

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

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7 **Abstract**

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

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

28 **Highlights**

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

36 **Nomenclature**

37	ACSH	Annual cost savings for the house due to energy savings in a uniform series, 38 continuing for n periods (\$/year)
39	ATTCCH	Average tolerable capital cost per house (\$)
40	CO _{2e}	Equivalent CO ₂ emitted per unit input energy (kg/kWh)
41	c	Specific heat (kJ/kgK)
42	E	Energy saving per period for each fuel type (unit depends on fuel type)
43	E _{RES}	Thermal energy considered from renewable sources (PJ)
44	e	Fuel cost escalation rate (decimal)
45	F	Fuel price per unit of each fuel type (\$/unit)
46	h _{store}	Storage tank height (m)
47	K _{AB}	Heat exchange coefficient between water and working fluids (kW/K)

48	i	Interest rate (decimal)
49	M	Mass of control volume (kg)
50	\dot{m}	Mass flow rate (kg/s)
51	NH	Number of houses that received the upgrade
52	n	Acceptable payback period (year)
53	P_c	Compressor power (kW)
54	$P_{el,pump.SH}$	Pump power in space heating loop (W)
55	$P_{el,pump.DHW}$	Pump power in DHW loop (W)
56	$P_{nom,burner}$	Nominal power of auxiliary boiler (W)
57	Q_{usable}	Gross final thermal energy delivered by heat pump (kJ)
58	RH_{amb}	Relative humidity of ambient air (%)
59	SPF	Seasonal performance factor
60	TCC	Tolerable capital cost (\$)
61	$TCCH$	Tolerable capital cost of the retrofit for the house (\$)
62	T_{amb}	Ambient temperature (K)
63	T_c	Reference temperature for boiler efficiency (K)
64	T_r	Return water temperature (K)
65	t_{def}	Defrost time (s)
66	t_{tr}	Duration of transient operation of boiler (s)
67	UA	Heat loss coefficient (kW/K)
68	V_{store}	Storage tank volume (m ³)
69	<i>Greek letters</i>	

70	η	Ratio between total gross production of electricity and the primary energy
71		consumption for electricity generation
72	η_b	Boiler efficiency (%)
73	η_0	Full load boiler efficiency at the reference temperature (%)
74	φ	Slope of the boiler efficiency curve (degree)
75	Δt	Simulation time step (s)
76	<i>Abbreviations</i>	
77	AB	Alberta
78	AL	Appliances and lighting
79	ASHP-WH	Air source heat pump water heating
80	AT	Atlantic Provinces
81	AWHP	Air to water heat pump
82	BC	British Columbia
83	CHREM	Canadian Hybrid Residential End-Use Energy and GHG Emissions model
84	CHS	Canadian housing stock
85	COP	Coefficient of performance
86	CSDDRD	Canadian Single-Detached Double/Row Database
87	DHW	Domestic hot water
88	EIF	Emission intensity factor
89	GHG	Greenhouse gas
90	ICE	Internal combustion engine
91	MB	Manitoba
92	NB	New Brunswick

93	NF	Newfoundland and Labrador
94	NG	Natural gas
95	NS	Nova Scotia
96	NZEB	Net zero energy building
97	OT	Ontario
98	QC	Quebec
99	PCM	Phase change material
100	PE	Prince Edward Island
101	PR	Prairie Provinces
102	SDHW	Solar domestic hot water
103	SE	Stirling engine
104	SK	Saskatchewan
105	SNEBRN	Smart Net-Zero Energy Buildings Strategic Research Network

106 **1. Introduction**

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

116 While the AWHP system is well established in Europe and Japan, it is relatively new to the
117 Canadian market [4]. Thus, an accurate and comprehensive study is needed to investigate the
118 feasibility of integrating AWHP systems into the Canadian housing stock (CHS). Recently, such
119 studies have been conducted for various regions of the world. For example, Kelly and Cockroft
120 [5] developed a numerical model to evaluate the performance of AWHP retrofit into a building
121 in Scotland. The simulation results were validated by laboratory data and the model was
122 integrated into a whole building performance simulation software. The model was well
123 representative of the AWHP operating conditions in the field trial. An equivalent condensing
124 natural gas boiler and an electric heating system were used as alternative heating systems for the
125 building, and annual energy consumption of the three systems were compared. The results
126 showed that GHG emissions of AWHP were lower compared to that of the condensing natural
127 gas boiler and the electric heating system. While the operating cost of the AWHP exceeds that of
128 the gas condensing boiler, incentives available for renewable thermal energy may make up the
129 difference. In another study, Kelly et al. [6] used the AWHP model to estimate the effectiveness
130 of integrated AWHP and thermal storage tank with phase change material (PCM) to restrict the
131 AWHP operation to the off-peak periods. The results showed that through manipulation of the
132 PCM chemistry, heat storage tank volume could be reduced by 50% with a minimum impact on
133 heat supply to the building in the UK climate. Cabrol and Rowley [7] used a numerical model to
134 study the performance of air source heat pump water heating (ASHP-WH) system with hydronic
135 heat delivery in various UK locations. A sensitivity analysis was conducted to evaluate the
136 impact of the building construction materials and off-peak period operation. The GHG emissions
137 and operating cost of ASHP-WH were found to be lower compared to those of an equivalent size
138 gas boiler, and the annual coefficient of performance (COP) of the ASHP-WH was found to be

139 about 3.5 and 4 for cold and mild UK climates, respectively. Johnson [8] found that in the UK
140 context the heat pump GHG emissions due to electricity consumption were higher compared to
141 gaseous fuels and lower compared to heating oil. Using a model for ASHP-WH system model
142 based on measured data from a field trial campaign Madonna and Bazzocchi [9] found that
143 climate has a significant role on the performance of ASHP-WH, and depending on climate, the
144 energy requirement for space heating could be reduced by up to 79% in new buildings in Italy. A
145 study by Hewitt et al. [10] that investigated AWHP retrofit options for existing houses in the UK
146 recommended using variable speed compressor, advanced evaporators and improving heat
147 delivery system to enhance the performance of AWHP in the European maritime climate
148 conditions. Bertsch and Groll [11] designed, simulated, constructed and tested an ASHP water or
149 air heating system with an operating range of -30°C to 10°C and return water temperature of
150 50°C for northern US climates. The issues related with the low temperature, high lift operation of
151 the heat pump were dealt with through design choices. The cost of the proposed ASHP system
152 was found to be lower compared to an equivalent ground source heat pump. Ibrahim et al. [12]
153 developed a simulation model to study the performance of ASHP-WH system and its potential
154 for energy savings and GHG emissions reductions in Lebanon. The results showed that COP
155 would vary in the range of 2.9 to 5 for the various climatic conditions of Lebanon. Lund et al.
156 [13] evaluated the role of district heating in the future renewable energy systems of Denmark
157 assuming that Danish energy supply will be entirely from renewable resources by 2060.
158 Assuming a 75% reduction in space heating demand individual heat pump systems were found to
159 be the best alternative to existing fossil fuel systems. The European Parliament and Council also
160 identified the aerothermal, geothermal and hydrothermal energy production of heat pump

161 systems as renewable energy under specific circumstances as published in the Directive
162 2009/28/EC [14].

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

182 In order to focus efforts and resources to reduce residential energy consumption and GHG
183 emissions an accurately designed strategy with specific goals is required. For this purpose, so far,

184 a wide range of retrofit options including envelope modifications such as glazing and window
185 shading upgrades, as well as installation of solar domestic hot water (SDHW) systems, phase
186 change material (PCM) thermal energy storage, internal combustion engine (ICE) and Stirling
187 engine (SE) based cogeneration systems and solar combisystem were studied [19-27] as part of a
188 national effort in Canada [28]. In this work, the techno-economic feasibility of AWHP system
189 retrofit in the Canadian housing stock is studied.

190 **2. Methodology**

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

199 **2.1. Housing stock model**

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

205 A high-resolution building energy simulation program ESP-r [34] is used as the simulation
206 engine of CHREM. ESP-r is an integrated modeling tool for evaluation of the thermal, visual and

207 acoustic performance as well as energy consumption and GHG emissions of buildings which
208 employs a finite difference control volume approach for energy simulation. The building domain
209 is discretized into control volumes and each control volume contain finite difference nodes.
210 Control volumes represent a wide range of building components such as air volume in thermal
211 zones, opaque and transparent structures, solid-fluid interfaces and plant components. Governing
212 equations are discretized based on the Crank-Nicolson finite difference method for all nodes in
213 the control volume. The system of algebraic equations is solved using a simultaneous direct
214 solution approach based on matrix partitioning and Gaussian elimination in each time step [35,
215 36]. The system of linearized mass balance equations is solved using the Newton-Raphson
216 iterative method. ESP-r has been validated through a vast amount of research results [37].
217 CHREM consists of six components that work together to provide predictions of the end-use
218 energy consumption and GHG emission of the CHS. These components are:

- 219 • The Canadian Single-Detached & Double/Row Housing Database [33],
- 220 • A neural network model of the appliances and lighting (AL) and DHW energy
221 consumption of Canadian households [38],
- 222 • A set of AL and DHW load profiles representing the usage profiles in Canadian
223 households,
- 224 • A high-resolution building energy simulation software (ESP-r) that is capable of
225 accurately predicting the energy consumption of each house file in CSDDRD,
- 226 • A model to estimate GHG emissions from marginal electricity generation in each
227 province of Canada and for each month of the year [39],
- 228 • A model to estimate GHG emissions from fossil fuels consumed in households.

229 The energy savings and GHG emissions reductions associated with any energy efficiency
230 upgrade or renewable/alternative energy technology, such as AWHP systems, can be estimated
231 using CHREM as follows:

- 232 (i) Identify houses suitable to receive the upgrade/technology: For AWHP system retrofit,
233 only houses with a basement or a mechanical room would be suitable. Therefore, a search
234 has to be conducted in the CSDDRD to identify such houses.
- 235 (ii) Modify the input files of the selected houses to add the upgrade/technology for use in the
236 ESP-r energy simulations.
- 237 (iii) Estimate the energy consumption and GHG emissions reductions (or increases) of the
238 CHS with the adopted upgrade/technology by comparing the energy consumption and
239 GHG emissions with the “base case” (i.e. current) values. The change in GHG emissions
240 due to a change in electricity consumption is estimated using the marginal GHG emission
241 intensity factors given by Farhat and Ugursal [39]. Since CSDDRD is representative of
242 the CHS, the CHREM estimates can be extrapolated to the entire CHS using scaling
243 factors [31, 32].

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

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

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

260 ***2.2.1. Air to water heat pump***

261 The AWHP model used in this work was developed and added to the ESP-r plant components by
262 Kelly and Cockroft [5]. This model incorporates three control volumes: a functional volume and
263 two lumped mass volumes as shown in Figure 2. The functional control volume represents the
264 working fluid loop and auxiliary parts, and calculates the COP of the heat pump and compressor
265 power consumption based on the ambient temperature, return water temperature and the control
266 signal. The total power use of the heat pump is the cumulative power consumption of compressor
267 and auxiliary components. The empirical expressions used for the COP and compressor power
268 consumption of an AWHP are given in Equations (1) and (2):

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

$$P_C = b_0 e^{b_1(T_r - T_{\text{amb}})} \quad (2)$$

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

272 a_2 and b_{0-1}) are derived based on the empirical data of the AWHP and the values used in this work
 273 are given in Table 1. The nominal heat supply of the heat pump is then determined as the
 274 compressor power consumption multiplied by the COP.

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

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

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

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

287 At low ambient temperature and high relative humidity the evaporator coil may operate below
 288 the frost temperature of ambient air. Under these circumstances the frost may accumulate on the
 289 evaporator coil surface and reduce the heat transfer between refrigerant and the outside air. Thus,
 290 the defrost cycle is considered to melt the frost [3]. A defrost algorithm predicts the status of the
 291 AWHP in a case that ambient temperature drops below the frost temperature. If the ambient
 292 temperature remains below the frost temperature for a long time a defrost lockout duration is

293 considered to dictate an interval between the defrost cycles. If the defrost cycle is turned on the
 294 heat supply of heat pump is set to zero. The duration of the defrost cycle is defined using
 295 Equation 5.

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

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

299 **2.2.2. Auxiliary boiler**

300 The boiler model that was developed and added to the ESP-r plant domain by Hensen [40] is
 301 used. The model can be used for both non-condensing and condensing auxiliary boilers. The
 302 governing equations, including conservation of mass and energy, are solved in each time step.
 303 The control signal that defines the ON/OFF status of the boiler is set the beginning of each time
 304 step, and the boiler remains in that status during a time step. In the case that boiler temperature
 305 exceeds the maximum allowable temperature limit, the control signal is discarded and boiler is
 306 turned off to determine the new boiler temperature for that time step.

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

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

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

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

316 **2.2.3. Thermal storage tank**

317 The thermal storage tank model developed and incorporated into the ESP-r by Thevenard and
318 Haddad [41] is used. The model represents a stratified tank with two immersed heat exchangers.

319 The tank is divided into N control volumes, and mass and energy balance equations are solved
320 for each control volume. The energy balance equation for each control volume considers heat
321 losses to the environment, convection and conduction heat transfer with the adjacent control
322 volumes as well as heat transfer due to water flow at inlet/outlet, where applicable.

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

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

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

329 **2.2.4. Heat delivery system**

330 The heat delivery system is assumed to be hydronic, consisting of piping, pumps and radiators.

331 The radiator and pump models developed and added to the ESP-r plant database by Hensen [40]

332 are used. Radiator heat emission is estimated based on the nominal heat emissions at reference

333 conditions and actual temperature conditions of radiator and environment based on radiator type,

334 dimensions, connection method and room characteristics. The electricity consumption of the

335 circulation pump defined based on actual mass flow rate, pressure drop, fluid density and pump
 336 efficiency with heat losses from the pump added to the energy balance.
 337 The number of radiators for each thermal zone is chosen to satisfy the design heating load and
 338 nominal radiator capacities selected from the Express Radiant Ltd product catalogue [43]. The
 339 hot water circulation pump power is estimated using empirical equations that Asaee et al. [27]
 340 used to estimate pump power in space and DHW heating loop for solar combisystem applications
 341 based on recommendations by Weiss [42]:.

$$P_{el,pump.SH} = 90W + 2 \times 10^{-4} P_{nom,burner} \quad (8)$$

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

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

344 **2.2.5. Domestic hot water system**

345 The AWHP system architecture shown in Figure 1 uses a combination of three-way diverting
 346 valve and three-way converting valve to maintain the DHW temperature in the desired range.
 347 Since the DHW heating coil is sized for maximum water draw calculated for the house, this
 348 architecture prevents overheating the DHW when the water draw is less than the nominal value.
 349 To simplify the modeling of this architecture in ESP-r, a fully mixed adiabatic tank with
 350 temperature control as shown in Figure 2 is used. As the DHW draw and equivalent main water
 351 addition is applied to the adiabatic tank, the tank temperature is maintained in the range of
 352 $55 \pm 0.5^\circ\text{C}$ by circulating hot water from the thermal storage tank to the adiabatic tank. Thus, the
 353 energy balance for the adiabatic tank is the same as for the three-way valve combination.

354 **2.2.6. AWHP system sizing**

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

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

377 ***2.2.7. Control algorithms***

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

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

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

389 The third control loop maintains the DHW temperature in the adiabatic tank in the range of
390 $55\pm 1^\circ\text{C}$ by running the DHW pump while the fourth loop controls the DHW draw and equivalent
391 main water supply to the adiabatic tank.

392 Fifth loop controls the zone temperature by maintaining the space heating pump operation.

393 CHREM provides for four space conditioning periods (winter - heating only, summer - cooling
394 only, and shoulder seasons - heating/cooling are both available). However, since cooling is not
395 available, two periods are used in this work as shown in Table 2:

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

398 During the heating period the space heating pump is controlled to maintain the main zone
399 temperature in the range of 20–22°C. The main-slave control strategy is used for temperature

400 control of other zones excluding the attic which is not conditioned. Since attic is free ventilated,
401 its temperature follows the ambient temperature.

402 **2.3. Methodology to select eligible houses for the AWHP system retrofit**

403 A basement or a mechanical room is necessary to install an AWHP system into a house. While
404 the presence of a basement is noted in the CHREM database, the presence of a mechanical room
405 is not. Therefore, it is assumed in this work that all houses that either have a basement or a
406 heating system that requires a mechanical room are suitable for AWHP retrofit. Based on this
407 assumption, all houses that use NG or oil for space heating are considered to be eligible for the
408 AWHP retrofit. Depending on the type of heating system and the presence of a basement, some
409 houses that use wood or electricity are also eligible for the retrofit. The percentage of houses
410 eligible for the retrofit in each province of Canada¹ is shown in Table 8.

411 **2.4. Estimation of GHG emissions**

412 CHREM determines the associated GHG emission due to onsite fossil fuel and electricity
413 consumption separately for each province due to the vast differences in the fuel mix used. GHG
414 emissions are calculated and reported as “equivalent CO₂” (CO_{2e}) emitted per unit input energy.
415 CO_{2e} is calculated by converting all GHG emissions from fossil fuel combustion, such as CH₄
416 and N₂O, to equivalent CO₂ emissions taking into account their global warming potentials as
417 shown in Equation 10 [32, 39].

$$418 \quad \text{CO}_{2e} = \text{CO}_2 + 25\text{CH}_4 + 298\text{N}_2\text{O} \quad (10)$$

418 Instantaneous GHG emissions due to onsite fuel consumption is calculated in each time step
419 based on the fuel type and efficiency of the energy conversion device. The emission of CO₂ 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).

420 to wood combustion is not accounted for in this study because it is assumed that combustion of
421 wood returns to the atmosphere the CO₂ that was recently removed by photosynthesis as the tree
422 grew [39].

423 To evaluate the GHG emissions related to electricity consumption the GHG emission intensity
424 factor (EIF) is used. The GHG EIF is the level of CO₂ emissions (kg/kWh) generated for the
425 generation and delivery of one kWh electricity to the end-user. In Canada electricity generation
426 is under the jurisdiction of provincial utility companies. Thus, provincial GHG EIF is defined
427 based on the primary energy mixture used for electricity generation and efficiency of energy
428 conversion as well as transmission and distribution losses. Also, typically utilities consider
429 different types of technologies for peak and base electricity generation. Thus, different average
430 and marginal GHG EIFs associated with base and peak electricity generation are required. The
431 provincial average and marginal GHG EIF developed by Farhat and Ugursal [39] and given in
432 Table 3 are used. Average GHG EIFs are used to estimate the emissions due to electricity
433 consumption of the existing housing stock (base case) while the marginal GHG EIFs are used to
434 estimate the GHG emission variation due to the change in electricity consumption in retrofitted
435 houses.

436 **3. Accounting of renewable energy from heat pump**

437 European Parliament and Council in the Directive 2009/28/EC [14] identified the gross final
438 consumption of energy from renewable resources as the summation of (a) gross final electricity
439 consumption, (b) heating and cooling gross final energy use and (c) gross final energy use for
440 transportation from renewable sources. In accordance to part (b) aerothermal, geothermal and
441 hydrothermal energy of heat pump can be assumed as renewable energy in a case that final gross
442 thermal energy production significantly exceeds the primary energy consumption for the heat

443 pump operations. For this purpose the European Parliament and Council Directive 2009/28/EC
444 introduced Equation 11 to define the amount of renewable thermal energy captured by heat
445 pumps.

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

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

$$SPF > 1.15 \times \frac{1}{\eta} \quad (12)$$

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

461 **4. Economic analysis based on tolerable capital cost**

462 Accurate estimation of AWHP system capital costs, at residential as well as commercial scale, is
463 difficult because installed costs can vary significantly depending on the scope of the plant

464 equipment, geographical area, competitive market conditions, special site requirements, and
 465 prevailing labor rates. Therefore the purchase and installation costs of AWHP systems in Canada
 466 vary substantially from manufacturer to manufacturer and location to location. Thus, it is not
 467 practicable to estimate realistic total investment costs for AWHP systems and to conduct a
 468 conventional economic feasibility analysis. Therefore, an alternative approach to conventional
 469 economic feasibility analysis is adopted here which involves the calculation of the “tolerable
 470 capital cost” (TCC) of the upgrades [51]. TCC is the capital cost for an energy saving upgrade
 471 that will be recovered based on the annual savings, the number of years allowed for payback, and
 472 the estimated annual interest and fuel cost escalation rates. Thus, to estimate the tolerable capital
 473 cost of the AWHP upgrade a reverse payback analysis is conducted as follows:

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

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

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

482
 483 where:

484	TCCH	Tolerable capital cost of the retrofit for the house (C\$)
485	<i>n</i>	Acceptable payback period (year)
486	<i>i</i>	Interest rate (decimal)
487	<i>e</i>	Fuel cost escalation rate (decimal)
488	ACSH	Annual cost savings for the house due to energy savings in a uniform series,
489		continuing for <i>n</i> periods (C\$)
490	<i>E</i>	Energy saving per period for each fuel type (unit depends on fuel type; kg, liter,
491		kWh, etc.)
492	<i>F</i>	Fuel price per unit of each fuel type (C\$/unit)
493	<i>m</i>	Number of different fuels used in a house
494		

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

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

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

503

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

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

506

507 NH = number of houses that received the upgrade.

508 To take into consideration the uncertainty associated with the future of interest and fuel price
509 escalation rates, a sensitivity analysis was conducted. The interest rates used in the analysis are
510 based on the Bank of Canada Prime Rate [52], which was about 1% in June, 2015. Thus, for the

511 sensitivity analysis, interest rates of 3%, 6% and 9% are used. These numbers were selected
512 based on the range of consumer loan rates.

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

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

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

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

527 **5. Results and discussion**

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

531 Using the criteria given in Section 2.3, eligible houses for the AWHP retrofit in CHREM were
532 identified. As shown in Table 8, about 71 percent of the houses in CHREM, representing
533 approximately 6.3 million existing houses in the CHS are eligible for the AWHP retrofit. After

534 identifying the eligible houses for the AWHP retrofit, CHREM was updated to reflect the AWHP
535 retrofit in these houses and simulations were carried out to evaluate the energy savings and GHG
536 emissions reduction due to the retrofit. As shown in Table 8, results indicate that 460.5 PJ end-
537 use energy and 15.16 Mt of GHG associated emissions would be saved by retrofitting all eligible
538 houses in the CHS by AWHP systems. Also as shown in Table 8, the energy savings and GHG
539 emission reductions vary substantially amongst provinces. This is discussed in detail below.

540 ***5.1. Energy savings***

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

546 Since AWHP compressors use electricity, the electricity use in all houses that receive the AWHP
547 retrofit increase. This increase translates to an increase in the electricity consumption of
548 retrofitted houses by 188.8 PJ (as shown in Table 10), or close to 85%, from 224.5 PJ to 413.3
549 PJ. This represents an increase of about 36% in the current electricity consumption of the CHS
550 (518.3 PJ as shown in Tables 7 and 9). The increase in the electrical consumption is beneficial in
551 reducing primary energy consumption in provinces where renewable resources are the main
552 source of electricity generation including NF, QC, MB and BC. However, in provinces that
553 utility electricity generation heavily relies on fossil fuel thermal power plants, AWHP retrofit
554 may not significantly affect primary energy savings.

555 The average SPF and thermal energy from renewable sources of heat pumps (E_{RES} as shown in
556 Equation 11) are given in Table 11. The SPF is calculated using the average value of SPF in

557 individual houses in each province. Comparing the SPF of AWHP and reference efficiencies of
558 electricity generation (given in Table 4) based on the European Parliament and Council Directive
559 2009/28/EC guidelines indicate that heat generation of AWHP can be considered as renewable
560 energy in Canada except in provinces that electricity generation is significantly from fossil fuel
561 resources (NS, NB, PE, SK, and AB). About 91%, 64%, 64%, 78% and 96% of electricity
562 generation is from fossil fuels in NS, NB, PE, SK and AB, respectively. Thus, thermal energy
563 from renewable sources (E_{RES}) is not calculated for these provinces. It should be noted that
564 E_{RES} only includes the amount of thermal energy captured from the ambient that can be
565 considered as renewable energy. However, in cases that electricity generation is mainly from
566 renewable resources (such as NF, QC, MB and BC) the total gross heat delivered (Q_{usable}) by the
567 heat pump is renewable energy. Results indicate that AWHP capture about 130.9 PJ additional
568 renewable energy, equivalent to 10% of the total existing energy consumption of the CHS
569 (1291.8 PJ as shown in Table 7).

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

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

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

582 ***5.2. GHG emissions reduction***

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

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

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

599 As shown in Table 11 AWHP retrofit result in a 23% reduction of GHG emissions in the CHS.

600 While the smallest value of GHG emission reductions occur in NB, overall GHG emissions
601 increase in NS, SK and AB. Unfavourable results of GHG emission variation in NS, SK and AB
602 are in agreement with prior observations regarding the primary energy consumption as discussed

603 in previous section. Since, fossil fuels are the main source of electricity generation in these
604 provinces, AWHP retrofit adds extra emissions. The low value of GHG emission reduction in
605 NB is because of the fuel shift from wood to electricity. As discussed earlier CO₂ emission of
606 wood combustion is considered as a complement of the natural carbon cycle and no GHG
607 emissions is attributed to wood burning heating systems. Since close to 30% of total energy use
608 (39.1 PJ as shown in Table 6) of existing houses in NB is supplied from wood (10.7 PJ as shown
609 in Table 6) this fuel shift strongly affects the total GHG emissions of eligible houses. As shown
610 in Table 9 about 6.8 PJ (equivalent of 17% of total energy use) of energy supply from wood is
611 replaced by electricity in NB. This effect is as to be expected since marginal electricity
612 generation in NB has the highest GHG EIF in the Canadian electricity market as shown in Table
613 6. On the other hand provinces that have a high renewable electricity generation provide
614 substantial GHG emission reductions due to AWHP retrofit.

615 ***5.3. Economic analysis***

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

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

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

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

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

647 **6. Conclusion**

648 Techno-economic impact of air to water heat pump (AWHP) system on the energy consumption
649 and GHG emissions of the Canadian housing stock (CHS) is presented and discussed. The
650 AWHP system delivers aerothermal energy to the water for space and domestic hot water
651 (DHW) heating purposes. The study was conducted using the Canadian Hybrid Residential End-
652 use Energy and GHG emissions (CHREM) model. A high resolution and versatile whole
653 building performance simulation software, ESP-r, was used to model the AWHP system
654 components (i.e. heat pump, auxiliary boiler, thermal storage tanks, pumps and radiators).
655 CHREM is based on the Canadian Single-Detached Double/Row Database (CSDDRD) which
656 statistically represents the CHS with close to 17,000 unique houses. A selection criteria was
657 defined and houses eligible for the AWHP retrofit were identified in CSDDRD. The AWHP
658 retrofit was introduced into all eligible houses and the simulation was conducted to obtain the
659 energy consumption, GHG emissions and annual energy cost. The results were compared with
660 the base case to evaluate techno-economic impact of AWHP retrofit in the CHS. Tolerable
661 capital cost (TCC) of the retrofit which is the maximum capital cost for an energy saving
662 upgrade based on the annual savings, the number of years allowed for payback, and the
663 estimated annual interest and fuel cost escalation rates.

664 The results indicate that about 71 percent of the houses in CHREM, representing approximately
665 6.3 million existing houses in the CHS are eligible for the AWHP retrofit. The AWHP retrofit
666 reduces about 520.8 PJ equivalent of 36 percent end-use energy consumption in the CHS if all of
667 the eligible houses receive the upgrade. The AWHP system retrofit is effective in reducing
668 primary energy consumption in provinces where renewable resources are the main source of
669 electricity generation including NF, QC, MB and BC. Comparing the seasonal performance
670 factor (SPF) of AWHP and reference efficiencies of electricity generation based on the European

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

678 This study is a part of the efforts to develop strategies, approaches and incentive measure to
679 approach net/near zero energy status for existing Canadian houses by introducing and integrating
680 high efficient and renewable/alternative energy technologies in new construction and existing
681 houses. The project was defined under the Smart Net-Zero Energy Buildings Strategic Research
682 Network (SNEBRN) umbrella to assess the techno-economic feasibility of converting the
683 Canadian housing stock (CHS) into net/near zero energy buildings. Performance assessment of
684 energy retrofit and renewable/alternative energy technologies in existing houses in regional and
685 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

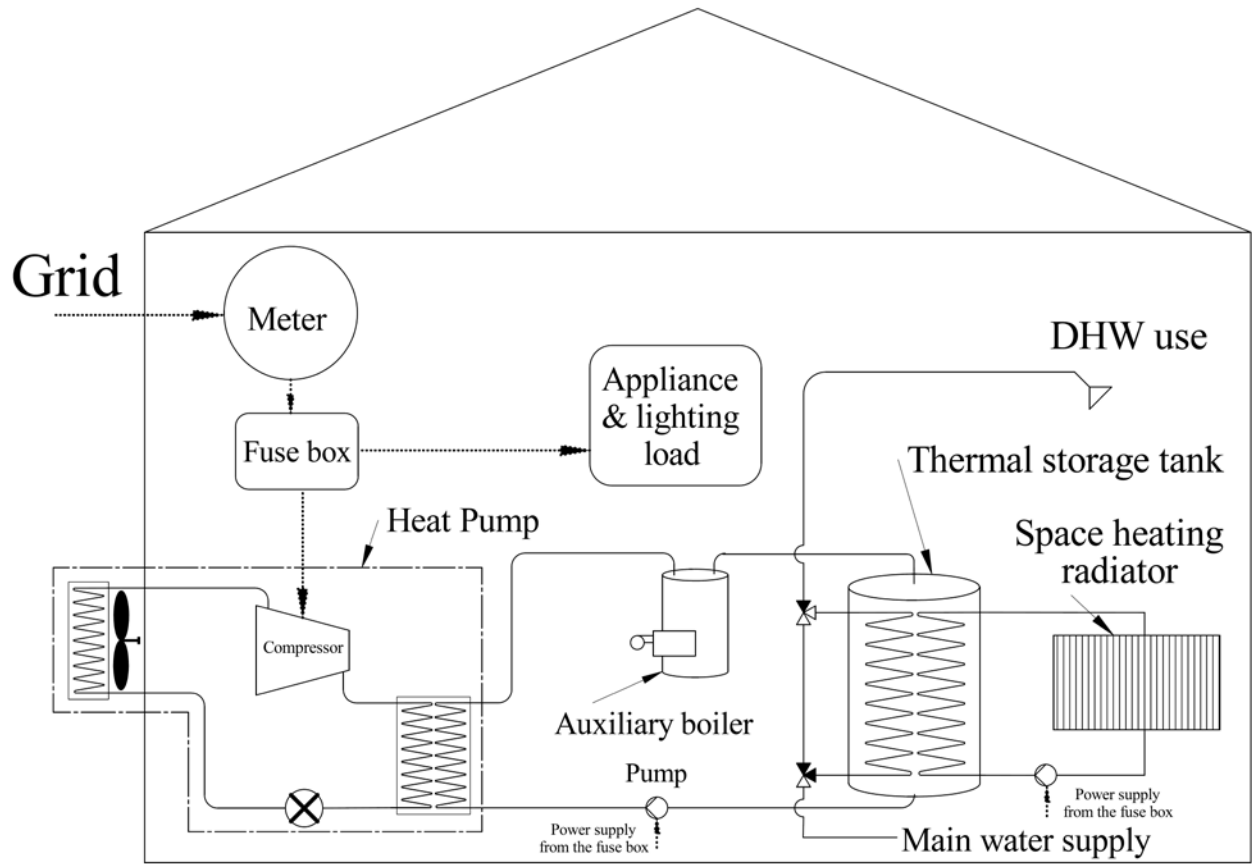
Figure captions:

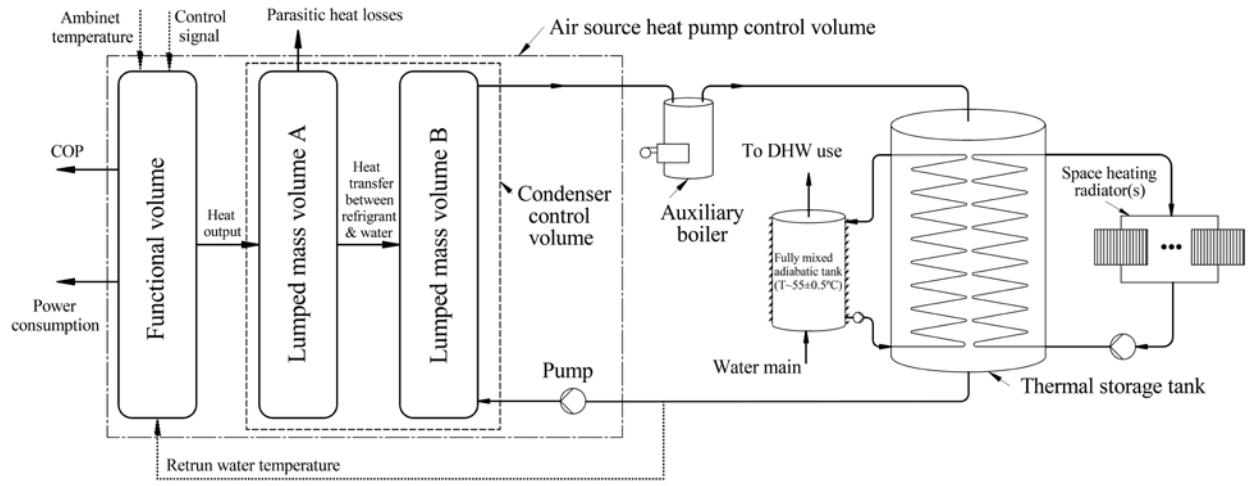
Fig. 1. A typical house with air to water heat pump retrofit.

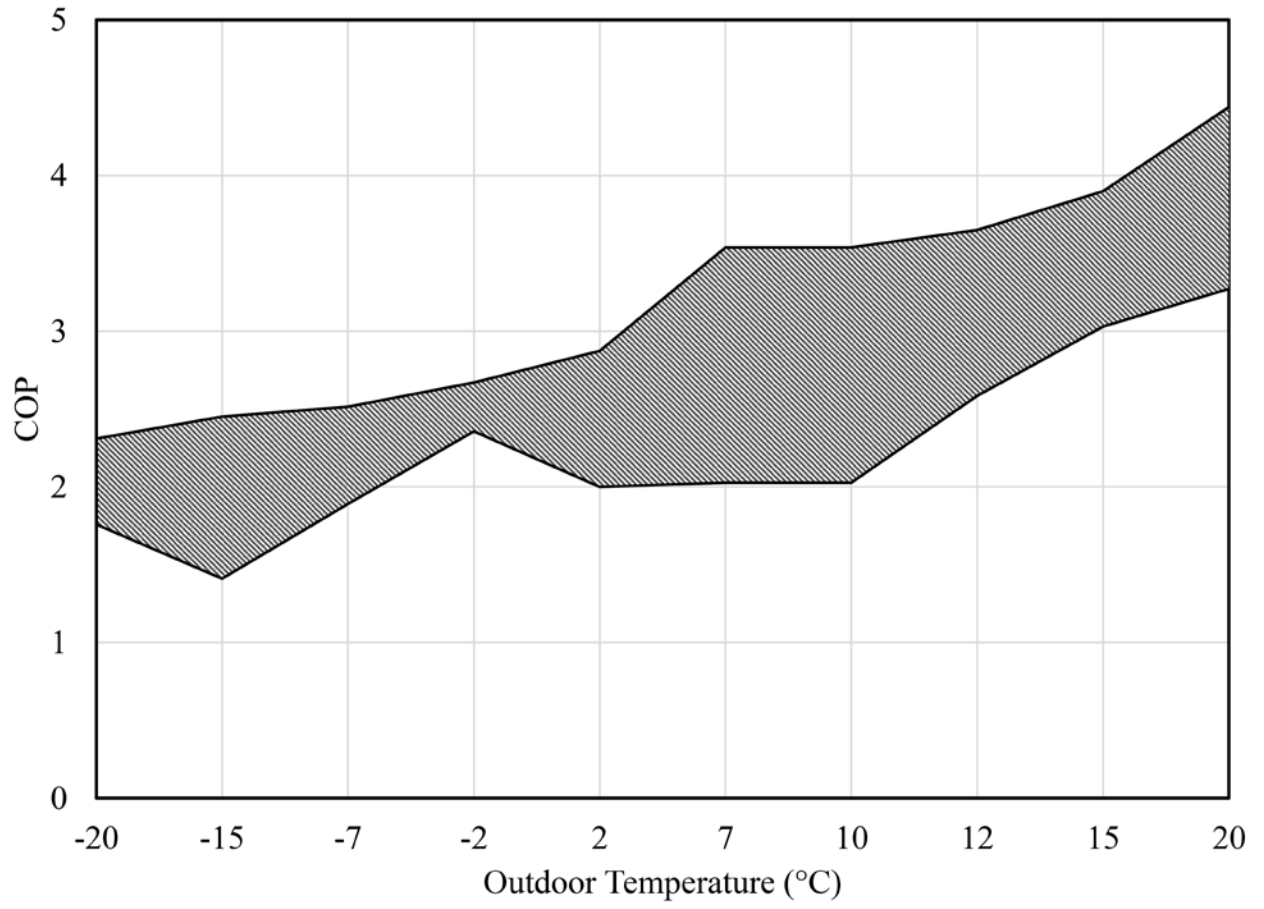
Fig. 2. Air to water heat pump modeling approach in ESP-r.

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).







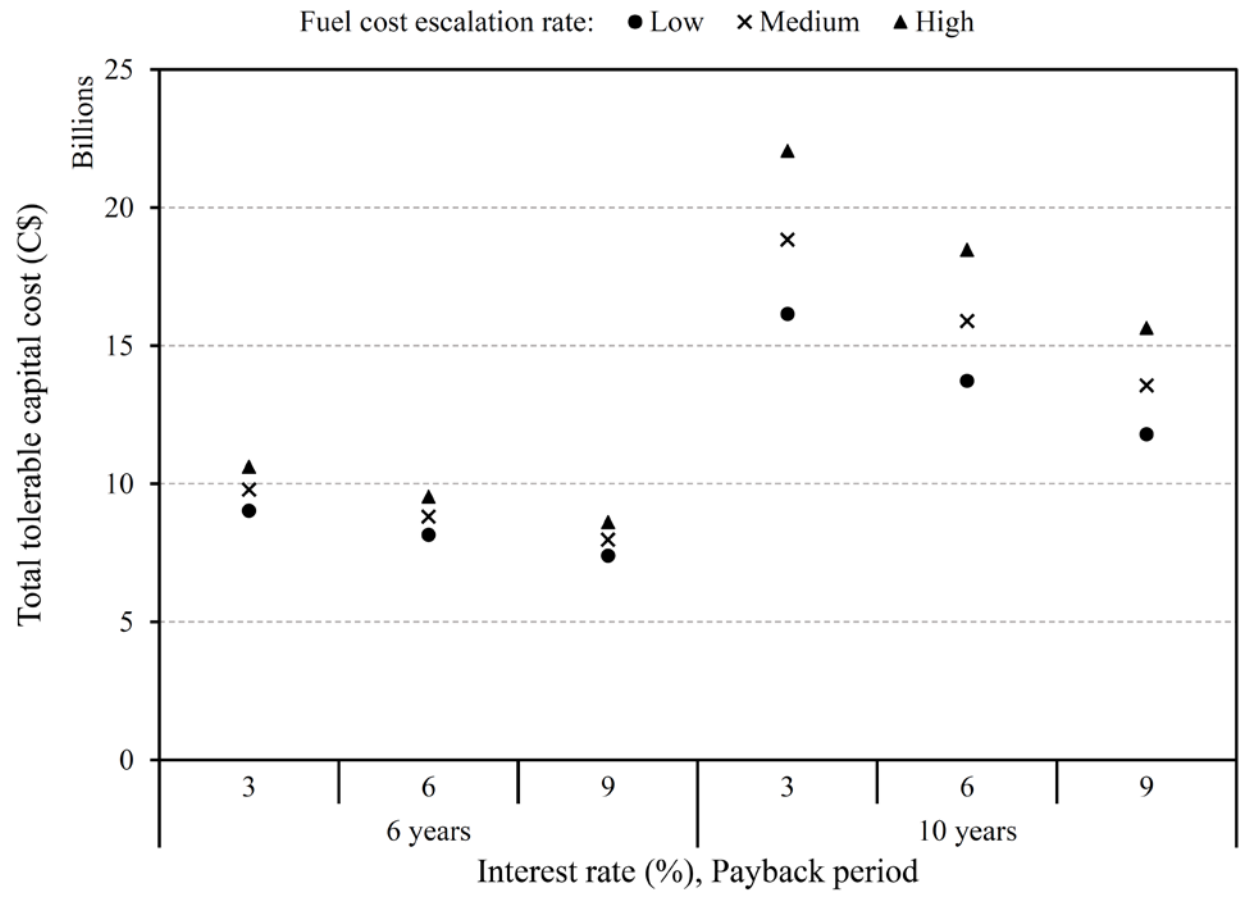


Table 1. Parameters of AWHP system components based on the existing heating system capacity

ASHP system components	Parameter	Unit	Existing heating system nominal capacity (kW)			Reference
			>21	11-16	<11	
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	[44]
	b ₁	K ⁻¹	-0.007	-0.006	-0.007	
Fan power	P _{fan}	W	480	230	190	[3, 44]
	t ₀	s		360		
Duration of defrost	t ₁	s/%		2.4		[3, 44]
	P _{nom,buner}	kW	19	19	18	
	(tan φ) _{T>50°C}	°C ⁻¹		-0.15		
(tan φ) _{T≤50°C}	°C ⁻¹		-0.25			
NG fired boiler	P _{nom,buner}	kW	18	18	11	[50]
	tan φ	°C ⁻¹		-0.15		
Oil fired boiler	V _{store}	USG	400	260	200	[43]
	M _{unit}	kg		49		
	C _{avg}	J/kgK		1350		
Radiator	Q ₀	W		967		[43]
	T _{s,0}	°C		55		
	T _{r,0}	°C		35		
	T _{env,0}	°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	17 Sep	3 Jun	Zone main 1	20	22
	pump	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	$1.15 \times 1/\eta$
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

Province	Energy (PJ)					GHG emissions (Mt of CO _{2e})			
	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		Exist	AWHPR	Exist	AWHPR	N-E	EL		N-E	EL	
		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

Province	Energy savings (PJ)					GHG emission reductions (Mt of CO _{2e})			
	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