias & Vavaroutsos, 2012). Thus, smart strategies are required for massive conversion of existing houses in the Canadian housing stock (CHS) into NZEBs. Due to the complicated nature of the problem and the presence of several parameters including climatic and geographical conditions, energy prices, owner's perception, greenhouse gas (GHG) emission reduction policy, technological barriers, various renewable energy supply options and grid interaction, such plans may be devised in municipal, provincial and national levels.

To address energy consumption and GHG emissions of the residential sector in Canada a roadmap is required to encourage existing house owners to convert their houses into NZEB. Thus a subproject was defined under the Smart Net-zero Energy Buildings Strategic Research Network (SNEBRN) umbrella to define strategies and approaches for a net/near zero energy housing stock perspective. To achieve this goal suitable retrofits should be introduced in existing houses.

The Canadian housing stock exhibits a high diversity in geometry and construction materials as well as heating, cooling and ventilation systems because of the wide range of climatic, geographical and economic conditions as well as the availability and price of fuels and energy sources in different regions. Thus the Building performance simulation is the most powerful tool to estimate the feasibility of retrofit options in existing houses across Canada. So far, a wide range of retrofit options including envelope modifications such as glazing and window shading upgrades, as well as installation of solar domestic hot water (SDHW) systems, phase change material (PCM) thermal energy storage, internal combustion engine (ICE) and Stirling engine (SE) based cogeneration systems and solar combisystem were studied (Asaee *et al.*, 2015a; Asaee *et al.*, 2015b; Asaee *et al.*, 2015c; 2016b; Asaee *et al.*, 2014; Nikoofard *et al.*, 2013; 2014a; b; c).

Energy saving and high energy efficiency technologies are essential components of any practical strategy for converting existing houses into NZEBs. An air to water heat pump (AWHP) system transfers aerothermal energy to water to deliver the required thermal energy for both space and domestic hot water heating from a single source. While the AWHP system is well established in Europe and Japan, it is relatively new to the Canadian market (CMHC-SCHL, 2015).

Since the heat pump is an electricity driven system, an AWHP may reduce the energy consumption for space and DHW heating while increasing the electricity consumption of the household depending on the nature of the existing heating system. Thus, to reduce the impact of AWHP on electricity consumption, a photovoltaic (PV) solar system can be added to the retrofitted houses where practicable. A typical schematic of a house with a combined AWHP and PV system retrofit is presented in Figure 1.

The PV modules are connected to a DC to AC inverter. PV generated electricity may be used to run the heat pump system including the compressor, pumps and auxiliary power for control devices as well as to provide electricity for appliances and lighting (AL). It is assumed that the houses can trade electricity with the utility at the same rate for import and export. Under these circumstances the grid becomes an infinite storage system for renewable electricity generated by the PV panels.

Recently, numerous studies have reported on the performance and feasibility of AWHPs for various regions of the world. For example, Kelly and Cockroft (Kelly & Cockroft, 2011) developed a numerical model to evaluate the performance of AWHP retrofit into a building in Scotland. The simulation results were validated by laboratory data and the model was integrated into a whole building performance simulation software. The model was a well representative of the AWHP operating conditions in the field trial. To evaluate the feasibility of the AWHP retrofit, an equivalent condensing natural gas boiler and an electric heating system were used as alternative heating systems for the building, and annual energy consumption of the three systems were compared. The results showed that GHG emissions of AWHP were lower compared to that of the condensing natural gas boiler and the electric heating system. While the operating cost of the AWHP exceeds that of the gas condensing boiler, incentives available for renewable thermal energy may make up the difference. In another study, Kelly et al. (Kelly *et al.*, 2014) used the AWHP model to estimate the effectiveness of integrated AWHP and thermal storage tank with phase change material (PCM) to restrict the AWHP operation to the off-peak periods. The study was conducted for a week in the climate of UK. The results showed that through manipulation of the PCM chemistry heat storage tank volume could be reduced by 50% with a minimum impact on heat supply to the building. Cabrol and Rowley (Cabrol & Rowley, 2012) used a numerical model to study the performance of AWHP system with hydronic heat delivery in various UK locations. The annual coefficient of performance (COP) of the AWHP was found to be about 3.5 and 4 for cold climate and mild climate, respectively. A sensitivity analysis was conducted to evaluate the impact of the building construction materials and off-peak period operation. They concluded that the GHG emissions and operating cost of AWHP were lower compared to those of an equivalent size gas boiler. Johnson (Johnson, 2011) studied the change in GHG emissions associated with the heat pump retrofit. It was concluded that in the UK context the heat pump GHG emissions due to electricity consumption were higher compared to gaseous fuels and lower compared to heating oil. Madonna and Bazzocchi (Madonna & Bazzocchi, 2013) built a model for AWHP system based on measured data from a field trial campaign. The model utilizes an hourly simulation approach using the ambient temperature, relative humidity, outlet water temperature and thermal load as parameters. They used the model to estimate performance of AWHP in residential buildings in various climate conditions in Italy. The results showed that climate has a significant role on the performance of AWHP, and depending on climate, the energy requirement for space heating could be reduced by up to 79% in new buildings. Hewitt et al. studied AWHP retrofit options for existing houses in the UK. They investigated a variety of options to maintain a high COP and a high temperature water supply for existing radiators. They recommended using variable speed compressor, advanced evaporators and improving heat delivery system to enhance the performance of AWHP in the European maritime climate conditions (Hewitt *et al.*, 2011). Bertsch and Groll (Bertsch & Groll, 2008) designed, simulated, constructed and tested an air-source heat pump (ASHP) water or air heating system with an operating range of -30°C to 10°C and return water temperature of 50°C for northern US climates. The issues related with high compressor discharge temperatures, low COP and heating capacity, as well as rapid on/off cycling of the low temperature ASHP during operation at high ambient temperature were dealt with through design choices. The cost of the proposed ASHP system was found to be lower compared to an equivalent ground source heat pump. Ibrahim et al. (Ibrahim *et al.*, 2014) developed a simulation model to study the performance of AWHP system and its potential for energy savings and GHG emissions reductions in Lebanon. The results showed that COP would vary in the range of 2.9 to 5 for the various climatic conditions of Lebanon.

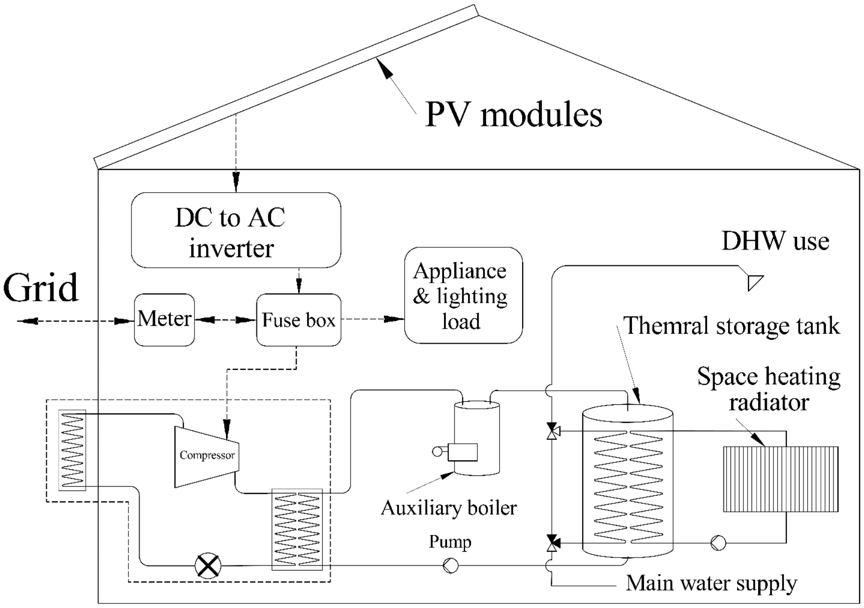

Figure 1. Schematic of the AWHP and PV System retrofit in a typical house

They presented the optimal management model for the AWHP for a winter day of Beirut and carried out a sensitivity analysis to estimate the impact of condenser size on the performance of the heat pump. Lund et al. (Lund *et al.*, 2010) evaluated the role of district heating in the future renewable energy systems of Denmark assuming that Danish energy supply will be entirely from renewable resources by 2060. To achieve this target the authors considered a 75% reduction in space heating demand and concluded that individual heat pump systems are the best alternative for the existing fossil fuel based heating systems. The European Parliament and Council also identified the aerothermal, geothermal and hydrothermal energy production of heat pump systems as renewable energy under specific circumstances as published in the Directive 2009/28/EC (EPC-EU, 2009). Most recently, Asaee, et al. (Asaee *et al.*, 2016a) has studied the techno-economic feasibility of retrofitting AWHP to the existing Canadian housing stock to achieve or approach NZE status.

As this brief review of the literature indicates, while numerous studies focused on the techno-economic feasibility of AWHP systems, AWHP with PV systems have not been studied. Therefore, a comprehensive study is being conducted to investigate the feasibility of large scale AWHP+PV systems retrofit in the CHS to approach NZE status for existing Canadian houses. The impact of AWHP+PV system retrofit on the energy consumption and GHG emissions of the Canadian housing stock is presented in this paper. The results of the economic analysis will be presented at a later date. Due to significantly different architecture of AWHP and conventional air to air heat pump system the eligibility criteria for such retrofits are not the same. Thus the latter retrofit option will be studied separately and results will be presented at a later date.

METHODOLOGY

This study was conducted using a representative model of the CHS that incorporates a whole building simulation approach. The methodology used in the study is discussed below.

Due to the wide range of climatic, geographical and economic conditions as well as the availability and price of fuels and energy sources in different regions of Canada, the CHS exhibits a high diversity in geometry and construction materials as well as heating, cooling and ventilation systems. Thus, this study was conducted using CHREM (Swan, 2010; Swan *et al.*, 2013), which is based on the Canadian Single-Detached Double/Row Database (CSDDRD) (Swan *et al.*, 2009) and is statistically representative of the CHS.

CHREM utilizes the high-resolution building energy simulation program ESP-r (ESRU, 2015) as its simulation engine, an integrated modeling tool for evaluation of the thermal, visual and acoustic performance as well as energy consumption and GHG emissions of buildings. Vast amount of research results has been used to validate the accuracy of ESP-r (Strachan *et al.*, 2008). CSDDRD was developed using the latest data available from the EnerGuide for Houses database, Statistics Canada housing surveys and other available housing databases, and consists of close to 17,000 unique houses representative of the CHS. CHREM consists of six components that work together to provide predictions of the end-use energy consumption and GHG emission of the CHS. These components are:

- The Canadian Single-Detached & Double/Row Housing Database (Swan *et al.*, 2009),
- A neural network model of the appliances and lighting (AL) and DHW energy consumption of Canadian households (Swan *et al.*, 2011),
- 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 (Farhat & Ugursal, 2010),
- A model to estimate GHG emissions from fossil fuels consumed in households.

As shown in Figure 2, the energy savings and GHG emissions reductions associated with any energy efficiency upgrade or renewable/alternative energy technology, such as heat pump systems, can be estimated using CHREM as follows:

(i) Identify houses suitable to receive the upgrade/technology: For AWHP system retrofit, only houses with a basement or a mechanical room would be suitable. Therefore, a search has to be conducted in the CSDDRD to identify such houses.

(ii) Modify the input files of the selected houses to add the upgrade/technology for use in the ESP-r energy simulations.

(iii) Estimate the energy consumption and GHG emissions reductions (or increases) of the CHS with the adopted upgrade/technology by comparing the energy consumption and GHG emissions with the “base case” (i.e. current) values. The change in GHG emissions due to a change in electricity consumption is estimated using the marginal GHG emission intensity factors given by Farhat and Ugursal (Farhat & Ugursal, 2010). Since CSDDRD is representative of the CHS, the CHREM estimates can be extrapolated to the entire CHS using scaling factors (Swan, 2010; Swan *et al.*, 2013).

CHREM determines the associated GHG emission due to onsite fossil fuel and electricity consumption separately for each province of Canada[1] due to the vast differences in the fuel mix used. GHG emissions are calculated and reported as “equivalent CO_2” (CO_{2e}) emitted per unit input energy. CO_{2e} is calculated by converting all GHG emissions from fossil fuel combustion, such as CH_4 and N_2O, to equivalent CO_2 emissions taking into account their global warming potentials (Farhat & Ugursal, 2010; Swan *et al.*, 2013).

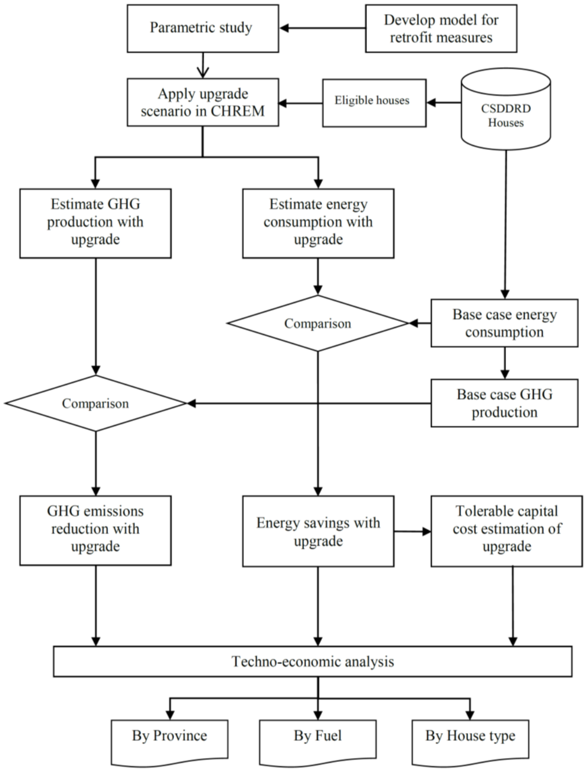

Figure 2. Workflow of CHREM (Nikoofard *et al.*, 2014a)

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[1] Provinces of Canada, from east to west, are: Newfoundland and Labrador (NF), Prince Edward Island (PE), Nova Scotia (NS), New Brunswick (NB), Quebec (QC), Ontario (OT), Manitoba (MB), Saskatchewan (SK), Alberta (AB), and British Columbia (BC). NF, PE, NS and NB are collectively referred to as Atlantic Provinces (AT) while MB, SK and AB are referred to as Prairie Provinces (PR).

Table 1. The average and marginal GHG emission intensity factors (g CO_{2e}/kWh) for each province of Canada (Farhat & Ugursal, 2010)

Electrical generation characteristics		Canadian provincial GHG EIF (CO_{2e} per kWh)									
		NF	NS	PE	NB	QC	OT	MB	SK	AB	BC
Annual $EIF_{Average}$		26	689	191	433	6	199	13	789	921	22
Annual $EIF_{Marginal}$		22	360	6	837			1	225		18
Monthly $EIF_{Marginal}$	Jan					23	395			825	
	Feb					0	352			825	
	Mar					0	329			795	
	Apr					0	463			795	
	May					0	501			795	
	Jun					0	514			780	
	Jul					0	489			780	
	Aug					0	491			780	
	Sep					0	455			780	
	Oct					0	458			795	
	Nov					0	379			825	
	Dec					4	371			825	
Transmission and distribution losses		9%	4%	6%	6%	4%	6%	12%	6%	4%	3%

The AWHP model used in this work was developed and added to the ESP-r plant components by Kelly and Cockroft (Kelly & Cockroft, 2011). This model incorporates three control volumes, calculates the COP of the heat pump and compressor power consumption based on the ambient temperature, return water temperature and the control signal. The total power use of the heat pump is the cumulative power consumption of compressor and auxiliary components. The empirical expressions used for the COP and compressor power consumption of an AWHP are given in Equations (1) and (2):

$$COP=a_0+a_1(T_r-T_{amb})+a_2(T_r-T_{amb})^2 \tag{1}$$

$$P_C=b_0e^{b_1(T_r-T_{amb})} \tag{2}$$

where T_r, T_{amb} and P_C represent the return water temperature, ambient temperature and compressor power consumption (kW), respectively.

The boiler model that was developed and added to the ESP-r plant domain by Hensen (Hensen, 1991) is used. The model can be used for both non-condensing and condensing auxiliary boilers. The governing equations, including conservation of mass and energy, are solved in each time step. The heat supply of the boiler is determined based on the fuel consumption, fuel heating value and boiler efficiency. Boiler efficiency is defined as a function of the return water temperature, which is a proxy for the load on the boiler.

The thermal storage tank model developed and incorporated into the ESP-r by Thevenard and Haddad (Thevenard & Haddad, 2010) is used. The model represents a stratified tank with two immersed heat exchangers. The tank is divided into *N* control volumes and mass and energy balance equations are solved for each control volume. The energy balance equation for each control volume considers heat losses to the environment, convection and conduction heat transfer with the adjacent control volumes as well as heat transfer due to water flow at inlet/outlet, where applicable.

A one-diode circuit model PV model that was added to the ESP-r by Mottillo, et al. (Mottillo *et al.*, 2006) is used in this study. A special material on the outermost surface of roof is defined to represent the PV modules. The PV power output is estimated based on the modules characteristics, insolation and actual PV temperature. Generated electricity is supplied to the electricity network in the house. In case the PV electricity generation exceeds the building demand, the surplus electricity is exported to the grid.

Instantaneous GHG emissions due to onsite fuel consumption is calculated in each time step based on the fuel type and efficiency of the energy conversion device. The emission of CO_2 due to wood combustion is not accounted for in this study because it is assumed that combustion of wood returns to the atmosphere the CO_2 that was recently removed by photosynthesis as the trees grew (Farhat & Ugursal, 2010).

To evaluate the GHG emissions related to electricity consumption, the GHG emission intensity factor (EIF) is used. The GHG EIF is the level of CO_2 emissions generated for the generation and delivery of one kWh electricity to the end-user. In Canada electricity generation is under the jurisdiction of provincial utility companies. Thus, provincial GHG EIF is defined based on the primary energy mixture used for electricity generation and efficiency of energy conversion as well as transmission and distribution losses. Also, typically utilities consider different types of technologies for peak and base electricity generation. Thus, different average and marginal GHG EIFs associated with base and peak electricity generation are required. The provincial average and marginal GHG EIF developed by Farhat and Ugursal (Farhat & Ugursal, 2010) and given in Table 1 are used. Average GHG EIFs are used to estimate the emissions due to electricity consumption of the existing housing stock (base case) while the marginal GHG EIFs are used to estimate the GHG emission variation due to the change in electricity consumption in retrofitted houses.

A basement or a mechanical room is necessary to install an AWHP system into a house. While the presence of a basement is noted in the CHREM database, the presence of a mechanical room is not. Therefore, it is assumed in this work that all houses that either have a basement or a heating system that requires a mechanical room are suitable for AWHP retrofit. Based on this assumption, all houses that use natural gas (NG) or oil for space heating are considered to be eligible for the AWHP retrofit. Depending on the type of heating system and the presence of a basement, some houses that use wood or electricity are also eligible for the AWHP retrofit.

Only houses with available roof toward south, south-east or south-west can receive the PV upgrade. Thus, eligible houses for AWHP retrofit that satisfy this condition can receive both AWHP and PV retrofits. The CSDDRDD was scanned to identify houses that satisfy both eligibility conditions.

RESULTS AND DISCUSSION

The CHREM estimates of the current energy consumption and GHG emissions of the CHS are given in Table 2. Swan et al. evaluated the validity of these results by comparing them with other estimates of Canadian residential energy consumption (Swan *et al.*, 2013).

Using the criteria given in previous Section, eligible houses for the AWHP+PV retrofit in CHREM were identified. The percentage of houses eligible for the retrofit in each province is shown in Table 3. As shown in Table 3, about 23 percent of the houses in CHREM, representing approximately 2.1 million existing houses in the CHS are eligible for the AWHP+PV retrofit. After identifying the eligible houses for the AWHP+PV retrofit, CHREM was updated to reflect the AWHP+PV retrofit in these houses and simulations were carried out to evaluate the energy savings and GHG emission reduction due to the retrofit.

End-use energy saving due to AWHP+PV retrofit in all eligible houses is 203.6 PJ (equivalent of 16%) which results in a 12% reduction (7.95 Mt of CO_{2e}) in the annual GHG emissions of the CHS, as shown in Table 3. The energy savings and GHG emission reductions vary substantially amongst provinces and energy sources. This is discussed in detail below.

Table 2. CHREM estimates of annual energy consumption and GHG emission for the CHS as a function of energy source

	Energy (PJ)					GHG emissions (Mt of CO_{2e})			
Province	Electricity	NG	Oil	Wood	Total	Electricity	NG	Oil	Total
NF	15.2	0.0	9.6	3.3	28.1	0.12	0.0	0.67	0.8
NS	17.7	0.0	22.6	6.0	46.3	3.77	0.0	1.6	5.4
PE	1.8	0.0	4.0	1.5	7.3	0.1	0.0	0.28	0.4
NB	18.7	0.0	9.7	10.7	39.1	2.39	0.0	0.69	3.1
QC	205.3	1.0	30.3	10.4	247.0	0.36	0.05	2.14	2.6
OT	137.2	337.4	47.4	0.0	522.0	8.07	17.12	3.36	28.6
MB	18.9	33.6	0.0	0.0	52.5	0.07	1.7	0.0	1.8
SK	10.6	40.2	0.0	0.0	50.8	2.46	2.04	0.0	4.5
AB	28.3	119.8	0.0	0.0	148.1	7.56	6.08	0.0	13.6
BC	64.6	83.9	0.0	2.1	150.6	0.41	4.25	0.0	4.7
Canada	518.3	615.9	123.6	34.0	1291.8	25.3	31.2	8.7	65.3

Since the existing houses in QC widely use electric baseboard heating systems, it provides the least penetration factor (6%) for the AWHP+PV retrofit. Existing houses in OT are responsible for 40% (522PJ) of national residential energy consumption (1291.8PJ) and about 46% (94.5PJ) of total energy savings (203.6PJ) due to the AWHP+PV retrofit in the existing houses of this province. This is because close to half of the eligible houses for AWHP+PV are located in OT.

To illustrate the suitability of AWHP+PV in each province the average energy savings and GHG emission reductions per house is presented in Table 4. AWHP+PV retrofit yields the highest energy savings in Atlantic provinces. However, due to the large share of coal in the fuel mixture for electricity generation, which causes a relatively high GHG EIF in NS, the GHG emission reduction due to AWHP+PV retrofit in this province is among the lowest in Canada.

The GHG emissions increase as a result of the AWHP+PV retrofit in AB and SK due to the dominant share of fossil fuels in the fuel mixture for electricity production in these two provinces. The highest GHG emission reduction is observed in NF. While a reason for this result is the high energy saving of AWHP+PV retrofit, it is not the only cause. In Atlantic provinces NG is not widely available for residential customers and existing houses use oil for space and DHW heating. Electricity generation in NF is mainly from renewable energy sources (i.e. hydro-electricity). Thus, the AWHP+PV retrofit yields substantial GHG emission reductions in NF by replacing oil consumption with hydro-electricity. Due to the same reason, significant GHG emission reductions occur in QC, OT, MB and BC where carbon free energy sources are used for a large proportion of electricity production. Since in these provinces NG is the fuel source for space and DHW heating, the relative magnitude of GHG emission reductions is less significant compared to its value in NF.

The energy consumption estimates before and after the AWHP+PV retrofit are presented in Table 4. As shown in Table 4, total current energy consumption in houses eligible for the retrofit (320.6PJ) is about 25% of the total energy consumption of the CHS (1291.8PJ as shown in table 2). Since electricity based space heating systems (e.g. baseboard convection units) are usually installed in the living space and do not utilize a central mechanical and heat delivery system, houses that use electricity for space heating purposes cannot satisfy the eligibility condition for the AWHP retrofit. Thus, the electricity consumption in eligible houses before the AWHP+PV retrofit is 73.7PJ, which is about 14% of the current electricity consumption in the CHS. Once these houses receive the retrofit, their electricity consumption increases due to the HP electricity use to 114.9PJ (56% higher compared to its existing value) in spite of the electricity produced by the PV systems. This indicates that the PV systems are not able to deliver the total electricity demand of the AWHP system.

Both oil and NG consumption values across Canada substantially decrease due to AWHP+PV retrofit. Although the AWHP+PV system includes an oil or NG burning auxiliary system, the oil and NG consumption after the retrofit is negligible in the houses eligible for the retrofit, indicating that these auxiliary systems are rarely needed as the heat pump is capable of supplying the energy required for space and DHW heating. Thus, the AWHP system is an effective option to significantly reduce fossil fuels consumption in the CHS. As shown in Table 4, over 20 percent of wood consumption in the CHS is reduced due to AWHP+PV retrofit, but this has no effect on the GHG emissions.

The annual energy savings and GHG emission reductions due to AWHP+PV retrofit are given in Table 5. Electricity consumption increases in all provinces excluding QC due to the electricity usage of the heat pumps. In QC many houses use electric resistance heating systems for DHW heating. Thus, retrofitting these existing DHW heating systems with AWHP+PV systems reduce electricity consumption. Electricity consumption of AL and heat pump system as well as electricity generation of PV system in houses eligible for the AWHP+PV upgrade are given in Table 6. The GHG emission reductions (shown by negative values) associated with PV electricity generation is determined based on the marginal GHG EIF.

The total electricity generation of PV systems is about 31 percent (25PJ) of the electricity consumption of heat pump systems (81.4PJ) in the houses eligible for the retrofit. PV electricity generation results in close to 35 percent (2.764Mt of CO_{2e}) reduction of total GHG emissions (7.95 Mt of CO_{2e}). The impact of PV electricity generation on GHG emissions of household is less significant in provinces where hydro-electricity provides the significant part of electricity supply (i.e. NF, QC, MB and BC). Thus, although the AWHP+PV system retrofit would reduce the energy consumption and GHG emissions of houses that are eligible for this retrofit, the reductions will not be sufficient to reach NZE status.

Table 3. AWHP+PV retrofit penetration levels and resulting energy savings and GHG emission reductions in the CHS

Province	Eligible houses		Total energy saved (PJ)	Average energy saving per house (GJ)	Total GHG reduced (Mt)	Average GHG reduction per house (kg)
	Number	Percent				
NF	35,566	20%	4.5	127	0.25	7,029
NS	87,949	29%	9.2	105	0.28	3,185
PE	23,397	52%	2.5	105	0.12	5,327
NB	50,512	21%	6.7	133	0.28	5,496
QC	119,650	6%	11.1	93	0.65	5,408
OT	938,904	27%	94.5	101	5.77	6,149
MB	80,628	24%	7.5	93	0.52	6,499
SK	119,382	38%	11.8	99	-0.40	-3,335
AB	339,423	35%	31.7	93	-0.78	-2,294
BC	263,845	24%	24.0	91	1.25	4,731
Canada	2,059,255	23%	203.6		7.95	

Since the fossil fuel consumption is negligible in houses eligible for the AWHP+PV retrofit, the objective of achieving or approaching NZE status may be realized by generating additional renewable electricity for heat pump operation, reducing energy demand for space and DHW heating and improving the performance of the AWHP+PV system by integrating the PV modules to building fabric in the form of a building integrated photovoltaic and thermal (BIPV-T) system. The latter requires duct work, which may further increase the cost of the retrofit. Providing additional onsite renewable electricity requires extra PV module installation on building site, a measure that may not be economically or practically feasible in high density urban areas where real state is limited and/or expensive.

Appliance and lighting loads (58.4PJ as shown in Table 6) are responsible for close to half of the electricity consumption in eligible houses after retrofit (114.9PJ as given in Table 4) and 80% of the current electricity consumption of eligible houses (73.7PJ).

Table 4. CHREM estimates of annual energy consumption (PJ) of houses not eligible (N-E) and eligible (EL) for the AWHP+PV retrofit with existing (Exist) and AWHP+PV retrofit (HPV) systems

	Electricity			NG			Oil			Wood			Total		
	N-E	EL		N-E	EL		N-E	EL		N-E	EL		N-E	EL	
Province		Exist	HPV		Exist	HPV		Exist	HPV		Exist	HPV		Exist	HPV
NF	13.4	1.8	2.2	0.0	0.0	0.0	6.0	3.6	0.0	2.0	1.3	0.0	21.4	6.7	2.2
NS	13.9	3.8	5.0	0.0	0.0	0.0	13.2	9.4	0.1	4.9	1.1	0.0	32.0	14.3	5.1
PE	1.0	0.8	1.2	0.0	0.0	0.0	1.7	2.3	0.0	1.0	0.5	0.0	3.6	3.7	1.2
NB	16.3	2.4	3.0	0.0	0.0	0.0	5.7	4.0	0.1	7.3	3.4	0.0	29.3	9.8	3.1
QC	197.9	7.4	6.6	0.7	0.3	0.1	21.2	9.1	0.0	9.3	1.1	0.0	229.2	17.8	6.7
OT	107.1	30.1	50.5	239.0	98.4	0.9	29.9	17.5	0.0	0.0	0.0	0.0	376.0	146.0	51.4
MB	16.6	2.3	5.5	22.8	10.8	0.1	0.0	0.0	0.0	0.0	0.0	0.0	39.4	13.1	5.6
SK	7.5	3.1	7.2	24.2	16.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	31.7	19.1	7.3
AB	18.4	9.9	20.4	77.2	42.6	0.4	0.0	0.0	0.0	0.0	0.0	0.0	95.6	52.5	20.8
BC	52.5	12.1	13.3	58.5	25.4	0.3	0.0	0.0	0.0	2.1	0.0	0.0	113.1	37.5	13.6
Canada	444.6	73.7	114.9	422.4	193.5	1.9	77.7	45.9	0.2	26.5	7.5	0.0	971.2	320.6	117.0

Table 5. Annual energy savings and GHG emission reductions due to AWHP+PV retrofit in the CHS

	Energy savings (PJ)					GHG emission reductions (Mt of CO_{2e})			
Province	Electricity	NG	Oil	Wood	Total	Electricity	NG	Oil	Total
NF	-0.3	0.0	3.6	1.3	4.5	0.00	0.00	0.25	0.25
NS	-1.3	0.0	9.3	1.1	9.2	-0.37	0.00	0.65	0.28
PE	-0.4	0.0	2.3	0.5	2.5	-0.04	0.00	0.16	0.12
NB	-0.6	0.0	3.9	3.4	6.7	0.00	0.00	0.28	0.28
QC	0.7	0.2	9.1	1.1	11.1	0.00	0.01	0.64	0.65
OT	-20.4	97.5	17.5	0.0	94.5	-0.38	4.93	1.23	5.77
MB	-3.2	10.7	0.0	0.0	7.5	-0.02	0.54	0.00	0.52
SK	-4.0	15.9	0.0	0.0	11.8	-1.20	0.80	0.00	-0.40
AB	-10.5	42.2	0.0	0.0	31.7	-2.91	2.14	0.00	-0.78
BC	-1.1	25.1	0.0	0.0	24.0	-0.02	1.27	0.00	1.25
Canada	-41.2	191.6	45.7	7.5	203.6	-4.95	9.69	3.21	7.95

Also, GHG emission (5.61 Mt of CO_{2e}) associated with energy consumption by AL is about 70 percent of the total GHG emission reduction (7.95 Mt of CO_{2e}) due to the AWHP+PV retrofit. Thus a significant step to approach net/near zero energy status for existing Canadian houses is to reduce the AL loads by encouraging homeowners to replace old AL with the high energy efficient ones through governmental incentives and subsidies.

Table 6. Electricity consumption of AL and heat pump (HP) and electricity generation of PV modules and associated GHG emissions in houses eligible for the AWHP+PV retrofit

	Electricity (PJ)			GHG emission (Mt of CO_{2e})		
Province	PV	AL	HP	PV*	AL	HP
NF	0.5	1.3	1.4	-0.003	0.01	0.01
NS	1.0	2.9	3.1	-0.103	0.62	0.66
PE	0.3	0.7	0.8	-0.001	0.04	0.04
NB	0.7	1.5	2.3	-0.175	0.19	0.29
QC	1.5	3.0	5.1	-0.001	0.01	0.01
OT	10.8	23.6	37.8	-1.450	1.38	2.22
MB	0.9	1.8	4.6	-0.000	0.01	0.02
SK	1.6	2.8	5.9	-0.104	0.66	1.37
AB	4.0	9.9	14.4	-0.908	2.61	3.84
BC	3.7	10.9	6.0	-0.019	0.08	0.04
Canada	25.0	58.4	81.4	-2.764	5.61	8.5

* GHG emission reductions

CONCLUSION

The impact of air to water heat pump and photovoltaic retrofit under net metering condition on the energy consumption and GHG emissions of the Canadian housing stock is presented and discussed. The AWHP system supplies thermal energy for space and domestic hot water heating while the renewable electricity generated by the PV is either used for heat pump system operation or to satisfy the appliance and lighting load. The Canadian Hybrid Residential End-use Energy and Emission model is used to conduct the study. The heat pump system components are modeled in ESP-r. The building performance simulation analysis conducted before and after retrofit, and estimates of annual energy consumption and GHG emission are compared. The results indicate that:

- About 23% of existing Canadian houses are eligible for AWHP+PV retrofit,
- AWHP+PV system retrofits in the existing houses yield 203.6PJ (16%) and 7.95 Mt of CO_{2e} (12%) of energy savings and GHG emission reductions in the CHS,
- Overall electricity consumption increases due to retrofit in all provinces excluding QC,
- Fossil fuel consumption (i.e. NG and heating oil) is reduced close to zero due to the AWHP+PV retrofit in all eligible houses,
- PV electricity generation can supply 31% of the AWHP electricity demand,
- While energy consumption and GHG emission significantly reduced due to AWHP+PV

retrofit in the houses that received the retrofit, the reduction is not sufficient to convert them to the NZEB, and further energy conservation and renewable energy supply options are needed,

- Appliance and lighting loads are about half of electricity consumption in eligible houses after retrofit; thus, improving electricity efficiency of appliances and lighting is necessary to approach net zero energy status for the existing houses in Canada.

This study is a part of the efforts to develop strategies, approaches and incentive measure to approach net/near zero energy status for existing Canadian houses. Comprehensive strategies will be developed using studied technologies including envelope modifications such as glazing and window shading upgrades, as well as installation of solar domestic hot water systems, phase change material thermal energy storage, internal combustion engine and Stirling engine based cogeneration systems, solar combisystem, solar assisted heat pump and building integrated photovoltaic thermal systems.

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NOMENCLATURE

AL	Appliance and lighting
ASHP	Air source heat pump
AWHP	Air to water heat pump
BIPV-T	Building integrated photovoltaic and thermal
CHREM	Canadian hybrid residential end-use energy and emission model
CHS	Canadian housing stock
COP	Coefficient of performance
CSDDRD	Canadian single detached and double/row houses database
DHW	Domestic hot water
EIF	Emission intensity factor
GHG	Greenhouse gas
ICE	Internal combustion engine
NG	Natural gas
NZE	Net Zero Energy
P_C	Compressor power consumption
PCM	Phase change material
PV	Photovoltaic
SDHW	Solar domestic hot water
SE	Stirling engine
SNEBRN	Smart Net-zero Energy Buildings Strategic Research Network
T_{amb}	Ambient temperature
T_r	Return water temperature

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