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Techno-economic Feasibility Evaluation of Air to Water Heat Pump Retrofit in the Canadian Housing Stock

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Abstract

This study was conducted to assess the techno-economic feasibility of converting the Canadian housing stock (CHS) into net/near zero energy buildings by introducing and integrating high efficient and renewable/alternative energy technologies in new construction and existing houses. Performance assessment of energy retrofit and renewable/alternative energy technologies in existing houses in regional and national scale is necessary to devise feasible strategies and incentive measures. The Canadian Hybrid Residential End-Use Energy and GHG Emissions model (CHREM) that utilizes a bottom-up modeling approach is used to investigate the techno-economic feasibility of air to water heat pump retrofit in the Canadian housing stock. The proposed energy retrofit includes an air to water heat pump, auxiliary boiler, thermal storage tank, hydronic heat delivery and domestic hot water (DHW) heating. Energy savings, GHG emission changes and economic feasibility of the air source heat pump retrofit are considered in this study. Results show that there is a potential to reduce 36% of energy consumption and 23% of GHG emissions of the CHS if all eligible houses undertake the retrofit. Economic analysis indicates that the feasibility of air to water heat pump systems is strongly affected by the current status of primary energy use for electricity generation and space and DHW heating as well as energy prices and economic conditions. Legislation, economic incentives and education for homeowners are necessary to enhance the penetration level of air to water heat pump retrofits in the CHS.

Keywords: Air to water heat pump**,** Canadian residential energy use, Canadian residential GHG emissions, Energy modeling

Highlights

- Techno-economic feasibility of air to water heat pump is assessed for Canadian houses.
- A state-of-the-art housing stock model is used for techno-economic analysis.
- AWHP retrofit reduced 36% of end-use energy consumption in the Canadian housing stock.
- AWHP retrofit decreased 23% of GHG emission of the Canadian housing stock.
- Aerothermal energy captured by HP can be assumed as renewable energy in most provinces

Nomenclature

ACSH	Annual cost savings for the house due to energy savings in a uniform series, continuing for *n* periods ($/year)
ATTCCH	Average tolerable capital cost per house ($)
CO_{2e}	Equivalent CO_2 emitted per unit input energy (kg/kWh)
c	Specific heat (kJ/kgK)
E	Energy saving per period for each fuel type (unit depends on fuel type)
E_{RES}	Thermal energy considered from renewable sources (PJ)
e	Fuel cost escalation rate (decimal)
F	Fuel price per unit of each fuel type ($/unit)
h_{store}	Storage tank height (m)
K_{AB}	Heat exchange coefficient between water and working fluids (kW/K)

i	Interest rate (decimal)
M	Mass of control volume (kg)
$\dot{m}$	Mass flow rate (kg/s)
NH	Number of houses that received the upgrade
n	Acceptable payback period (year)
P_C	Compressor power (kW)
$P_{el,pump.SH}$	Pump power in space heating loop (W)
$P_{el,pump.DHW}$	Pump power in DHW loop (W)
$P_{nom,burner}$	Nominal power of auxiliary boiler (W)
Q_{usable}	Gross final thermal energy delivered by heat pump (kJ)
RH_{amb}	Relative humidity of ambient air (%)
SPF	Seasonal performance factor
TCC	Tolerable capital cost ($)
TCCH	Tolerable capital cost of the retrofit for the house ($)
T_{amb}	Ambient temperature (K)
T_c	Reference temperature for boiler efficiency (K)
T_r	Return water temperature (K)
t_{def}	Defrost time (s)
t_{tr}	Duration of transient operation of boiler (s)
UA	Heat loss coefficient (kW/K)
V_{store}	Storage tank volume (m^3)

Greek letters

η	Ratio between total gross production of electricity and the primary energy consumption for electricity generation
η_b	Boiler efficiency (%)
η_0	Full load boiler efficiency at the reference temperature (%)
φ	Slope of the boiler efficiency curve (degree)
Δt	Simulation time step (s)

Abbreviations

AB	Alberta
AL	Appliances and lighting
ASHP-WH	Air source heat pump water heating
AT	Atlantic Provinces
AWHP	Air to water heat pump
BC	British Columbia
CHREM	Canadian Hybrid Residential End-Use Energy and GHG Emissions model
CHS	Canadian housing stock
COP	Coefficient of performance
CSDDRD	Canadian Single-Detached Double/Row Database
DHW	Domestic hot water
EIF	Emission intensity factor
GHG	Greenhouse gas
ICE	Internal combustion engine
MB	Manitoba
NB	New Brunswick

NF	Newfoundland and Labrador
NG	Natural gas
NS	Nova Scotia
NZEB	Net zero energy building
OT	Ontario
QC	Quebec
PCM	Phase change material
PE	Prince Edward Island
PR	Prairie Provinces
SDHW	Solar domestic hot water
SE	Stirling engine
SK	Saskatchewan
SNEBRN	Smart Net-Zero Energy Buildings Strategic Research Network

1. Introduction

Shrinking the energy footprint of residential buildings is a promising option to reduce national greenhouse gas (GHG) emissions. While developing and implementing improved building codes for new construction is necessary, it is not sufficient to achieve this goal. A housing policy with focus on retrofitting existing houses is an essential part of a strategic plan to reduce the GHG emissions associated with the housing stock [1]. While the most feasible and effective retrofit options might be improving building skin, installing high efficiency heating systems and incorporating renewable energy systems [2], adding an air to water heat pump (AWHP) system to a house could also be a suitable option to reduce energy consumption [3]. AWHP system can provide space and domestic hot water (DHW) heating energy requirement from a single source.

While the AWHP system is well established in Europe and Japan, it is relatively new to the Canadian market [4]. Thus, an accurate and comprehensive study is needed to investigate the feasibility of integrating AWHP systems into the Canadian housing stock (CHS). Recently, such studies have been conducted for various regions of the world. For example, Kelly and Cockroft [5] 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 well representative of the AWHP operating conditions in the field trial. 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. [6] 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 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 in the UK climate. Cabrol and Rowley [7] used a numerical model to study the performance of air source heat pump water heating (ASHP-WH) system with hydronic heat delivery in various UK locations. A sensitivity analysis was conducted to evaluate the impact of the building construction materials and off-peak period operation. The GHG emissions and operating cost of ASHP-WH were found to be lower compared to those of an equivalent size gas boiler, and the annual coefficient of performance (COP) of the ASHP-WH was found to be about 3.5 and 4 for cold and mild UK climates, respectively. Johnson [8] found 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. Using a model for ASHP-WH system model based on measured data from a field trial campaign Madonna and Bazzocchi [9] found that climate has a significant role on the performance of ASHP-WH, and depending on climate, the energy requirement for space heating could be reduced by up to 79% in new buildings in Italy. A study by Hewitt et al. [10] that investigated AWHP retrofit options for existing houses in the UK recommended using variable speed compressor, advanced evaporators and improving heat delivery system to enhance the performance of AWHP in the European maritime climate conditions. Bertsch and Groll [11] designed, simulated, constructed and tested an 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 the low temperature, high lift operation of the heat pump 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. [12] developed a simulation model to study the performance of ASHP-WH 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. Lund et al. [13] 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. Assuming a 75% reduction in space heating demand individual heat pump systems were found to be the best alternative to existing fossil fuel 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 [14].

To achieve substantial reductions in national energy consumption, massive energy retrofits in building stocks are required. The unique challenges that such massive retrofits require have recently been the focus of researchers. For example, Dall'O' et al. [15] presented a method to estimate the energy savings due to retrofitting existing houses in a building stock and applied it for five municipalities in the province of Milan, Italy. Amstalden et al. [16] studied the cost-effectiveness of energy retrofit options from house owners' point of view in the Swiss housing sector, including the effect of various incentives. They concluded that energy price has the most significant impact on the profitability of retrofit options and efficiency retrofits were economically viable with the current energy prices and future energy cost elevations would improve the feasibility of energy retrofits. Tommerup and Svendsen [17] assessed the performance of energy saving measures for existing Danish houses. The study was conducted for two typical buildings and results showed that retrofits were economically viable in 30 years in the presence of sufficient education and training for house owners. Nemry et al. [18] studied the life cycle impact of 72 building types with different construction properties in various geographical locations of European Union countries. The results showed that heating demand was the dominant energy consumption component in the life cycle energy consumption of both existing and new buildings. It was also found that in most buildings at least 20% energy savings were cost effective with infiltration reduction by sealing and additional roof and façade insulation.

In order to focus efforts and resources to reduce residential energy consumption and GHG emissions an accurately designed strategy with specific goals is required. For this purpose, 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 [19-27] as part of a national effort in Canada [28]. In this work, the techno-economic feasibility of AWHP system retrofit in the Canadian housing stock is studied.

2. Methodology

Under the current circumstances where GHG emissions are considered to be as important as energy consumption and costs, the evaluation of the feasibility of an energy retrofit measure for a house has to consider house energy consumption, associated GHG emissions and energy costs before and after the retrofit. To evaluate the feasibility of massive implementation of energy efficient retrofits in a regional or national housing stock, a representative and accurate housing stock model is necessary to predict the system-wide energy savings, emission reductions and economic feasibility. Comprehensive reviews of housing stock models and modeling efforts are presented in Swan and Ugursal [29] and Kavgic et al. [30].

2.1. Housing stock model

In this work the Canadian Hybrid Residential End-Use Energy and GHG Emissions Model (CHREM) [31, 32] is used. CHREM is based on the Canadian Single-Detached Double/Row Database (CSDDRD) [33]. CSDDRD statistically represents the CHS with close to 17,000 unique houses that were extracted from the latest data available from the EnerGuide for Houses database, Statistics Canada housing surveys and other available housing databases.

A high-resolution building energy simulation program ESP-r [34] is used as the simulation engine of CHREM. ESP-r is an integrated modeling tool for evaluation of the thermal, visual and acoustic performance as well as energy consumption and GHG emissions of buildings which employs a finite difference control volume approach for energy simulation. The building domain is discretized into control volumes and each control volume contain finite difference nodes. Control volumes represent a wide range of building components such as air volume in thermal zones, opaque and transparent structures, solid-fluid interfaces and plant components. Governing equations are discretized based on the Crank-Nicolson finite difference method for all nodes in the control volume. The system of algebraic equations is solved using a simultaneous direct solution approach based on matrix partitioning and Gaussian elimination in each time step [35, 36]. The system of linearized mass balance equations is solved using the Newton-Raphson iterative method. ESP-r has been validated through a vast amount of research results [37]. 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 [33],
- A neural network model of the appliances and lighting (AL) and DHW energy consumption of Canadian households [38],
- 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 [39],
- A model to estimate GHG emissions from fossil fuels consumed in households.

The energy savings and GHG emissions reductions associated with any energy efficiency upgrade or renewable/alternative energy technology, such as AWHP 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 [39]. Since CSDDRD is representative of the CHS, the CHREM estimates can be extrapolated to the entire CHS using scaling factors [31, 32].

Since its initial development, the modeling capability of CHREM has been gradually expanded, to include PCM thermal energy storage, SDHW heating system, ICE and SE engine based cogeneration and solar combisystem [19-27].

The schematic of the AWHP retrofit considered in this work for existing houses is given in Figure 1. The system is capable to deliver heat for space and DHW heating. Cooling is not considered in this study because adding an air handling unit to use the chilled water for space cooling purposes will substantially increase retrofit costs to compromise economic feasibility.

Also, an AWHP system cannot provide hot water for DHW heating and chilled water for space cooling simultaneously. Thus only space and DHW heating features are considered for retrofit. To assess the techno-economic feasibility of AWHP integration into the CHS in this work, first an AWHP modeling capability was added to CHREM as discussed in sections 2.2.1-2.2.7. Then a set of criteria was established to identify houses in CHREM that are suitable for AWHP retrofit. These criteria are presented and discussed in Section 2.3. The method used to estimate GHG emissions is presented in Sections 2.4. Methodologies for accounting of renewable energy from heat pump and economic feasibility analysis are elaborated in Sections 3 and 4, respectively.

2.2.1. Air to water heat pump

The AWHP model used in this work was developed and added to the ESP-r plant components by Kelly and Cockroft [5]. This model incorporates three control volumes: a functional volume and two lumped mass volumes as shown in Figure 2. The functional control volume represents the working fluid loop and auxiliary parts, and 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):

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

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

where T_r, T_{amb} and P_C represent the return water temperature (K), ambient temperature (K) and compressor power (kW), respectively. In each time step of the simulation, the COP and P_C are calculated based on the instantaneous water and ambient temperatures. The constants factors (a_0-

$_2$ and $b_{0\text{-}1}$) are derived based on the empirical data of the AWHP and the values used in this work are given in Table 1. The nominal heat supply of the heat pump is then determined as the compressor power consumption multiplied by the COP.

To model the condenser of the AWHP two lumped capacitance control volumes are used. The lumped capacitance volume (A) represents the working fluid side of the condenser and the lumped capacitance volume (B) represents the water side of the condenser. The nominal heat supply of the AWHP is transferred to the lumped capacitance volume (A). Heat losses from the condenser to the environment are considered in the energy balance of lumped capacitance volume (A). Heat transfer between the working fluid and water is estimated by a heat exchange coefficient between lumped mass volumes (A) and (B). The energy balance equations for lumped mass volumes (A) and (B) are given in Equations (3) and (4), respectively:

$$M_A c_A \frac{dT_A}{dt} = P_C \times COP - UA(T_A - T_{amb}) - K_{AB}(T_A - T_B) \quad (3)$$

$$M_B c_B \frac{dT_B}{dt} = K_{AB}(T_A - T_B) - \dot{m} c_w (T_w - T_B) \quad (4)$$

where M is the mass of control volume (kg), c is the specific heat (kJ/kgK), UA is the heat loss coefficient (kW/K), K_{AB} is the heat exchange coefficient between water and working fluids (kW/K) and $\dot{m}$ is the water mass flow rate (kg/s). The values of these parameters used in this work are given in Table 1.

At low ambient temperature and high relative humidity the evaporator coil may operate below the frost temperature of ambient air. Under these circumstances the frost may accumulate on the evaporator coil surface and reduce the heat transfer between refrigerant and the outside air. Thus, the defrost cycle is considered to melt the frost [3]. A defrost algorithm predicts the status of the AWHP in a case that ambient temperature drops below the frost temperature. If the ambient temperature remains below the frost temperature for a long time a defrost lockout duration is considered to dictate an interval between the defrost cycles. If the defrost cycle is turned on the heat supply of heat pump is set to zero. The duration of the defrost cycle is defined using Equation 5.

$$t_{def}=t_0+t_1\times RH_{amb} \quad (5)$$

where t_{def} is the defrost time (s) and RH_{amb} is the relative humidity of ambient air (%). t_0 (s) and t_1 (s/%) are empirical coefficients determined by experimentation. The values used here are given in Table 1. The typical duration of defrost cycle is between 4 to 10 minutes [3].

2.2.2. Auxiliary boiler

The boiler model that was developed and added to the ESP-r plant domain by Hensen [40] 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 control signal that defines the ON/OFF status of the boiler is set the beginning of each time step, and the boiler remains in that status during a time step. In the case that boiler temperature exceeds the maximum allowable temperature limit, the control signal is discarded and boiler is turned off to determine the new boiler temperature for that time step.

The heat supply of the boiler is determined based on the fuel consumption, fuel heating value and boiler efficiency. Boiler efficiency is a function of temperature with the condensing effect considered for gas-fired boilers as shown in Equation 6:

$$\eta_b=\left[\eta_0-\tan\varphi\times(T_c-T_1)\right] \quad (6)$$

where η_b is the boiler efficiency (%), η_0 is the full load boiler efficiency (%) at the reference temperature, φ is the slope of the efficiency curve (%/K), T_c is the reference temperature (K), T_1 is the return water temperature (K). During the start-up and shutdown periods the boiler efficiency is reduced by the $\left(\frac{\Delta t-t_{tr}}{\Delta t}\right)$ factor, where t_{tr} is the duration of transient operation (i.e.

start-up and shutdown) and Δt is the simulation time step (s). For a condensing boiler, the reference temperature is the condensing temperature. The values used a given in Table 1.

2.2.3. Thermal storage tank

The thermal storage tank model developed and incorporated into the ESP-r by Thevenard and Haddad [41] 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.

Asaee et al. [27] used the approach suggested by Weiss [42] to define thermal storage tank size for residential solar combisystems. Since the tank height affects stratification and due to similar temperature ranges found in the thermal storage tanks of solar combisystems and AWHP systems, the same approach is used here to estimate the thermal storage tank height as shown in Equation 7.

$$h_{store}=\max\left[\min\left(2.2,1.78+0.39\ln\frac{V_{store}}{m^3}\right),1.25\right] \tag{7}$$

where h_{store} is the storage tank height (m) and V_{store} is the storage tank volume (m^3).

2.2.4. Heat delivery system

The heat delivery system is assumed to be hydronic, consisting of piping, pumps and radiators. The radiator and pump models developed and added to the ESP-r plant database by Hensen [40] are used. Radiator heat emission is estimated based on the nominal heat emissions at reference conditions and actual temperature conditions of radiator and environment based on radiator type, dimensions, connection method and room characteristics. The electricity consumption of the circulation pump defined based on actual mass flow rate, pressure drop, fluid density and pump efficiency with heat losses from the pump added to the energy balance.

The number of radiators for each thermal zone is chosen to satisfy the design heating load and nominal radiator capacities selected from the Express Radiant Ltd product catalogue [43]. The hot water circulation pump power is estimated using empirical equations that Asaee et al. [27] used to estimate pump power in space and DHW heating loop for solar combisystem applications based on recommendations by Weiss [42]:.

$$P_{el,pump.SH}=90W+2\times10^{-4}P_{nom,burner} \tag{8}$$

$$P_{el,pump.DHW}=49.4W\times\exp\left(0.0083\frac{P_{nom,burner}}{kW}\right) \tag{9}$$

where $P_{el,pump.SH}$ is the pump power in space heating loop (W), $P_{el,pump.DHW}$ is the pump power in DHW loop (W) and $P_{nom,burner}$ is the nominal power of auxiliary boiler (kW).

2.2.5. Domestic hot water system

The AWHP system architecture shown in Figure 1 uses a combination of three-way diverting valve and three-way converting valve to maintain the DHW temperature in the desired range. Since the DHW heating coil is sized for maximum water draw calculated for the house, this architecture prevents overheating the DHW when the water draw is less than the nominal value. To simplify the modeling of this architecture in ESP-r, a fully mixed adiabatic tank with temperature control as shown in Figure 2 is used. As the DHW draw and equivalent main water addition is applied to the adiabatic tank, the tank temperature is maintained in the range of 55±0.5°C by circulating hot water from the thermal storage tank to the adiabatic tank. Thus, the energy balance for the adiabatic tank is the same as for the three-way valve combination.

2.2.6. AWHP system sizing

The nominal capacity of AWHP components are defined based on the existing heating system capacity of individual buildings as shown in Table 1.

Since the goal of this study is to push the CHS towards net zero energy buildings (NZEB) by introducing AWHP retrofit in the existing houses, the COP and power consumption profile are derived for the AWHP systems that represents the most efficient technologies available in the market that fits the Canadian climatic conditions. For this purpose a series of AWHP systems from different manufacturers including Mitsubishi electric, Toshiba, Viessmann, Fujitsu and Stiebel Eltron are reviewed [44-48]. The COP range reported by the manufacturers for those AWHP systems is presented in Figure 3. The size and performance parameters of the AWHP units used in this work are based on the Viessmann Vitocal 350-A as given in Table 1. Operating temperature, heating capacity and COP of Vitocal 350-A AWHP system is in the similar range with other reviewed products. All of these systems can operate in the Canadian Climatic conditions. The cut-out temperature for the AWHP system is -15°C. The control system deactivates the AWHP at ambient temperature below the cut-out temperature and reverts to the back-up system. The AWHP size for each house is selected such that the AWHP is capable of satisfying major part of the design heating load. The capacity of the thermal storage tank is chosen such that the tank can store the heat generated by the AWHP during a 30 minute long operation at its maximum output. The fuel used in the auxiliary heating system is chosen based on the availability of natural gas. Thus, natural gas (NG) fired boilers are assumed to be the auxiliary heating system in every region of Canada except in the Atlantic region where oil fired boilers are used. The nominal capacity of auxiliary heating system is chosen to be equal to the AWHP nominal capacity [49, 50].

2.2.7. Control algorithms

Control algorithms for the AWHP system include the loops that operate the heat pump, auxiliary boiler and pumping system according to the space and DHW temperatures. The detailed control loop data are presented in Table 2.

Space and DHW heating are supplied in two stages. The first stage is supplied by the heat pump and the second stage is by auxiliary heat. Due to this dual mode of operation, the water supply to the space heating radiators is between 50°C and 55°C; i.e. the circulation pump is turned on when the temperature drops to 50°C and turned off when the temperature reaches 55°C.

The first control loop operates the AWHP to heat the water up to 50°C. The second loop operates the auxiliary heater. The 50°C hot water leaving the AWHP is heated by the boiler to a maximum 55°C. With this control scheme, it is ensured that the auxiliary heating system is operated only when the AWHP is not capable of meeting the demand.

The third control loop maintains the DHW temperature in the adiabatic tank in the range of 55±1°C by running the DHW pump while the fourth loop controls the DHW draw and equivalent main water supply to the adiabatic tank.

Fifth loop controls the zone temperature by maintaining the space heating pump operation. CHREM provides for four space conditioning periods (winter - heating only, summer - cooling only, and shoulder seasons - heating/cooling are both available). However, since cooling is not available, two periods are used in this work as shown in Table 2:

- September 17 to June 3: heating available,
- June 4 to September 16: heating not available.

During the heating period the space heating pump is controlled to maintain the main zone temperature in the range of 20–22°C. The main-slave control strategy is used for temperature control of other zones excluding the attic which is not conditioned. Since attic is free ventilated, its temperature follows the ambient temperature.

2.3. Methodology to select eligible houses for the AWHP system retrofit

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 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 retrofit. The percentage of houses eligible for the retrofit in each province of Canada[1] is shown in Table 8.

2.4. Estimation of GHG emissions

CHREM determines the associated GHG emission due to onsite fossil fuel and electricity consumption separately for each province 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 as shown in Equation 10 [32, 39].

$$CO_{2e}=CO_2+25CH_4+298N_2O \tag{10}$$

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

[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).

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 tree grew [39].

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 (kg/kWh) 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 [39] and given in Table 3 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.

3. Accounting of renewable energy from heat pump

European Parliament and Council in the Directive 2009/28/EC [14] identified the gross final consumption of energy from renewable resources as the summation of (a) gross final electricity consumption, (b) heating and cooling gross final energy use and (c) gross final energy use for transportation from renewable sources. In accordance to part (b) aerothermal, geothermal and hydrothermal energy of heat pump can be assumed as renewable energy in a case that final gross thermal energy production significantly exceeds the primary energy consumption for the heat pump operations. For this purpose the European Parliament and Council Directive 2009/28/EC introduced Equation 11 to define the amount of renewable thermal energy captured by heat pumps.

$$E_{RES}=Q_{usable}\times\left(1-\frac{1}{SPF}\right) \qquad (11)$$

where E_{RES} is the thermal energy considered from renewable sources (kJ), Q_{usable} is the gross final thermal energy delivered by heat pump (kJ) and SPF is the average seasonal performance factor. SPF is defined as the ratio of the delivered heat to the electricity consumption of the heat pump. To fulfill the above mentioned criterion (part (b)) the following condition is defined to identify eligible heat pumps:

$$SPF>1.15\times {}^{1}/_{\eta} \qquad (12)$$

where η is the ratio between total gross production of electricity and the primary energy consumption for electricity generation. Asaee et al. [24] evaluated provincial efficiency of utility electricity generation, inclusive of transmission and distribution losses, from fossil fuels. In each province the electricity generation is from a mixture of fossil fuels and renewable resources. To obtain the reference efficiency that represents the total gross electricity production, the efficiency of electricity generation from fossil fuels is divided by the fossil fuel contribution in the fuel mixture for utility electricity generation. The reference efficiency is therefore in the range of 0 to 1. In the case that the electricity generation exceeds the primary energy consumption due to a vast electricity production from non-fossil fuel sources the reference efficiency value is set to 1. The provincial fossil fuel contributions and reference efficiencies are given in Table 4.

4. Economic analysis based on tolerable capital cost

Accurate estimation of AWHP system capital costs, at residential as well as commercial scale, is difficult because installed costs can vary significantly depending on the scope of the plant equipment, geographical area, competitive market conditions, special site requirements, and prevailing labor rates. Therefore the purchase and installation costs of AWHP systems in Canada vary substantially from manufacturer to manufacturer and location to location. Thus, it is not practicable to estimate realistic total investment costs for AWHP systems and to conduct a conventional economic feasibility analysis. Therefore, an alternative approach to conventional economic feasibility analysis is adopted here which involves the calculation of the "tolerable capital cost" (TCC) of the upgrades [51]. TCC is the capital cost for an energy saving upgrade that will be recovered based on the annual savings, the number of years allowed for payback, and the estimated annual interest and fuel cost escalation rates. Thus, to estimate the tolerable capital cost of the AWHP upgrade a reverse payback analysis is conducted as follows:

1. The annual fuel and electricity savings for each upgrade is estimated (C$).
2. A realistic cost of money (interest rate) for residential customers borrowing money to finance the retrofit is assumed.
3. A realistic fuel cost escalation rate for fuels and electricity is assumed.
4. A realistic payback period that would be acceptable for the residential customer is assumed.
5. A reverse payback analysis is conducted to determine the tolerable capital cost of the upgrade for each house (TCCH) that will result in the assumed payback period:

$$TCCH=\begin{cases} ACSH\left[\frac{1-(1+e)^{n}(1+i)^{-n}}{i-e}\right] & \text{for} \quad i\neq e \\ ACSH\times n(1+i)^{-1} & \text{for} \quad i=e \end{cases} \quad (13)$$

$$ACSH=\sum_{j=1}^{m}(F\times E)_j \quad (14)$$

where:

TCCH	Tolerable capital cost of the retrofit for the house (C$)
n	Acceptable payback period (year)
i	Interest rate (decimal)
e	Fuel cost escalation rate (decimal)
ACSH	Annual cost savings for the house due to energy savings in a uniform series, continuing for n periods (C$)
E	Energy saving per period for each fuel type (unit depends on fuel type; kg, liter, kWh, etc.)
F	Fuel price per unit of each fuel type (C$/unit)
m	Number of different fuels used in a house

The additional maintenance cost of the AWHP system over and above that of the replaced system is assumed to be included in the TCC as a present value of the annual maintenance cost over the lifetime of the AWHP system.

It is not useful or practical to report the TCC for each house in the CSDDRD, or for that matter within the CHS, because from a macro level of interest, data on individual houses have no utility. Thus, the "average tolerable capital cost per house" (ATCCH) is used to evaluate the economic feasibility of the AWHP system retrofit. ATCCH is calculated by dividing the total tolerable capital cost by the number of houses:

$$ATCCH = TTCC/NH \qquad (15)$$

where, TTCC is the total tolerable capital cost as a result of the AWHP system upgrade (C$), calculated as follows:

$$TTCC = \sum_{i=1}^{NH} TCCH_i \qquad (16)$$

NH = number of houses that received the upgrade.

To take into consideration the uncertainty associated with the future of interest and fuel price escalation rates, a sensitivity analysis was conducted. The interest rates used in the analysis are based on the Bank of Canada Prime Rate [52], which was about 1% in June, 2015. Thus, for the sensitivity analysis, interest rates of 3%, 6% and 9% are used. These numbers were selected based on the range of consumer loan rates.

For each province, fuel prices for residential customers for natural gas, heating oil, electricity and wood were obtained to calculate the energy cost savings due to retrofits. The fuel prices that are used in this study are presented in Table 5 [53, 54].

For each fuel type, a set of low, medium and high fuel cost escalation rates shown in Table 6 are used in the sensitivity analysis. These values are based on the medium rates extracted from the National Energy Board of Canada [55] and Energy Escalation Rate Calculator [56].

Payback periods of six and ten years are used in the sensitivity analysis. Both values are comfortably within the economical lifetime of 15 to 20 years for AWHP systems reported by Natural Resources Canada [57].

It is likely that an AWHP retrofit would increase the market value of a house. However, the estimation of the increase in market value due to such a retrofit is not straightforward due to a number of reasons including buyer perception and sophistication, market forces, and energy prices. Due to the complex nature of the impact of upgrades on the market value of a house this issue was not considered in this work.

5. Results and discussion

The CHREM estimates of the current energy consumption and GHG emissions of the CHS are given in Table 7. Swan et al. [32] verified the validity of these results by comparing them with other estimates of Canadian residential energy consumption.

Using the criteria given in Section 2.3, eligible houses for the AWHP retrofit in CHREM were identified. As shown in Table 8, about 71 percent of the houses in CHREM, representing approximately 6.3 million existing houses in the CHS are eligible for the AWHP retrofit. After identifying the eligible houses for the AWHP retrofit, CHREM was updated to reflect the AWHP retrofit in these houses and simulations were carried out to evaluate the energy savings and GHG emissions reduction due to the retrofit. As shown in Table 8, results indicate that 460.5 PJ end-use energy and 15.16 Mt of GHG associated emissions would be saved by retrofitting all eligible houses in the CHS by AWHP systems. Also as shown in Table 8, the energy savings and GHG emission reductions vary substantially amongst provinces. This is discussed in detail below.

5.1. Energy savings

The existing annual energy consumption and energy consumption with the AWHP retrofit are given in Table 9 for each province, disaggregated according to the heating fuel used. As discussed in Section 2.3, whereas all houses that use NG or oil are eligible for the retrofit, only a portion of the houses that use electricity and wood are eligible. Thus, the energy consumption of the houses that are not eligible for the retrofit is shown separately in Table 9.

Since AWHP compressors use electricity, the electricity use in all houses that receive the AWHP retrofit increase. This increase translates to an increase in the electricity consumption of retrofitted houses by 188.8 PJ (as shown in Table 10), or close to 85%, from 224.5 PJ to 413.3 PJ. This represents an increase of about 36% in the current electricity consumption of the CHS (518.3 PJ as shown in Tables 7 and 9). The increase in the electrical consumption is beneficial in reducing primary energy consumption in provinces where renewable resources are the main source of electricity generation including NF, QC, MB and BC. However, in provinces that utility electricity generation heavily relies on fossil fuel thermal power plants, AWHP retrofit may not significantly affect primary energy savings.

The average SPF and thermal energy from renewable sources of heat pumps (E_{RES} as shown in Equation 11) are given in Table 11. The SPF is calculated using the average value of SPF in individual houses in each province. Comparing the SPF of AWHP and reference efficiencies of electricity generation (given in Table 4) based on the European Parliament and Council Directive 2009/28/EC guidelines indicate that heat generation of AWHP can be considered as renewable energy in Canada except in provinces that electricity generation is significantly from fossil fuel resources (NS, NB, PE, SK, and AB). About 91%, 64%, 64%, 78% and 96% of electricity generation is from fossil fuels in NS, NB, PE, SK and AB, respectively. Thus, thermal energy from renewable sources (E_{RES}) is not calculated for theses provinces. It should be noted that E_{RES} only includes the amount of thermal energy captured from the ambient that can be considered as renewable energy. However, in cases that electricity generation is mainly from renewable resources (such as NF, QC, MB and BC) the total gross heat delivered (Q_{usable}) by the heat pump is renewable energy. Results indicate that AWHP capture about 130.9 PJ additional renewable energy, equivalent to 10% of the total existing energy consumption of the CHS (1291.8 PJ as shown in Table 7).

An AWHP system utilizes an auxiliary heating system that uses NG or oil as fuel source. However, the NG and oil consumption is drastically reduced in eligible houses due to AWHP retrofit. Thus, the current end-use energy consumption of eligible houses (981.3 PJ as shown in Table 8) is reduced by about 47% due to AWHP retrofits (520.8 PJ as shown in Table 8). However, the primary energy use increases in provinces with relatively low reference efficiency of electricity generation, i.e. in NS, NB, PE, SK and AB.

Annual end-use energy savings due to AWHP upgrade is summarized in Table 11. AWHP retrofit yields 36% energy savings in the CHS. The lowest energy savings is associated with QC because of the small penetration level of AWHP system in this province (19% houses in QC are eligible). On the other end of the spectrum, the penetration level of AWHP system is above 90%

in OT, SK and AB (as shown in Table 7) resulting in more than 40% energy savings in these provinces.

5.2. GHG emissions reduction

The GHG emission reductions due to AWHP retrofit in all eligible houses based on the energy source in each province are presented in Table 10.

As to be expected, GHG emissions associated with electricity use increase due to AWHP retrofit in the CHS. As shown in Table 3 the GHG EIF are small in NF and QC where major share of electricity generation is from renewable resources. Thus, the GHG emission variations are negligible despite the increase of electricity consumption in these provinces. The total GHG emission increase (19.12 Mt of CO_{2e}) associated with electricity use is about 75% of national GHG emissions (25.3 Mt of CO_{2e}) associated with electricity use in the CHS. This significant increase of GHG emissions is associated with 36% increase in the electricity use in the CHS as mentioned in the previous section. Close to half of GHG emissions increase (19.12 Mt of CO_{2e}) due to AWHP retrofit in the CHS is from AB (8.35 Mt of CO_{2e}). Thus, AB has the least favourability for the AWHP retrofit from this point of view.

Although AWHP retrofit yields a significant increase of GHG emissions associated with electricity use, close to 86% of GHG emissions associated with onsite fossil fuel consumption is reduced in the CHS. This occurs because of fuel shift from NG and oil as discussed in previous section.

As shown in Table 11 AWHP retrofit result in a 23% reduction of GHG emissions in the CHS. While the smallest value of GHG emission reductions occur in NB, overall GHG emissions increase in NS, SK and AB. Unfavourable results of GHG emission variation in NS, SK and AB are in agreement with prior observations regarding the primary energy consumption as discussed in previous section. Since, fossil fuels are the main source of electricity generation in these provinces, AWHP retrofit adds extra emissions. The low value of GHG emission reduction in NB is because of the fuel shift from wood to electricity. As discussed earlier CO_2 emission of wood combustion is considered as a complement of the natural carbon cycle and no GHG emissions is attributed to wood burning heating systems. Since close to 30% of total energy use (39.1 PJ as shown in Table 6) of existing houses in NB is supplied from wood (10.7 PJ as shown in Table 6) this fuel shift strongly affects the total GHG emissions of eligible houses. As shown in Table 9 about 6.8 PJ (equivalent of 17% of total energy use) of energy supply from wood is replaced by electricity in NB. This effect is as to be expected since marginal electricity generation in NB has the highest GHG EIF in the Canadian electricity market as shown in Table 6. On the other hand provinces that have a high renewable electricity generation provide substantial GHG emission reductions due to AWHP retrofit.

5.3. Economic analysis

The results of economic analysis for AWHP retrofit using two payback periods, three interest rate scenarios and three fuel escalation rates in each province in the CHS based on the tolerable capital cost are given in Table 12.

The operating cost of AWHP system is higher compared to that of the existing systems for space and DHW heating in OT and PR region (excluding MB). Thus TCC is not given for OT, SK and AB provinces in Table 12. Also, TCC in MB is fairly small compared other provinces. The higher operating costs in these provinces are due to significantly lower price of NG (8.23, 7.77 and 4.62 C$/GJ as shown in Table 5) compared to price of electricity (24.25, 42.00, 43.19 C$/GJ as shown in Table 5) in MB, SK and AB, respectively. As shown in Table 5 similar to the one in the PR region, the electricity price (39.72 C$/GJ) is much higher than NG price (7.99 C$/GJ) in

OT. Thus, TCC for AWHP in OT is not sufficient to justify the initial investment cost in the absence of incentive programs.

The major share of space and DHW heating energy is currently supplied from oil in AT and QC regions. Due to comparable price of oil (~30 C$/GJ as shown in Table 5) and electricity (~22–45 C$/GJ as shown in Table 5) in these provinces, the highest TCC for AWHP retrofit is observed in NF, NS, PE, NB and QC.

The high TCC with short payback period may increase a homeowner's willingness to invest in the AWHP retrofit. However, the investment cost might be higher than the TCC in some provinces. In that case incentive programs and subsidies might be helpful if the provincial or federal governments decide to promote the AWHP retrofit in the housing stock. However, the subsidy program might not be the only tool for the government to motivate homeowners for energy retrofits. Tommerup and Svendsen [17] argue that legislation is an effective and vital part of strategies in this regard, since a rational reaction to traditional market forces is not expected in the energy saving market. The value of TCC per house has less utility for provincial and national decision makers to develop strategies to enhance the penetration level of AWHP retrofit in the housing stock. Thus, TTCC for AWHP retrofit in the CHS is estimated and results for various scenarios are presented in Figure 4. Under the most favourable condition (10 years payback period, 3% interest rate and high fuel escalation rate) the total Canadian (excluding OT and PR) homeowners can invest about 22 Billion Canadian Dollars in AWHP retrofit. If the economic conditions varies or the investment cost is higher compared to the TTCC subsidies may cover the shortfall.

6. Conclusion

Techno-economic impact of air to water heat pump (AWHP) system on the energy consumption and GHG emissions of the Canadian housing stock (CHS) is presented and discussed. The AWHP system delivers aerothermal energy to the water for space and domestic hot water (DHW) heating purposes. The study was conducted using the Canadian Hybrid Residential End-use Energy and GHG emissions (CHREM) model. A high resolution and versatile whole building performance simulation software, ESP-r, was used to model the AWHP system components (i.e. heat pump, auxiliary boiler, thermal storage tanks, pumps and radiators).

CHREM is based on the Canadian Single-Detached Double/Row Database (CSDDRD) which statistically represents the CHS with close to 17,000 unique houses. A selection criteria was defined and houses eligible for the AWHP retrofit were identified in CSDDRD. The AWHP retrofit was introduced into all eligible houses and the simulation was conducted to obtain the energy consumption, GHG emissions and annual energy cost. The results were compared with the base case to evaluate techno-economic impact of AWHP retrofit in the CHS. Tolerable capital cost (TCC) of the retrofit which is the maximum capital cost for an energy saving upgrade based on the annual savings, the number of years allowed for payback, and the estimated annual interest and fuel cost escalation rates.

The results indicate that about 71 percent of the houses in CHREM, representing approximately 6.3 million existing houses in the CHS are eligible for the AWHP retrofit. The AWHP retrofit reduces about 520.8 PJ equivalent of 36 percent end-use energy consumption in the CHS if all of the eligible houses receive the upgrade. The AWHP system retrofit is effective in reducing primary energy consumption in provinces where renewable resources are the main source of electricity generation including NF, QC, MB and BC. Comparing the seasonal performance factor (SPF) of AWHP and reference efficiencies of electricity generation based on the European

Parliament and Council Directive 2009/28/EC guidelines indicate that heat generation of AWHP can be considered as renewable energy in Canada except in provinces that electricity generation is significantly from fossil fuel resources (NS, NB, PE, SK, and AB). Onsite fossil fuel (i.e. oil and NG) consumption is significantly reduced in the CHS after retrofit. The energy savings cause 15.16 Mt of GHG associated emission reductions in the CHS. Economic analysis indicate that the AWHP system retrofit is not feasible in OT, MB, SK and AB in absence of governmental subsidies and incentive programs.

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 by introducing and integrating high efficient and renewable/alternative energy technologies in new construction and existing houses. The project was defined under the Smart Net-Zero Energy Buildings Strategic Research Network (SNEBRN) umbrella to assess the techno-economic feasibility of converting the Canadian housing stock (CHS) into net/near zero energy buildings. Performance assessment of energy retrofit and renewable/alternative energy technologies in existing houses in regional and national scale is necessary to devise feasible strategies and incentive measures.

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Highlights

- Techno-economic feasibility of air to water heat pump is assessed for Canadian houses.
- A state-of-the-art housing stock model is used for techno-economic analysis.
- AWHP retrofit reduced 36% of end-use energy consumption in the Canadian housing stock.
- AWHP retrofit decreased 23% of GHG emission of the Canadian housing stock.
- Aerothermal energy captured by HP can be assumed as renewable energy in most provinces

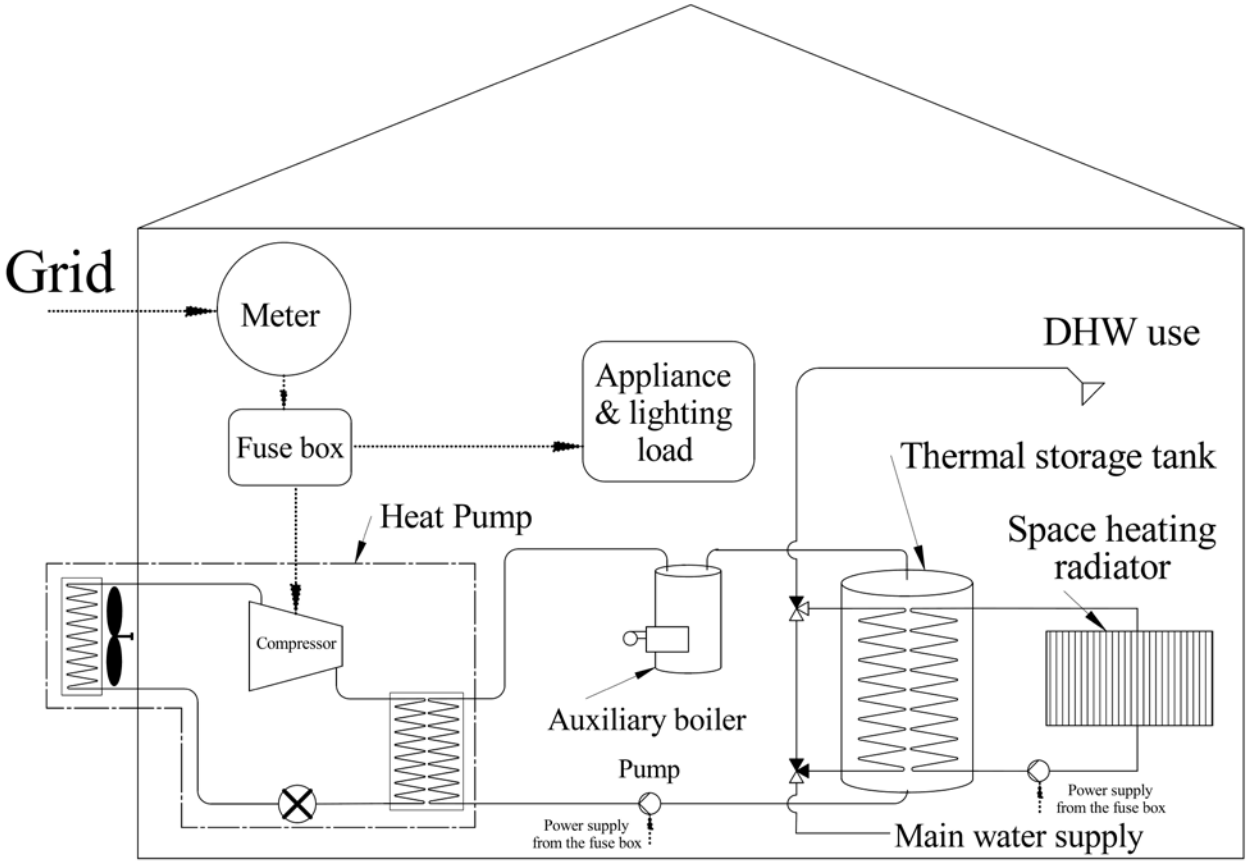
Figure captions:

Fig. 1. A typical house with air to water heat pump retrofit.

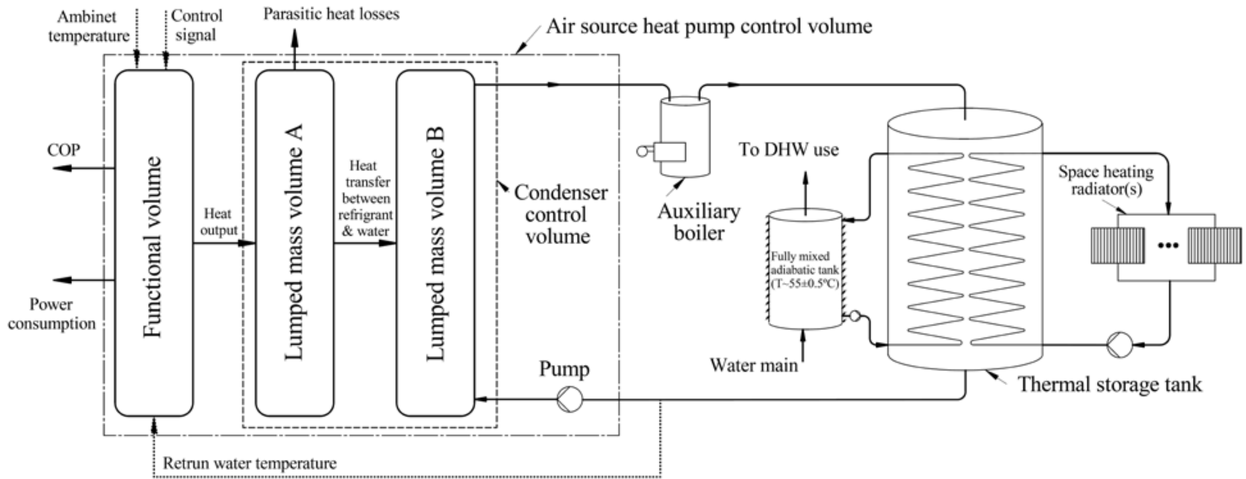
Fig. 2. Air to water heat pump modeling approach in ESP-r.

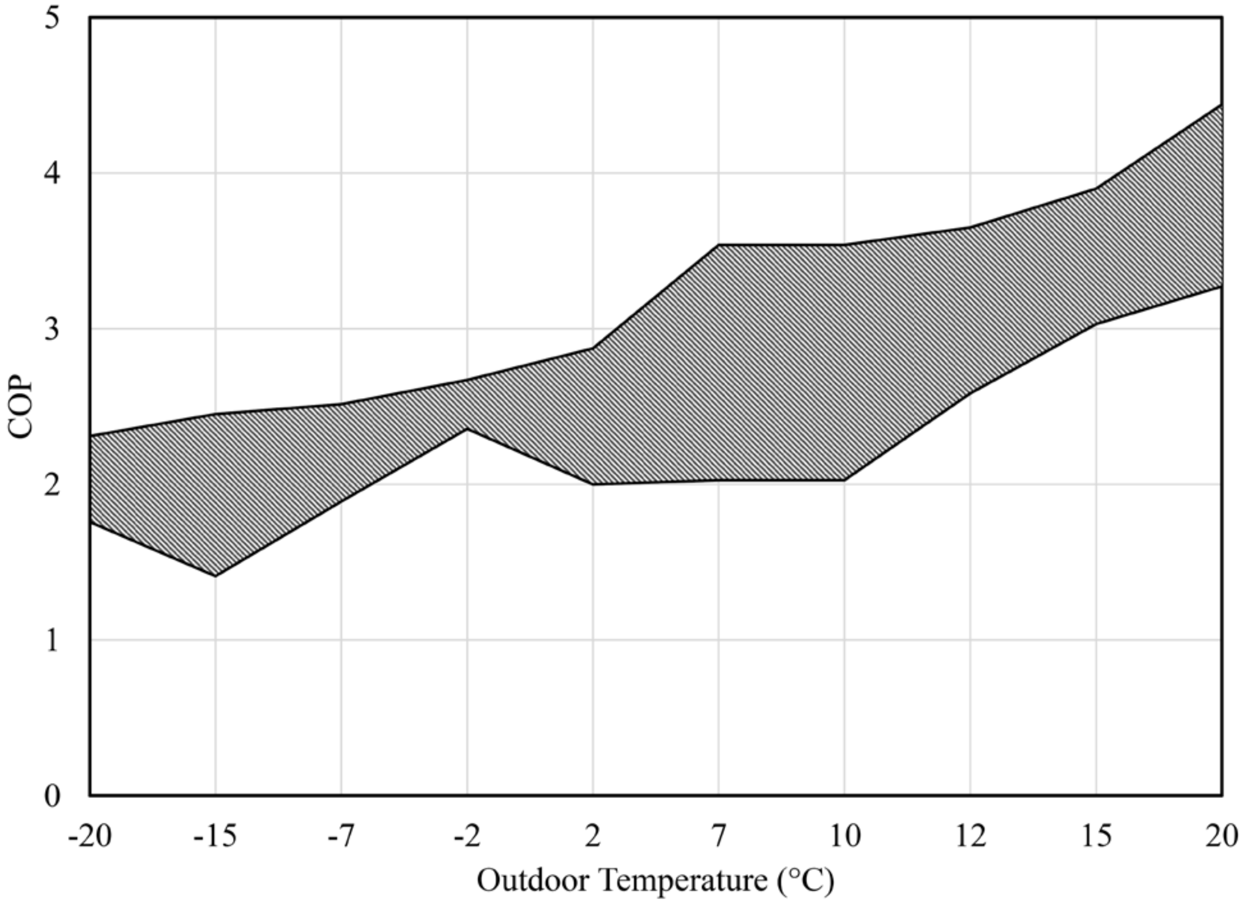
Fig. 3. COP range of various commercially available AWHP systems [44-48].

Fig. 4. Total national excluding PR provinces tolerable capital cost due to air to water heat pump upgrade for different interest rates and fuel cost escalation rates (Low, Medium and High as per Table 6).



Grid
Meter
Fuse box
Appliance
& lighting
load
DHW use
Thermal storage tank
Heat Pump
Space heating
radiator
Compressor
Auxiliary boiler
Pump
Power supply
from the fuse box
Power supply
from the fuse box
Main water supply


Ambinet temperature
Control signal
Parasitic heat losses
Air source heat pump control volume
COP
Power consumption
Functional volume
Heat output
Lumped mass volume A
Heat transfer between refrigrant & water
Lumped mass volume B
Condenser control volume
Pump
Retrun water temperature
Auxiliary boiler
To DHW use
Fully mixed adiabatic tank (T~55±0.5°C)
Water main
Thermal storage tank
Space heating radiator(s)



COP
0
1
2
3
4
5
-20
-15
-7
-2
2
7
10
12
15
20
Outdoor Temperature (°C)

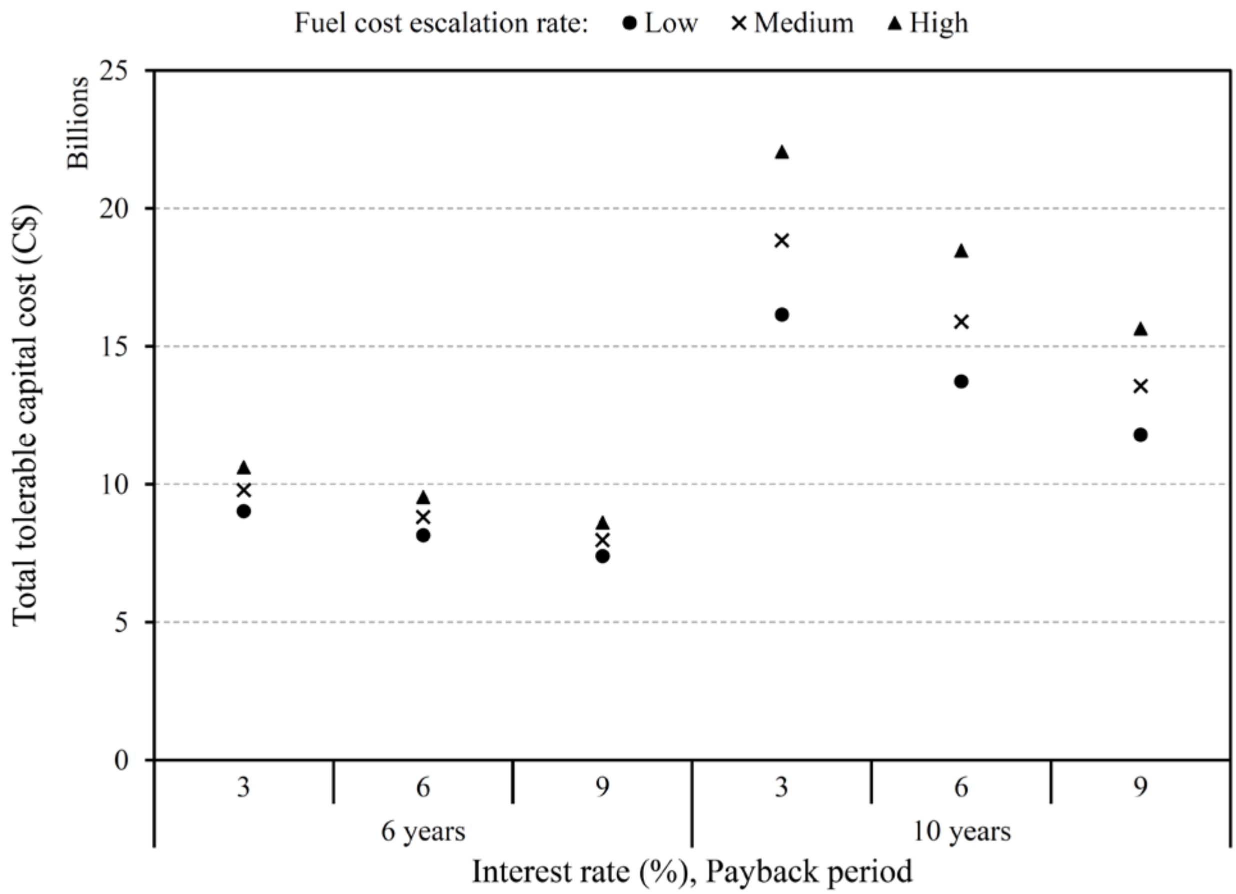

Fuel cost escalation rate: ● Low × Medium ▲ High
Billions
Total tolerable capital cost (C$)
25
20
15
10
5
0
3
6
9
3
6
9
6 years
10 years
Interest rate (%), Payback period

Table 1. Parameters of AWHP system components based on the existing heating system capacity

ASHP system components	Parameter	Unit	Existing heating system nominal capacity (kW) >21	11-16	<11	Reference
COP	a_0	--	5.2202	5.0948	5.6818	[44]
	a_1	K^{-1}	-0.077	-0.0583	-0.0864	
	a_2	K^{-2}	4×10^{-4}	3×10^{-4}	5×10^{-4}	
Compressor power rating	b_0	kW	10.424	7.3568	5.6681	
	b_1	K^{-1}	-0.007	-0.006	-0.007	
Fan power	P_{fan}	W	480	230	190	
Duration of defrost	t_0	s		360		[3, 44]
	t_1	s/%		2.4		
NG fired boiler	$P_{nom,buner}$	kW	19	19	18	[49]
	$(\tan\varphi)_{T>50^\circ C}$	$^\circ C^{-1}$		-0.15		
	$(\tan\varphi)_{T\leq50^\circ C}$	$^\circ C^{-1}$		-0.25		
Oil fired boiler	$P_{nom,buner}$	kW	18	18	11	[50]
	$\tan\varphi$	$^\circ C^{-1}$		-0.15		
Thermal storage tank	V_{store}	USG	400	260	200	
Radiator	M_{unit}	kg		49		[43]
	C_{avg}	J/kgK		1350		
	Q_0	W		967		
	$T_{s,0}$	$^\circ C$		55		
	$T_{r,0}$	$^\circ C$		35		
	$T_{env,0}$	$^\circ C$		21		

Table 2. Control strategy for AWHP, space heating and DHW supply

Control loop	Actuator	Period		Sensor location	Setpoint	
		start	end		on	off
Two stage heating	ASHP	1 Jan	31 Dec	Thermal storage tank outlet to zone	45	50
	Boiler	1 Jan	31 Dec	Boiler outlet	50	55
DHW heating and supply	DHW Pump	1 Jan	31 Dec	DHW tank	54	56
	DHW tank	1 Jan	31 Dec	DHW draw	--	--
Space heating	Radiator pump	17 Sep	3 Jun	Zone main 1	20	22
		4 Jun	16 Sep		0	1*

* The heating system will not turn on due to the low temperature setpoint during the cooling only season

Table 3. The average and marginal GHG intensity factors (g CO_{2e}/kWh) for each province of Canada [39]

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%

Table 4. Average seasonal performance factor (SPF) of AWHP retrofits in the CHS and reference efficiency electricity generation and distribution losses in Canada [24]

Province	Fossil fuel contribution (%)	Reference efficiency	1.15×1/η
NF	2.4	1	1.15
NS	90.8	0.35	3.28
PE	63.4	0.57	2.02
NB	63.4	0.57	2.02
QC	0.4	1	1.15
OT	19.1	1	1.15
MB	0.3	1	1.15
SK	78.1	0.41	2.80
AB	95.9	0.32	3.59
BC	3	1	1.15

Table 5. Fuel prices in each province of Canada

	unit	NF	PE	NS	NB	QC	OT	MB	SK	AB	BC
Electricity[1]	cents/kWh	13.17	16.95	16.22	13.36	7.89	14.30	8.73	15.12	15.55	9.55
	C$/GJ	36.58	45.06	47.08	37.11	21.92	39.72	24.25	42.00	43.19	26.53
Natural gas[2]	cents/m^3	N/A	N/A	N/A	N/A	46.41	29.87	30.77	29.05	17.26	42.45
	C$/GJ	N/A	N/A	N/A	N/A	12.41	7.99	8.23	7.77	4.62	11.35
Home heating oil[3]	cents/litre	114.9	110.2	113.1	119.3	121.2	127.2	117.6	113.9	N/A	128.3
	C$/GJ	29.63	28.42	29.17	30.76	31.25	32.80	30.33	29.37	N/A	33.08
Wood[4]	C$/tonne	156.3	156.3	156.3	218.8	159.4	187.5	162.5	156.3	312.5	150
	C$/GJ	11.20	11.20	11.20	15.69	11.43	13.44	11.65	11.20	22.40	10.75

[1] Hydro-Quebec [53]

[2] Statistics Canada handbook [54]

[3] Statistics Canada Handbook [54]

[4] Local companies

Table 6. Real fuel escalation type for each fuel type

	Low	Medium	High
Electricity*	2	6	10
Natural gas‡	2	5	8
Light fuel oil‡	6	10	14
Mixed wood§	3	6	9

* National Energy Board of Canada [55]

‡ Energy Escalation Rate Calculator (EERC) [56]

§ Equal to interest rate as there is no source for its escalation rate

Table 7. CHREM estimates of annual energy consumption and GHG emissions 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

Table 8. Energy savings and GHG emission reductions for the CHS due to AWHP retrofit

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	88,207	50	8.3	94	0.59	6,709
NS	205,592	69	17.1	83	-0.04	-173
PE	38,997	87	2.9	74	0.17	4,336
NB	122,070	51	11.4	93	0.14	1,150
QC	385,809	19	24.7	64	1.77	4,579
OT	3,084,282	90	234.1	76	11.79	3,823
MB	243,288	72	17.2	71	1.16	4,781
SK	287,895	91	21.3	74	-0.58	-2,025
AB	970,120	100	65.2	67	-3.47	-3,573
BC	876,761	79	58.3	66	3.62	4,131
Canada	6,303,021	71	460.5		15.16	

Table 9. CHREM estimates of annual energy consumption (PJ) with existing (Exist) and AWHP retrofit (AWHPR) in houses eligible (EL) and houses not eligible (N-E) for AWHP retrofit

Province	Electricity			NG[a]		Oil[a]		Wood			Total		
	N-E	EL						N-E	EL		N-E	EL	
		Exist	AWHPR	Exist	AWHPR	Exist	AWHPR		Exist	AWHPR		Exist	AWHPR
NF	10.9	4.3	7.4	0.0	0.0	9.6	0.9	0.6	2.7	0.0	11.5	16.6	8.3
NS	9.1	8.6	15.6	0.0	0.0	22.6	2.2	2.3	3.7	0.0	11.4	34.9	17.8
PE	0.4	1.4	2.7	0.0	0.0	4.0	0.6	0.7	0.8	0.0	1.1	6.2	3.3
NB	12.7	6.0	8.8	0.0	0.0	9.7	2.3	3.9	6.8	0.0	16.6	22.5	11.1
QC	181.7	23.6	24.9	1.0	8.2	30.3	0.0	7.5	2.9	0.0	189.2	57.8	33.1
OT	40.6	96.6	206.5	337.4	40.8	47.4	0.0	0.0	0.0	0.0	40.6	481.4	247.3
MB	12.1	6.8	13.2	33.6	10.0	0.0	0.0	0.0	0.0	0.0	12.1	40.4	23.2
SK	3.1	7.5	16.6	40.2	9.8	0.0	0.0	0.0	0.0	0.0	3.1	47.7	26.4
AB	0.0	28.3	59.7	119.8	23.2	0.0	0.0	0.0	0.0	0.0	0.0	148.1	82.9
BC	23.2	41.4	57.9	83.9	9.5	0.0	0.0	1.7	0.4	0.0	24.9	125.7	67.4
Canada	293.8	224.5	413.3	615.9	101.5	123.6	6.0	16.7	17.3	0.0	310.5	981.3	520.8

[a] Since entire houses with existing oil or NG fired heating system is eligible for AWHP retrofit, NG and oil consumption in not eligible houses is not shown

Table 10. Annual energy savings and GHG emission reductions due to AWHP retrofits in the CHS

	Energy savings (PJ)					GHG emission reductions (Mt of CO_{2e})			
Province	Electricity	NG	Oil	Wood	Total	Electricity	NG	Oil	Total
NF	-3.1	0.0	8.7	2.7	8.3	-0.02	0.00	0.61	0.59
NS	-7.0	0.0	20.4	3.7	17.1	-1.47	0.00	1.43	-0.04
PE	-1.3	0.0	3.4	0.8	2.9	-0.07	0.00	0.24	0.17
NB	-2.8	0.0	7.4	6.8	11.4	-0.38	0.00	0.52	0.14
QC	-1.3	-7.2	30.3	2.9	24.7	0.00	-0.36	2.13	1.77
OT	-109.9	296.6	47.4	0.0	234.1	-6.54	15.00	3.33	11.79
MB	-6.4	23.6	0.0	0.0	17.2	-0.03	1.19	0.00	1.16
SK	-9.1	30.4	0.0	0.0	21.3	-2.12	1.54	0.00	-0.58
AB	-31.4	96.6	0.0	0.0	65.2	-8.35	4.88	0.00	-3.47
BC	-16.5	74.4	0.0	0.4	58.3	-0.14	3.76	0.00	3.62
Canada	-188.8	514.4	117.6	17.3	460.5	-19.12	26.01	8.27	15.16

Table 11. Average seasonal performance factor, thermal energy considered from renewable sources, annual energy savings and GHG emission reductions due to AWHP retrofits in the CHS

Province	SPF	E_{RES} (PJ)	Energy Savings (%)	GHG emission reductions (%)
NF	2.04	3.4	30	75
NS	1.87	N/A	37	-1
PE	1.83	N/A	40	44
NB	1.89	N/A	29	5
QC	1.83	10.6	10	69
OT	1.80	90.5	45	41
MB	1.95	5.4	33	66
SK	1.71	N/A	42	-13
AB	1.70	N/A	44	-25
BC	2.59	21	39	78
Canada		130.9	36	23

Table 12. Average TCC per house (C$/house)

Province	Payback (yr)	Interest rate 3%			6%			9%		
		Fuel cost escalation rate: Low	Medium	High	Low	Medium	High	Low	Medium	High
NF	10	14,904	17,743	21,196	12,612	14,893	17,656	10,791	12,643	14,875
	6	7,996	8,766	9,613	7,206	7,878	8,615	6,528	7,117	7,763
NS	10	13,540	16,204	19,453	11,419	13,557	16,153	9,739	11,470	13,564
	6	7,035	7,731	8,495	6,331	6,937	7,603	5,728	6,258	6,840
PE	10	8,190	9,778	11,703	6,867	8,136	9,669	5,822	6,846	8,079
	6	4,014	4,394	4,811	3,602	3,933	4,295	3,249	3,539	3,855
NB	10	17,375	20,390	24,017	14,773	17,203	20,112	12,700	14,677	17,034
	6	9,742	10,607	11,553	8,796	9,552	10,377	7,984	8,647	9,369
QC	10	17,296	20,818	25,155	14,701	17,540	21,018	12,634	14,945	17,762
	6	9,667	10,683	11,809	8,728	9,615	10,597	7,921	8,700	9,560
MB	10	819	612	297	703	536	284	610	474	271
	6	501	438	360	454	399	331	413	365	306
BC	10	3,123	3,300	3,447	2,682	2,826	2,947	2,328	2,447	2,546
	6	1,910	1,972	2,031	1,731	1,785	1,837	1,576	1,624	1,670