Techno-economic Assessment of Solar Assisted Heat Pump System Retrofit in the Canadian Housing Stock

S. Rasoul Asaee[1], V. Ismet Ugursal[1], Ian Beausoleil-Morrison[2]

1 Department of Mechanical Engineering, Dalhousie University, Halifax, NS Canada B3H 4R2

2 Sustainable Building Energy Systems, Department of Mechanical and Aerospace Engineering, Carleton University, Ottawa, ON Canada K1S 5B6

Abstract

The techno-economic feasibility of retrofitting existing Canadian houses with solar assisted heat pump (SAHP) is investigated. The SAHP architecture is adopted from previous studies conducted for the Canadian climate. The system utilizes two thermal storage tanks to store excess solar energy for use later in the day. The control strategy is defined in order to prioritise the use of solar energy for space and domestic hot water heating purposes. Due to economic and technical constraints a series of eligibility criteria are introduced for a house to qualify for the retrofit. A model was built in ESP-r and the retrofit was introduced into all eligible houses in the Canadian Hybrid Residential End-Use Energy and GHG Emissions model. Simulations were conducted for an entire year to estimate the annual energy savings, and GHG emission reductions. Results show that the SAHP system performance is strongly affected by climatic conditions, auxiliary energy sources and fuel mixture for electricity generation. Energy consumption and GHG emission of the Canadian housing stock can be reduced by about 20% if all eligible houses receive the SAHP system retrofit. Economic analysis indicates that the incentive measures will likely be necessary to promote the SAHP system in the Canadian residential market.

Keywords: Solar thermal, Heat pump, Building performance simulation, Residential energy consumption, Residential GHG emission

Nomenclature

ACSH	annual cost savings for the house due to energy savings in a uniform series, continuing for n periods (C$)
ATCCH	average tolerable capital cost per house (C$)
CO_{2e}	equivalent CO_2 (kg)
E	energy saving per period for each fuel type (unit depends on fuel type; kg, liter, kWh, etc.)
E_{aux}	energy consumption of auxiliary heating system (GJ)
E_{ref}	energy consumption of reference heating system (GJ)
E_{total}	total energy consumption (GJ)
$E_{total,ref}$	total energy consumption of reference system (GJ)
e	fuel cost escalation rate (decimal)
F	fuel price per unit of each fuel type (C$/unit)
F_R	collector heat removal factor
$f_{sav,ext}$	extended fractional energy saving (%)
$f_{sav,therm}$	fractional thermal energy saving (%)
f_{sol}	solar fraction (%)
G_T	solar radiation incident upon the collector (W/m^2)
i	interest rate (decimal)
m	number of different fuels used in a house
NH	number of houses
n	acceptable payback period (year)
$P_{el,pump.DHW}$	pump power for DHW heating loop (W)
$P_{el,pump.SH}$	pump power for heat delivery to the space (W)
$P_{nom,burner}$	nominal capacity of auxiliary boiler (W)
Q_{DHW}	thermal energy for domestic hot water heating (GJ)
Q_{SH}	thermal energy for space heating (GJ)
Q_{sol}	thermal energy delivered by solar system (GJ)
SPF_{SAHP}	Seasonal performance factor of solar assisted heat pump
TCC	tolerable capital cost (C$)

TCCH	tolerable capital cost of the upgrade for each house (C$)
TTCC	total tolerable capital cost (C$)
T_{amb}	ambient temperature (K)
T_c	cold side temperature (°C)
T_h	hot side temperature (°C)
T_{in}	collector inlet temperature (K)
T_{ref}	reference temperature (°C)
T_{ret}	return water temperature (°C)
$W_{el,SAHP}$	electricity consumption of solar assisted heat pump (GJ)
W_{HP}	electricity consumption of heat pump (GJ)
W_{par}	parasitic power (GJ)
$W_{par,ref}$	parasitic power of reference system (GJ)

Greek symbols

$(\tau\alpha)_n$	normal-incidence transmittance–absorptance
ΔT	temperature difference
η_b	boiler efficiency
η_{el}	electrical efficiency (inclusive of electricity generation, transmission and distribution efficiency)
η_{ref}	full load boiler efficiency at the reference temperature
φ	slope of the efficiency curve

Abbreviations

AB	Alberta
AL	appliance and lighting
AT	Atlantic provinces (i.e. NF, NS, PE and NB)
AWHP	air to water heat pump
BC	British Columbia
CHREM	Canadian Hybrid Residential End-Use Energy and GHG Emissions model

COP	coefficient of performance
CSDDRD	Canadian single detached and double/row database
DHW	domestic hot water
EIF	emission intensity factor
GHG	greenhouse gas
HP	heat pump
ICE	internal combustion engine
IEA	international energy agency
MB	Manitoba
NB	New Brunswick
NF	Newfoundland and Labrador
NG	natural gas
NS	Nova Scotia
NZE	net zero energy
OT	Ontario
PCM	phase change material
PE	Prince Edward Island
PR	Prairie provinces (i.e. MB, SK and AB)
QC	Quebec
SAHP	solar assisted heat pump
SDHW	solar domestic hot water
SE	Stirling engine
SHC	solar heating and cooling
SK	Saskatchewan

Introduction

Solar energy is one of the main sources of renewable energy for residential applications. Solar thermal energy is used for space heating and cooling as well as domestic hot water (DHW) heating in the residential sector. The non-concentrating liquid cooled thermal collector (e.g. flat plate collector) is the most popular technology to utilize solar energy in buildings. Depending on the geographical location, climatic condition and solar thermal collector installation, water supply temperature from a flat plate collector may vary widely through the year. Thus, traditionally an auxiliary source of energy is integrated into the solar based heating systems to supply energy when solar energy is either not available (i.e. at night) or not sufficient (e.g. on cloudy days) to meet the demand. Integrating solar thermal collectors with a heat pump (HP) system is an energy efficient alternative for this purpose. Heat pumps capture aerothermal, geothermal or hydrothermal energy at the expense of thermodynamic work. Solar thermal collector and HP systems can be combined in different ways. A common method is to deliver the solar thermal energy to the evaporator of the heat pump in a series configuration to enhance the system performance [1]. In this configuration, efficiency gains compared to standalone solar thermal and HP systems are realized because the high evaporator temperature increases the COP of the HP [1]. Thus, the solar assisted heat pump (SAHP) system is expected to provide superior performance compared to conventional solar thermal systems such as solar domestic hot water (SDHW) and solar combisystem; however, long term field performance and economic feasibility require in-depth study. To address these issues, numerous studies were conducted, and results reported in the literature.

The International Energy Agency (IEA) Solar Heating and Cooling (SHC) programme launched Task 44 [2] with the goal to deliver optimized integration of solar thermal and heat pump systems, primarily for single family houses. Several systems were investigated and a series of recommendations were provided for SAHP system design and optimization. According to the survey conducted within the IEA SHC Task 44 most of the market ready SAHP systems are designed to serve both space and DHW heating [1]. Different system architectures are categorized under four main sections (a) parallel, (b) series, (c) regenerative, and (d) complex. A wide range of measured data was gathered from 50 different systems in seven European countries for one to two years. Simulation results within the IEA SHC Task 44 indicated that solar contribution can be significant to reduce primary energy consumption and greenhouse gas (GHG) emissions. It was concluded that the solar and HP systems will be a part of solutions to fulfill the demands for net zero annual energy balance [1].

The performance of SAHP systems in different climatic and operating conditions was studied by several researchers. For example, Chu et al. [3] assessed the feasibility of a SAHP system in a high performance house designed and built for the U.S. Department of Energy's Solar Decathlon 2013 Competition. A numerical model was developed in TRNSYS 17 [4] for this study. Results show that the free energy ratio (the energy not purchased such as solar energy divided by total energy used) of 0.583 can be achieved using SAHP system in Ottawa, Ontario. The study revealed that flat plate collectors provide a superior performance compared to evacuated tube solar collectors for SAHP applications. Impact of heat pump performance, source side and load side input temperatures, solar collector array area and stratifications in the thermal storage tank on the overall performance of the SAHP system were investigated. Bakirci and Yuksel [5] carried out an experimental study to evaluate the performance of a SAHP system for a residential application in Erzurum, Turkey. Data were collected from an actual system from January to June when the outdoor temperature was in -10.8°C to 14.6°C range. Results indicated that the overall COP of the SAHP system was about 2.9. They concluded that the various parameters including operating conditions, economic viability and environmental impacts may affect the SAHP system selection and design. Thermal storage was found to be a significant component that affects the overall performance of a SAHP system. Liang et al. [6] used a numerical model to study a solar assisted air source heat pump system with flexible operational modes. The impact of solar collector area on the overall performance of the system was investigated. Results show that the COP of the heat pump increased due to increasing solar collector area and solar radiation intensity or sunny days in the heating season. Moreno-Rodríguez et al. [7] developed a mathematical model to determine the operating characteristics of a direct expansion SAHP system. The model predicts the evaporator temperature and energy transfer based on the outdoor temperature, global radiation and wind speed. The model was validated using experimental data. The measured COP was between 1.7 and 2.9 for the load temperature of 51°C. Kong et al. [8] studied a direct expansion SAHP system for DHW heating and used a simulation approach to predict the system performance. The model was validated using experimental measurements. Results show that the solar radiation, ambient temperature and compressor speed have the largest impact on the system performance.

In an extensive effort the Solar Thermal Research Laboratory at the University of Waterloo conducted a series of studies to investigate the solar thermal system performance in Canada. Sterling and Collins [9] used a numerical model in TRNSYS to compare the energy consumption of a dual tank indirect SAHP system to that of a traditional SDHW and an electric DHW system. An identical load profile and water draw were applied to each system. Results show that the SAHP system provides the lowest energy consumption and operating costs. Wagar [10] experimentally investigated a single tank indirect SAHP system and used measured data to validate a TRNSYS model. Using the validated model they found that the heat pump capacity should not exceed the capacity of the solar thermal array under moderate solar heating conditions. Temperature limits impose additional restrictions on heat pump operation and limits its solar collection benefits when little solar radiation is available and load temperature exceeds 45°C. Using a small or variable speed heat pump was recommended to increase the cycle time and match the heat input of the solar collector. Using findings of this study, Banister et al. [11-14] built a dual tank SAHP system to create additional modes of operation and decrease the amount of purchased energy. Results show that the system was able to maintain the hot water temperature in the 53-57°C range during 99.9% of the year. The proposed SAHP system configuration showed a superior performance compared to single tank SAHP and SDHW systems.

In a review paper, Chu and Cruickshank [15] reviewed a series of studies on SAHP system for residential applications. They were not able to identify an optimal system configuration for the Canadian residential sector among the systems reported in the literature. They concluded that integration of solar thermal and heat pump systems provides an opportunity to offset space and DHW heating in the Canadian residential sector. Since the overall energy consumption and environmental footprint of a building is affected by parameters such as climatic condition, building geometry, construction material, occupancy level, occupant behaviour, primary energy source, and heating, ventilation and air conditioning system performance, it is necessary to evaluate the heating system performance in an integrated analysis for an accurate assessment of system performance.

This study is a part of ongoing effort to introduce strategies and incentive measures to convert existing houses across Canada into net/near-net zero energy (NZE) buildings [16]. The techno-economic feasibility of a series of high efficiency and alternative energy technology retrofits including envelope modifications such as glazing and window shading upgrades, as well as installation of SDHW systems, phase change material (PCM) thermal energy storage, internal combustion engine (ICE) and Stirling engine (SE) based cogeneration systems, solar combisystem, and air to water heat pump (AWHP) systems have been investigated [17-26]. This study evaluates the techno-economic performance of SAHP system.

2. Methodology

This study is focused on large scale retrofit of SAHP systems in existing houses across Canada. Thus, the Canadian Hybrid Residential End-Use Energy and GHG Emissions Model (CHREM)[1] [27, 28] is used. CHREM is based on the Canadian Single-Detached Double/Row Database (CSDDRD) [29] which statistically represents the CHS with close to 17,000 unique house files. The CSDDRD was developed from the survey data from the EnerGuide for Houses database [30], Statistics Canada and Natural Resources Canada housing surveys [31] and other available housing databases.

CHREM uses a high-resolution building energy simulation program ESP-r [32] as the simulation engine. ESP-r is an integrated energy modeling software which evaluates the thermal, visual and acoustic performance as well as energy consumption and GHG emissions of buildings. ESP-r has been validated through a vast amount of research results [33] and has been used in many research studies.

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 [29],
- A neural network model of the appliances and lighting (AL) and DHW energy consumption of Canadian households [34],

---

[1] CHREM was developed through the Solar Building Research Network (SBRN) and was expanded through the Smart Net-zero Energy Building Strategic Research Network (SNEBRN).

- 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 [35],
- 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 SAHP systems, can be estimated using CHREM as follows:

(i) Identify houses suitable to receive the upgrade/technology: For SAHP system retrofit, only houses with a basement or a mechanical room and a proper location for collector installation would be suitable. Therefore, such houses has to be identified in the CSDDRD.

(ii) Modify the CHREM to add the upgrade/technology retrofit to the input files of selected houses 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 [35]. Since CSDDRD is representative of the CHS, the CHREM estimates can be extrapolated to the entire CHS using scaling factors [27, 28].

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, solar combisystem and AWHP system [17-26].

2.1. System configuration

The SAHP system configuration developed by Banister et al. [11] is used in this study. Banister et al. investigated the solar thermal system for the Canadian climate and recommended a dual tank configuration to enhance solar energy contribution. As shown in Figure 1, the SAHP system is comprised of a flat plate collector array, a float tank, auxiliary heating, a hot water tank, a hydronic heat delivery system and a DHW system. The float tank and the associated three-way valves (valves A, B, C and D shown in Figure 1) are included to enable the system to harvest solar energy even during low radiation periods. This is achieved by controlling the flow to the float tank so that tank temperature follows the collector temperature [11]. When the system calls for heat and the float tank temperature is above the hot water tank temperature, the water is circulated directly from the float tank into the hot water tank. As shown in Figure 1, a combination of diverging and converting three-way flow valves are used to maintain the DHW temperature. This strategy ensures that the hot water supply temperature remains in the desired range while the DHW water draw varies during a day.

The HP extracts heat from float tank when its temperature is below the hot water tank. This enables the system to capture more solar energy compared to a conventional solar thermal system. If the HP nominal capacity is much larger compared to the thermal capacity of float tank, the float tank temperature will drop in a short time causing instability in the operation of the SAHP [13].

When the SAHP is unable to supply the total heat demand of the building, an auxiliary heating system makes up the shortfall. The three-way converging and diverting flow valves are used to achieve this strategy. When the solar energy exceeds the building load and both storage tanks are charged up to maximum capacity the excess thermal energy is discarded to the environment.

2.2. Modeling of the SAHP system

Each system component and building section (including thermal zones, walls, windows and doors) is expressed as a control volume in the ESP-r simulation domain. The conservation of mass and energy equations are solved for each control volume. Conduction, convection and radiation heat transfer modes are considered where applicable. The DHW draw and AL load profiles along with the space heating demand define the building loads in individual houses. A brief discussion of the major components of the SAHP and the control system is presented below.

2.2.1. Flat plate collector array

The flat plate collector model used in this work was developed and incorporated into the ESP-r by Thevenard et al. [36]. Flat plate collectors are modelled using a second order polynomial equation that defines the collector efficiency as shown in Equation (1).

$$\eta = F_R(\tau\alpha)_n - a\frac{\Delta T}{G_T} - b\frac{\Delta T^2}{G_T} \tag{1}$$

$$\Delta T = T_{in} - T_{amb} \tag{2}$$

where the F_R is the collector heat removal factor, $(\tau\alpha)_n$ is the normal-incidence transmittance–absorptance, and G_T is the solar radiation incident upon the collector. ΔT is the temperature difference between the collector inlet temperature (T_{in}), and the ambient temperature (T_{amb}) as shown in Equation (2), which is based on the North-American definition of solar collector efficiency [37]. Flow rate and incidence angle corrections in off-test conditions are done using methods discussed in Duffie and Beckman [37]. The flat plate collector data used in the simulations are given in Table 1 [38] and correspond to a typical residential flat plate collector available in Canadian market.

2.2.2. Storage tanks

The storage tanks are modeled as stratified tanks with immersed helical heat exchangers. The model developed and incorporated into ESP-r by Thevenard and Haddad [39] is used. The storage tank is divided into 100 control volumes to simulate the stratification. Conservation of mass and energy equations are solved for each control volume, in which the fluid properties are considered to be uniform. The heat transfer inside and through the walls of immersed heat exchangers are assumed to be forced convection and conduction, respectively, while mixed free and forced convection are assumed to govern the heat transfer outside the heat exchangers.

2.2.3. Auxiliary heating

The auxiliary heating system is modeled as a condensing boiler where natural gas is available, and non-condensing boiler where heating oil is used. The model was developed and incorporated into ESP-r by Hensen [40]. An efficiency curve is defined for each boiler to determine the instantaneous thermal efficiency based on the return water temperature as shown in Equation (3).

$$\eta_b = \left[\eta_{ref} - tan\,\varphi \times \left(T_{ref} - T_{ret}\right)\right] \tag{3}$$

where η_b is the boiler efficiency, η_{ref} is the full load boiler efficiency at the reference temperature, φ is the slope of the efficiency curve, T_{ref} is the reference temperature, T_{ret} is the return water temperature. The transient status of boiler during the start-up and shutdown is modeled using a multiplier in the efficiency equation in that period. The data used in this study are given in Table 1. These data are representative of the commonly used residential boilers in the Canadian market [41, 42].

2.2.4. Heat pump system

The heat pump system is modeled using a grey-box approach. Instead of modeling individual components of the HP, the behaviour of the HP system is modeled as a whole based on actual performance data. This approach was used for modeling of different energy systems including cogeneration [43] and air to water heat pump [44] in ESP-r. Banister et al. [12, 13] developed a series of third order polynomial equations for compressor power draw, heat capture and net heat delivery of a water source HP. In this study the second order polynomial Equation (4) is used to calculate the COP of the HP.

$$\mathrm{COP}=a_0+a_1(T_h-T_c)+a_2(T_h-T_c)^2 \quad (4)$$

where the T_h and T_c are the hot side and cold side temperature, respectively. The constant factors (a_0-a_2) are derived using the data reported by Banister et al [12, 13] and performance data published for commercially available water source heat pumps in the Canadian market [45]. The constant factors are provided in Table 1. The COP remains constant for the cold side temperatures greater than or equal to 30°C. The heat supply of HP is calculated based on the COP, return water temperature and flow rate. The power draw of the compressor is then calculated based on the load on the HP and the instantaneous COP of the HP. The heat extraction and heat addition of HP are then added as source terms in the energy balance equations of the evaporator and condenser, respectively.

2.2.5. System sizing

As discussed earlier, the HP enables the SAHP system to extract solar energy at a lower temperature compared to a conventional solar thermal system. Asaee et al. [25] investigated the impact of solar combisystem retrofit in existing Canadian houses. The results showed that solar energy captured by the solar combisystem is not sufficient to fulfill the thermal energy demand of a house in Canada over a whole year. Thus, this study adds a HP to the system to increase the solar contribution, and uses the same solar array design used in the above mentioned study [25] for the SAHP system, i.e. solar collectors connected in parallel rows, with each row containing three collectors. The gross and aperture areas of the selected flat plate collector are 2.982 m^2 and 2.870 m^2, respectively, and the number of rows is determined based on the existing heating system capacity and the available roof area of each house. When the desired area for solar collectors is equal to or larger than the total available roof area (facing south, south-east, and south-west), the roof is considered to be totally covered with solar collectors [25]. Also as in the previous study, the hot water tank volume is determined to maintain a storage volume to collector area ratio between 50 to 100 L/m^2. Since the float tank temperature can exceed the hot water tank temperature, its presence is to enhance the overall solar energy utilization of the SAHP. However, since the float tank will occupy space in the building, its volume is limited to 450 litre according to the recommendation of Banister et al. [11, 13].

2.2.6. Hydronic system

The components of the hydronic system are sized based on the nominal capacity of the heating system. Pumping power is calculated using Equations (5) and (6) [24].

$$P_{el,pump.SH} = 90\text{W} + 2\times10^{-4} P_{nom,burner} \tag{5}$$

$$P_{el,pump.DHW} = 49.4\text{W}\times\exp\left(0.0083\,\frac{P_{nom,burner}}{\text{kW}}\right) \tag{6}$$

where $P_{el,pump.SH}$ is the pump power for heat delivery to the space, $P_{el,pump.DHW}$ is the pump power for DHW heating loop and $P_{nom,buner}$ is the nominal capacity of auxiliary boiler.

A standard radiator selected from the Express Radiant Ltd product catalogue [46] is used. CHREM apportions the capacity of a space heating system to each conditioned zone based on volume [27].

Thus, the number of radiators installed in each thermal zone is determined based on the ratio of each thermal zone volume to the total building volume.

2.3. Control strategy

The control of the system is accomplished in three modules: (a) collector loop, (b) thermal management, and (c) heat delivery.

The collector loop module includes the flat plate collector array, solar pump and float tank. As discussed earlier, the float tank temperature is not controlled and its temperature follows the collector temperature variations. Hence, when solar energy is available and the float tank has available capacity for thermal energy storage, heat is delivered from the collectors to the tank. To simulate this operation, a control loop was implemented in the simulation model to turn on the solar pump when the collector temperature and float tank temperature difference exceeds 5°C and continue until the temperature difference drops to 1°C. This strategy ensures that the solar pump does not experience rapid ON/OFF cycles.

The thermal management module includes the heat pump, auxiliary boiler, hot water tank and three-way converging and diverging flow valves. This module is the most complex part of the SAHP system control algorithm. The main objective of the SAHP system is to capture as much free renewable energy as possible. Thus, the thermal management control algorithm is designed to prioritize the use of free renewable energy. The control algorithm follows the order below:

1. When the hot water tank is not fully charged (the hot water tank is below 50°C), the system calls for heat,
2. The call for heat signal from the hot water tank initially turns ON the hot water pump,

3. When the float tank temperature is above the hot water tank temperature the system bypasses the HP and circulates water directly from the float tank into the hot water tank. For this purpose the B.2 and D.2 outlet legs of the three-way diverging valves B and D are closed and water is directed through the B.3 and D.3 outlet legs (Figure 1),
4. When the float tank temperature is below the hot water tank temperature but it is not fully depleted (float tank temperature is above 2°C), the water is circulated through the HP. For this purpose, the B.3 and D.3 outlet legs of the three-way diverging valves B and D are closed and water is directed through the B.2 and D.2 outlet legs (Figure 1). In this state, both the HP and float tank pumps are ON,
5. When the available thermal energy in the float tank is not sufficient (float tank temperature is below 1°C), the system bypasses the float tank by closing the B.3 outlet leg of the three-way diverging valve B and circulates water through the B.2 outlet leg (Figure 1). In this state the HP and float tank pump are OFF and the auxiliary boiler supplies heat to the water,
6. When temperature of water that leaves the auxiliary boiler is below the 50°C the auxiliary boiler is turned ON to heat the water to 55°C.
7. The call for heat is terminated as soon as the hot water tank temperature reaches 55°C. The value of control system trigger for each component is presented in Table 2.

The hydronic system module is designed to control the delivery of the heat from the hot water tank for space and DHW heating. The hydronic heat delivery system supplies heat for space heating. Temperature control is by the main zone thermostat, thus the other zones receive heat only when the main zone calls for it. The space heating pump is triggered when the main zone temperature drops below the thermostat set point (20°C) and deactivates as the main zone temperature exceeds the upper limit of the dead-band temperature (22°C). To simplify the model, the operation of the combination of DHW service valves is simulated as a small fully mixed adiabatic tank held at 55±1°C and DHW draw and equivalent main water supply is applied into this tank, emulating the operation of the valves in a real system.

2.4. Eligible houses

Due to geometrical constraints not all houses in the Canadian housing stock are suitable for a SAHP system retrofit. To retrofit a flat plate collector on an existing house, a suitable roof area is necessary in terms of area and exposure. For residential heating in adverse climates, Iqbal [47] recommends to use a collector tilt angle of “latitude–10°” in case of 10-20% solar contribution in thermal load supply, and a linear increase to “latitude+15°” for 80% solar contribution. Since major Canadian cities are located in a latitude range of 45-55°, 45° is selected as the collector tilt angle for installation on flat roofs. Also, this tilt angle reduces the chance of snow accumulation on collectors during the winter time. The solar insolation in northern hemisphere is maximum in the south direction. Thus, to be considered eligible for SAHP retrofit, a house should have the required roof area in the south, southeast or southwest direction for collector installation.

Since the SAHP retrofit will require the addition of new mechanical equipment as shown in Figure 1, a house needs to have a basement or mechanical room for the installation of this equipment. The presence of a mechanical room is not identified in CHREM. However, since all natural gas or oil fired hydronic and forced air systems require a mechanical room, houses that use such heating systems are considered eligible for SAHP retrofit. Since shading data are not provided in the CSDDRD, the reduction in solar collector performance due to neighbouring obstructions is not considered in this study.

2.5. GHG emission estimation

The GHG emission are evaluated and reported as “equivalent CO_2” (CO_{2e}) emitted per unit input energy. CO_{2e} is defined by converting GHG emissions from a fossil fuel combustion, such as CH_4 and N_2O, to equivalent CO_2 emission taking into account their global warming potentials as shown in Equation (7) [28, 35].

$$CO_{2e}=CO_2+25CH_4+298N_2O \tag{7}$$

Due to availability of different onsite fuels, various types of energy conversion devices in existing houses and vast differences in the fuel mixture for electricity generation in each province, CHREM estimates the GHG emission of a house by adding the emissions from fossil fuels consumed onsite and the emissions from electricity generation, determined separately for each province.

The GHG emissions due to onsite fossil fuel consumption is determined based on the fuel type and efficiency of the energy conversion device. The GHG emission is updated in each time step using the actual fossil fuel consumption [28]. The CO_2 emission by wood combustion returns to the atmosphere where the CO_2 that was recently removed by photosynthesis as the tree grew. Hence, this process can be accounted as a stage in natural carbon cycle and thus no GHG emission is reported for the combustion of wood [35].

The GHG emission associated with electricity use is determined based on the amount of fossil fuel consumption to generate and deliver electricity to a dwelling. For this purpose, the GHG emission intensity factor (EIF) is defined for electricity generation and delivery. The GHG EIF is defined as the level of CO_{2e} emission for generation and delivery of 1 kWh electricity to the end-user. In Canada electricity generation is under the jurisdiction of provincial utility companies. Thus, provincial GHG EIF is estimated using the primary energy mixture used for electricity generation, efficiency of energy conversion and transmission, and distribution losses. Also, typically utilities consider different types of electricity generation methods during peak and base periods. Thus, different average and marginal GHG EIFs are developed to address electricity generation within the base and peak periods. The provincial average and marginal GHG EIF developed by Farhat and Ugursal [35] 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.

2.6. Performance measures

Dimensionless performance factors are useful to compare the energetic performance of different types of renewable energy systems. Here, four performance factors are used:

- Seasonal performance factor (SPF) is the overall energy efficiency of the whole system over a year (or a season) calculated as the ratio of the overall useful energy output to the overall driving energy input [1]. For a SAHP system the useful energy output is defined as the total thermal energy delivered by the SAHP system for space and DHW heating minus the auxiliary energy, while the energy input is the energy consumption of the HP. Thus, the SPF of a SAHP is as shown in Equation (8).

$$SPF_{SAHP} = \frac{Q_{SH}+Q_{DHW}}{W_{el,SAHP}+E_{aux}} \tag{8}$$

- Solar fraction (f_{sol}) is the ratio of delivered solar energy to the total energy demand. In a SAHP system the total energy demand consists of the space and DHW heating demand. Thus, for an SAHP system, f_{sol} is defined as shown in Equation (9):

$$f_{\mathrm{sol}} = \frac{Q_{Sol}}{Q_{SH}+Q_{DHW}} \tag{9}$$

- Fractional thermal energy saving ($f_{sav,\ therm}$) is an indicator to assess the impact of a specific retrofit option such as solar thermal system in relation to a reference system on thermal energy use [1]. For an SAHP, this is defined as shown in Equation (10):

$$f_{\mathrm{sav,therm}}=1-\frac{E_{aux}}{E_{ref}} \tag{10}$$

Existing heating systems in the houses are taken as the reference system.

- Extended fractional energy saving is an indicator to assess the impact of a specific retrofit option such as solar thermal system in relation to a reference system on total auxiliary energy use [1]. For an ASHP, this is defined as shown in Equation (11):

$$f_{\mathrm{sav,ext}}=1-\frac{E_{total}}{E_{total,ref}}=1-\frac{E_{aux}+\frac{W_{par}+W_{HP}}{\eta_{el}}}{E_{ref}+\frac{W_{par,ref}}{\eta_{el}}} \tag{11}$$

Asaee et al. [25] studied techno-economic performance of solar combisystem retrofit in the CHS. Fractional thermal energy saving and extended fractional energy saving were used to assess the performance of solar combisystem in the Canadian context. To compare the performance of solar combisystem and SAHP system and evaluate the impact of HP on solar thermal system retrofit in existing Canadian houses these parameters are used in this study with the same criteria. The fractional energy savings definition remains the same while power consumption of HP is added to the extended fractional energy saving definition as shown in Equations (10) and (11).

The value of these parameters are evaluated for individual houses and provincial average are also calculated.

2.7. Economic analysis methodology

Accurate estimation of SAHP system initial investment 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 SAHP 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 SAHP 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 [48]. 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 SAHP 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:

$$\mathrm{TCCH}=\begin{cases}\mathrm{ACSH}\left[\dfrac{1-(1+e)^{n}(1+i)^{-n}}{i-e}\right] & \text{for} \quad i\neq e\\ \mathrm{ACSH}\times n(1+i)^{-1} & \text{for} \quad i=e\end{cases} \tag{12}$$

$$\mathrm{ACSH}=\sum_{\mathrm{j}=1}^{\mathrm{m}}(\mathrm{F}\times\mathrm{E})_{\mathrm{j}} \tag{13}$$

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 SAHP 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 SAHP 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 SAHP system retrofit. ATCCH is calculated by dividing the total tolerable capital cost by the number of houses:

$$\text{ATCCH}=\text{TTCC}/\text{NH} \qquad (14)$$

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

$$\mathrm{TTCC}=\sum_{i=1}^{NH}\mathrm{TCCH}_i \tag{15}$$

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 is conducted. The interest rates used in the analysis are based on the Bank of Canada Prime Rate [49], which was about 1% in June, 2016. 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 4 [50, 51].

For each fuel type, a set of low, medium and high fuel cost escalation rates shown in Table 5 are used in the sensitivity analysis. These values are based on the medium rates extracted from the National Energy Board of Canada [52] and Energy Escalation Rate Calculator [53].

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 SAHP systems.

It is likely that an SAHP 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.

3. Results and Discussion

The energy consumption and GHG emissions of the CHS in its current state (base case) estimated using CHREM are given in Table 6 by energy source and province. The accuracy of the base case estimates of CHREM was validated in Swan et al. [28].

The CSDDRD was examined to identify houses that have proper roof area in desired direction and suitable space for mechanical system installation. The results show that about 37% of existing Canadian houses can satisfy both conditions. Due to different construction characteristics the penetration levels are not the same in all provinces as shown in Table 7. The predicted penetration level of SAHP is relatively low in QC. Since the majority of existing houses in QC use baseboard convection electric heating systems, they do not have mechanical rooms. If energy efficiency incentives encourage the homeowners to allocate a space for a mechanical room, the penetration level of SAHP systems in QC would likely increase.

As shown in Table 6, energy consumption and GHG emission values vary significantly across Canada. Parameters including fuel availability, cost, house vintage and heating system type influence the choice of energy source in each province. Due to rich hydro-electric sources in NF, QC, MB and BC, electricity prices in these provinces are lower compared to other provinces, and electricity use for space and DHW heating is higher. For example, in QC about 83% of energy demand for residential customer is supplied by electricity. As a result of such fundamental differences between provinces, SAHP system retrofit energy savings and feasibility show substantial differences. Hence, the results are presented below in three sections: energy savings, GHG emission reductions and economic feasibility.

3.1. Energy savings

Bulk energy savings and average energy savings per house are presented in Table 7. Average annual energy savings per house for all provinces other than NB and BC vary within the range of 79 GJ and 93 GJ due to the differences in the fuel mix and house characteristics. The existing low efficiency heating systems in NB cause a higher energy saving per house for the SAHP system retrofit. In contrast the higher efficiency existing heating systems in BC (compared to existing heating system in other provinces) reduce the amount of energy savings per house in that province. However, the total energy savings differ widely from province to province due to the large differences in the size of the housing stock and number of houses eligible for retrofit. It is important to consider both values because while the average energy saving per house provides an insight regarding the suitability of the SAHP retrofit, the total energy savings illustrate the size of the opportunity for energy savings. These results are useful in devising national and regional incentive and legislative measures to promote SAHP technologies.

To further clarify the impact of SAHP retrofit, the current energy consumption of eligible and non-eligible houses along with the energy consumption of eligible houses after the SAHP retrofit is presented in Table 8 broken down according to energy source and location. As seen from the table, the SAHP retrofit results in a substantial reduction in fossil fuel (i.e. NG and oil) consumption, and complete elimination of wood combustion (since no wood burning auxiliary system is used in the retrofitted houses). Overall, SAHP retrofit in eligible houses reduces the NG consumption of the CHS by 33%, oil consumption by 48% and wood consumption by 29%, and increases electricity consumption by close to 1%. As discussed earlier, a condensing NG boiler is assumed to be the auxiliary heating system where NG is widely available for residential customers. Thus, in QC and OT, oil use is completely eliminated in eligible houses. Table 9 shows the magnitude of energy savings in each fuel and each province while Table 10 shows the savings in percentage. As shown in Table 10, SAHP retrofit of all eligible houses would result in an energy savings of 21% in the entire CHS.

The performance parameters are presented in Table 10. The SPF of SAHP system is relatively low in the CHS. The free solar energy can be delivered to the building if the supply temperature is above hot water tank temperature (generally 50°C to 55°C) without operating HP system. Solar fraction in all provinces is below 50% which indicates that other energy retrofit measures need to be used in addition to SAHP system to achieve net zero energy status for the existing houses in the CHS.

As shown in Table 10, the fractional thermal energy saving of the SAHP system is higher than that of the solar combisystem retrofit in all provinces, indicating that integrating the HP and solar thermal system enhances energetic performance. However, when the electricity use of the HP system is included in the comparison, i.e. the extended fractional energy saving parameters are compared, the solar combisystem is more advantageous as shown in Table 10. As discussed earlier electricity generation in Canada is under provincial jurisdiction, and each province has a different fuel mixture for electricity generation based on the available resources. In provinces where there is a significant renewable energy component in the electricity generation, the extended fractional energy saving is higher for the SAHP compared to the solar combisystem. This is due to the lower efficiency of electricity generation from fossil fuels, which is taken into consideration in the definition of extended fractional energy saving as shown in Equation (11).

3.2. GHG emission reduction

One of the main objectives of renewable energy and energy efficiency retrofit measures is to reduce the building's environmental footprint. As shown in Table 6, the results of the base case analysis show that the CHS is responsible for 65.3 Mt of CO_{2e} emissions annually. Close to half of the GHG emissions is associated with NG consumption. Hence, it is expected that reducing the demand for thermal energy and replacing the conventional sources of energy with renewable options would shrink the building footprint. As shown in Table 9, the SAHP system yields a 19% reduction in the annual GHG emissions of the CHS (equivalent to 12.59 Mt of CO_{2e}). About 80% of that reduction is contributed by the GHG emission reduction associated with NG savings. To illustrate the SAHP system retrofit performance in each province the average GHG emission reduction per house is calculated and presented in Table 7. Results show that the houses located in AT region (excluding NB), OT, MB and SK experience higher opportunity for GHG emission reduction compared to other provinces. In AT provinces majority of the existing houses utilize oil based systems for space and DHW heating. Also, most of electricity generation is from fossil fuels except in NF where hydro-electricity is dominant. Thus, replacing existing oil based heating system in AT region and electric based heating system in NS, NB and PE with SAHP system eliminates a major source of GHG emission in buildings. In NB about 10% of the total energy use in existing houses (28.1 PJ) is supplied by wood (3.3 PJ as shown in Table 6). The CO_2 emission due to wood burning is considered to be part of the natural carbon cycle and not counted. As a result, the average GHG emission reduction per house in NB is lower compared to other AT provinces. In OT the use of oil in eligible houses is completely eliminated with the retrofit and the NG consumption is significantly reduced. In addition, the GHG EIF for electricity generation is relatively low in OT. Thus, the SAHP retrofit yields a high GHG emission reduction per house in OT. In QC and BC the GHG emission reduction per house is not high because in these provinces many houses utilize electric heating systems, and electricity production is predominantly hydro based. Therefore, although the SAHP system lowers the electricity demand for heating purposes, there is little or no GHG emission reduction. In QC oil consumption has replaced by NG in eligible houses after retrofit. Since GHG EIF of oil is higher compared to NG the total GHG emission reduction is affected by this fuel shift in QC. As a result the GHG emission per house in QC is yet higher compared to BC. Results show the multi-faceted nature of GHG emission in residential sector. As a result an energy saving measure that expected to yield GHG emission reduction may produce unexpected outcomes. Energy modeling and housing stock modeling are the least expensive approaches to measure the impact of large scale modifications in residential sector energy use to prevent unfavorable consequences.

3.3. Economic feasibility

The average TCC per house for three interest rates, three fuel cost escalation rates and two payback periods is presented in Table 11 for each province. Results show that the AT and QC region have the highest TCC in Canada. In the AT region, this is due to the relatively high cost of energy (~30C$/GJ for oil and ~36-47 C$/GJ for electricity and absence of NG for residential customers). Thus, the SAHP system provides a reliable opportunity for homeowners to reduce their energy costs. In case that the TCC is not sufficient to cover the investment cost, the difference could be offset by government incentives. In QC relatively inexpensive hydro-electricity is widely available for residential customers. Thus, many houses use electric resistance heaters for space and DHW heating. Introducing HP systems can lower the electricity demand in those houses. Integrating the HP with solar thermal system would increase the overall performance of the system, but due to the relatively higher investment cost of HP compared to solar collectors, it is likely that the SAHP system economic feasibility is less favorable compared to solar combisystem. High cost of electricity (~43 C$/GJ) compared to the relatively cheap NG (~5-8 C$/GJ) in the PR region narrows the TCC margin because the SAHP system replace NG (used by condensing boiler) with electricity (used by HP) as auxiliary source of energy. The average TCC might not provide the required information for government and decision makers. Thus, the total TCC for introducing the SAHP systems into the entire eligible houses across Canada is presented in Figure 2. The amount of investment shows the scale of market for residential customers. Thus, if the CHS moves toward the low energy design the SAHP system manufactures may introduce new products in the Canadian market and more contractors provide related services which can lower the overall system price. It should be noted that if Canadians decide to take retrofits in a short period of time the growing demand may increase the market price. Thus, devising a roadmap for converting existing houses might be helpful to control the market.

4. Conclusion

The SAHP retrofit is introduced into existing Canadian houses to reduce energy consumption and GHG emission. The SAHP system include flat plate collectors, float tank, HP, hot water storage tank, a series of three converging and diverging valves, hydronic heat delivery system and DHW heating system. Retrofit is applied to all eligible houses in Canada and assessment is performed from energy saving, GHG emission and economic feasibility perspective. Results can be summarised as below:

- About 37% of existing Canadian houses are eligible for the SAHP system retrofit. Number of eligible houses vary across provinces due to parameters such as vintage, building geometry, existing HVAC systems and population density.
- On average annual energy consumption of an existing house in Canada will reduce about 80-90 GJ due to SAHP system retrofit.

- Fossil fuel consumption in the CHS is substantially lowered while electricity use change is almost negligible. In total about 21% of annual energy consumption in the CHS is reduced if all eligible houses receive SAHP retrofit.
- Solar fraction in all provinces is below 50%, fractional thermal energy saving is higher compared to solar combisystem while the solar combisystem is more efficient from extended fractional energy saving perspective.
- About 19% of GHG emission (equivalent to 12.59 Mt of CO_{2e}) of the CHS is reduced. Major reduction of GHG emission is associated with NG saving.
- Energy saving and GHG emission reduction is strongly affected by climate, auxiliary energy source and fuel mixture for electricity generation.
- Economic feasibility of SAHP retrofit is assessed using tolerable capital cost parameter. Due to varying price of energy in different provinces the tolerable capital cost of SAHP system changes considerably across Canada. Thus, provincial government might have a radical role to promote SAHP retrofit using incentive measures and proper legislation. Growing demand for such retrofits, if occurs gradually, can help to lower the cost of parts and services for residential customers.

According to the results of the present study integration of HP into solar thermal systems is not sufficient to convert existing Canadian houses into NZEBs. Thus, other energy efficient retrofits such as energy saving measures and seasonal thermal energy storage is likely to be helpful to achieve the NZE status for existing Canadian houses. Further studies are required to assess performance of such options in the Canadian context.

Acknowledgement

The authors gratefully acknowledge the financial support provided to this project through the NSERC funded Smart Net-Zero Energy Buildings Strategic Research Network and V.I. Ugursal's NSERC Discovery Grant. Rasoul Asaee is thankful to the Atlantic Computational Excellence Network for the ACENET Research Fellowship and the Government of Nova Scotia for the Nova Scotia Graduate Scholarship.

Computational resources for this study are provided by the Atlantic Computational Excellence Network (ACENET), the regional advanced research computing consortium for universities in Atlantic Canada. ACENET is funded by the Canada Foundation for Innovation (CFI), the Atlantic Canada Opportunities Agency (ACOA), and the provinces of Newfoundland and Labrador, Nova Scotia, and New Brunswick.

References

1. Hadorn, J.-C. *Solar and Heat Pump Systems for Residential Buildings*. 2015: John Wiley & Sons.
2. IEA-SHC. *Solar and Heat Pump Systems*. 2016; [Last accessed: 2016/05/26]; Available from: http://task44.iea-shc.org/.
3. Chu, J., Choi, W., Cruickshank, C.A., and Harrison, S.J. *Modeling of an Indirect Solar Assisted Heat Pump System for a High Performance Residential House*. Journal of Solar Energy Engineering 2014; **136**(4): p. 041003-041003. DOI: 10.1115/1.4027486
4. TRNSYS. *Transient system simulation tool*. 2016; [Last accessed: 2016/08/21]; Available from: http://www.trnsys.com/.

5. Bakirci, K., and Yuksel, B. *Experimental thermal performance of a solar source heat-pump system for residential heating in cold climate region.* Applied Thermal Engineering 2011; **31**(8–9): p. 1508-1518. DOI: http://dx.doi.org/10.1016/j.applthermaleng.2011.01.039

6. Liang, C.-h., Zhang, X.-s., Li, X.-w., and Zhu, X. *Study on the performance of a solar assisted air source heat pump system for building heating.* Energy and Buildings 2011; **43**(9): p. 2188-2196. DOI: http://dx.doi.org/10.1016/j.enbuild.2011.04.028

7. Moreno-Rodríguez, A., González-Gil, A., Izquierdo, M., and Garcia-Hernando, N. *Theoretical model and experimental validation of a direct-expansion solar assisted heat pump for domestic hot water applications.* Energy 2012; **45**(1): p. 704-715. DOI: http://dx.doi.org/10.1016/j.energy.2012.07.021

8. Kong, X.Q., Zhang, D., Li, Y., and Yang, Q.M. *Thermal performance analysis of a direct-expansion solar-assisted heat pump water heater.* Energy 2011; **36**(12): p. 6830-6838. DOI: http://dx.doi.org/10.1016/j.energy.2011.10.013

9. Sterling, S.J., and Collins, M.R. *Feasibility analysis of an indirect heat pump assisted solar domestic hot water system.* Applied Energy 2012; **93**: p. 11-17. DOI: http://dx.doi.org/10.1016/j.apenergy.2011.05.050

10. Wagar, W.R. *Simulation and validation of a single tank heat pump assisted solar domestic water heating system, MSc Thesis*, in *Mechanical Engineering*. 2013, University of Waterloo: Waterloo, Ontario, Canada.

11. Banister, C.J., and Collins, M.R. *Development and performance of a dual tank solar-assisted heat pump system.* Applied Energy 2015; **149**: p. 125-132. DOI: http://dx.doi.org/10.1016/j.apenergy.2015.03.130

12. Banister, C.J., Wagar, W.R., and Collins, M.R. *Solar-assisted Heat Pump Test Apparatus.* Energy Procedia 2014; **48**: p. 489-498. DOI: http://dx.doi.org/10.1016/j.egypro.2014.02.058

13. Banister, C.J. *Design, analysis, and optimization of a dual tank solar-assisted heat pump system, PhD Thesis*, in *Mechanical Engineering*. 2015, University of Waterloo: Waterloo, Ontario, Canada.

14. Banister, C.J., Wagar, W.R., and Collins, M.R. *Validation of a Single Tank, Multi-mode Solar-assisted Heat Pump TRNSYS Model.* Energy Procedia 2014; **48**: p. 499-504. DOI: http://dx.doi.org/10.1016/j.egypro.2014.02.059

15. Chu, J., and Cruickshank, C.A. *Solar-Assisted Heat Pump Systems: A Review of Existing Studies and Their Applicability to the Canadian Residential Sector.* Journal of Solar Energy Engineering 2014; **136**(4): p. 041013-041013. DOI: 10.1115/1.4027735

16. SNEBRN. *NSERC Smart Net-zero Energy Buildings Strategic Research Network.* 2012; [Last accessed: 2015/10/16].

17. Nikoofard, S., Ugursal, V.I., and Beausoleil-Morrison, I. *Technoeconomic Assessment of the Impact of Window Improvements on the Heating and Cooling Energy Requirement and Greenhouse Gas Emissions of the Canadian Housing Stock.* Journal of Energy Engineering 2013; **140**(2): p. 04013018.

18. Nikoofard, S., Ugursal, V.I., and Beausoleil-Morrison, I. *Technoeconomic assessment of the impact of window shading retrofits on the heating and cooling energy consumption and GHG emissions of the Canadian housing stock.* Energy and Buildings 2014; **69**: p. 354-366.

19. Nikoofard, S., Ugursal, V.I., and Beausoleil-Morrison, I. *An investigation of the technoeconomic feasibility of solar domestic hot water heating for the Canadian housing stock.* Solar Energy 2014; **101**: p. 308-320.

20. Nikoofard, S., Ugursal, V.I., and Beausoleil-Morrison, I. *Techno-economic assessment of the impact of phase change material thermal storage on the energy consumption and GHG emissions of the Canadian Housing Stock.* Building Simulation: An International Journal 2014; **8**(2): p. 225-238.

21. Asaee, S.R., Ugursal, V.I., and Beausoleil-Morrison, I. *Techno-economic evaluation of internal combustion engine based cogeneration system retrofits in Canadian houses–A preliminary study*. Applied Energy 2015; **140**: p. 171-183. DOI: 10.1016/j.apenergy.2014.11.068

22. Asaee, S.R., Ugursal, V.I., and Beausoleil-Morrison, I. *An investigation of the techno-economic impact of internal combustion engine based cogeneration systems on the energy requirements and greenhouse gas emissions of the Canadian housing stock.* Applied Thermal Engineering 2015; **87**: p. 505-518. DOI: 10.1016/j.applthermaleng.2015.05.031

23. Asaee, S.R., Ugursal, V.I., and Beausoleil-Morrison, I. *Stirling engine based cogeneration system retrofit impact on the energy requirement and greenhouse gas emissions of the Canadian housing stock*, in *The 28th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems*. 2015: Pau, France.

24. Asaee, S.R., Ugursal, V.I., Beausoleil-Morrison, I., and Ben-Abdallah, N. *Preliminary study for solar combisystem potential in Canadian houses.* Applied Energy 2014; **130**: p. 510-518. DOI: 10.1016/j.apenergy.2013.12.048

25. Asaee, S.R., Ugursal, V.I., and Beausoleil-Morrison, I. *Techno-economic study of solar combisystem retrofit in the Canadian housing stock.* Solar Energy 2016; **125**: p. 426-443. DOI: 10.1016/j.solener.2015.12.037

26. Asaee, S.R., Ugursal, V.I., and Beausoleil-Morrison, I. *Techno-economic feasibility evaluation of air to water heat pump retrofit in the Canadian housing stock.* Applied Thermal Engineering 2017; **111**: p. 936-949. DOI: 10.1016/j.applthermaleng.2016.09.117

27. Swan, L.G. *Residential sector energy and GHG emissions model for the assessment of new technologies*. 2010, Doctoral Dissertation, Dalhousie University, Halifax, NS, Canada.

28. Swan, L.G., Ugursal, V.I., and Beausoleil-Morrison, I. *Hybrid residential end-use energy and greenhouse gas emissions model – development and verification for Canada.* Journal of Building Performance Simulation 2013; **6**(1): p. 1-23. DOI: 10.1080/19401493.2011.594906

29. Swan, L.G., Ugursal, V.I., and Beausoleil-Morrison, I. *A database of house descriptions representative of the Canadian housing stock for coupling to building energy performance simulation.* Journal of Building Performance Simulation 2009; **2**(2): p. 75-84. DOI: 10.1080/19401490802491827

30. SBC. *EnerGuide for houses database*. 2006, Sustainable Buildings and Communities, CANMET Energy Technology Centre, Natural Resources Canada.: Ottawa.

31. OEE. *Survey of Household Energy Use (SHEU) – Detailed Statistical Report*. 2006, Office of Energy Efficiency, Natural Resources Canada.: Ottawa.

32. ESRU. *ESP-r*. Energy Systems Research Unit (ESRU), University of Strathclyde: Glasgow, UK 2015; [Last accessed: 2015/10/19]; Available from: http://www.esru.strath.ac.uk/Programs/ESP-r.htm.

33. Strachan, P.A., Kokogiannakis, G., and Macdonald, I.A. *History and development of validation with the ESP-r simulation program.* Building and Environment 2008; **43**(4): p. 601-609. DOI: http://dx.doi.org/10.1016/j.buildenv.2006.06.025

34. Swan, L.G., Ugursal, V.I., and Beausoleil-Morrison, I. *Occupant related household energy consumption in Canada: Estimation using a bottom-up neural-network technique.* Energy and Buildings 2011; **43**(2–3): p. 326-337. DOI: http://dx.doi.org/10.1016/j.enbuild.2010.09.021

35. Farhat, A.A., and Ugursal, V.I. *Greenhouse gas emission intensity factors for marginal electricity generation in Canada.* International Journal of Energy Research 2010; **34**(15): p. 1309-1327.

36. Thevenard, D., Haddad, K., and Purdy, J. *Development of a new solar collector model in ESP-r*. in *Canadian Solar Buildings Conference, Montreal, Canada*. 2004.

37. Duffie, J.A., and Beckman, W.A. *Solar Engineering of Thermal Processes*. 2006, JOHN WILEY & SONS, INC. NY.

38. Thermo Dynamics Ltd. *G series solar collectors, technical specifications*. 2013; [Last accessed: 2016/06/10]; Available from: http://www.thermo-dynamics.com/technical_specs/G_series_technical.html.

39. Thevenard, D., and Haddad, K. *Development of a stratified tank model with immersed heat exchangers in ESP-r*, in *The 6th IBPSA Canada Conference, Winnipeg*. 2010.

40. Hensen, J.L.M. *On the thermal interaction of building structure and heating and ventilating system*. 1991, Doctoral Dissertation, Technische Universiteitt Eindhoven.

41. Viessmann. *Gas fired boilers*. 2015; [Last accessed: 2015/02/05]; Available from: https://www.viessmann.com/com/en/products/Gas-fired_condensing_boilers.html.

42. Viessmann. *Oil fired boilers*. 2015; [Last accessed: 2015/02/05]; Available from: https://www.viessmann.com/com/en/products/Oil_fired_boilers.html.

43. Ferguson, A., Kelly, N., Weber, A., and Griffith, B. *Modelling residential-scale combustion-based cogeneration in building simulation.* Journal of Building Performance Simulation 2009; **2**(1): p. 1-14. DOI: 10.1080/19401490802588424

44. Kelly, N.J., and Cockroft, J. *Analysis of retrofit air source heat pump performance: Results from detailed simulations and comparison to field trial data.* Energy and Buildings 2011; **43**(1): p. 239-245. DOI: http://dx.doi.org/10.1016/j.enbuild.2010.09.018

45. Mitsubishi Electric. *City Multi series*. 2016; [Last accessed: 2016/05/21]; Available from: http://www.mitsubishielectric.ca/en/hvac/city_multi/wr2_series.html.

46. Express Radiant Ltd. *Product catalogue*. 2015; [Last accessed: 2015/02/05]; Available from: http://www.expressradiant.ca/pdfs/product_catalogue.pdf.

47. Iqbal, M. *Optimum collector slope for residential heating in adverse climates.* Solar Energy 1979; **22**(1): p. 77-79. DOI: http://dx.doi.org/10.1016/0038-092X(79)90062-8

48. Nikoofard, S., Ugursal, V.I., and Beausoleil-Morrison, I. *Economic analysis of energy upgrades based on tolerable capital cost.* Journal of Energy Engineering 2014; **141**(3): p. 06014002–1–6. DOI: 10.1061/(ASCE)EY.1943-7897.0000203

49. BOC. *Bank of Canada*. 2015; [Last accessed: 2015/10/21]; Available from: http://www.bankofcanada.ca/.

50. Hydro-Quebec. *Comparison of electricity prices in major North American cities*. 2014; [Last accessed: 2014/02/15]; Available from: http://www.hydroquebec.com/publications/en/comparison_prices/pdf/comp_2013_en.pdf.

51. Statistics Canada. *Energy Statistics Handbook*. 2013; [Last accessed: 2013/02/15]; Available from: http://www.statcan.gc.ca/pub/57-601-x/57-601-x2012001-eng.pdf.

52. NEB. *National energy board of Canada*. 2014; [Last accessed: 2014/07/11]; Available from: http://www.nebone.gc.ca/clf-nsi/rnrgynfmtn/prcng/prcng-eng.html.

53. WBDG. *WBDG, Energy Escalation Rate Calculator (EERC), National Institute of Building Sciences*. 2014; [Last accessed: 2014/08/25]; Available from: http://www.wbdg.org/tools/eerc.php?c=8.

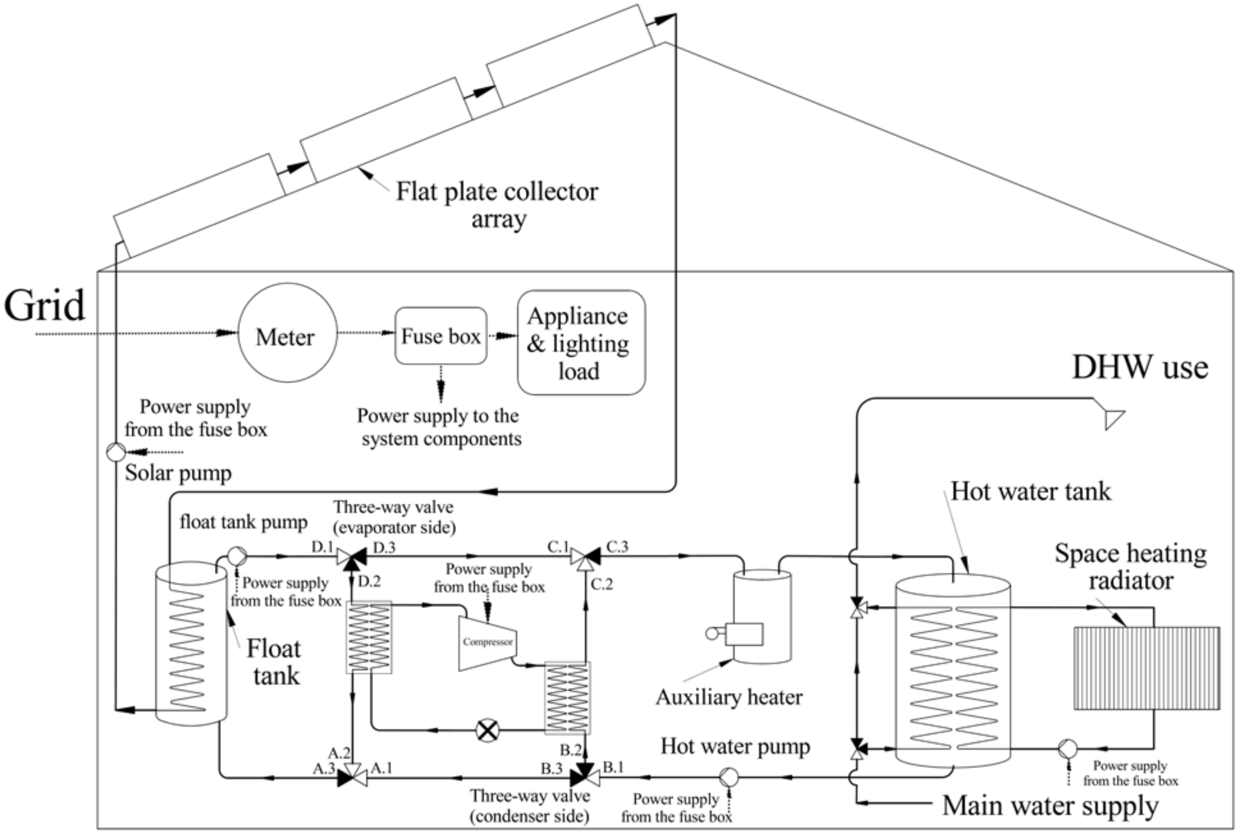
Highlights

- Techno-economic performance of SAHP in the Canadian housing stock is investigated
- A dual tank system is used to maximise the solar energy capture during a day
- Several energy performance indicators are used to evaluate the system performance
- SAHP enhance the energy savings compared to conventional solar thermal systems
- About 19% of GHG emission of the Canadian housing stock is reduced by SAHP retrofit

Figure captions:

Fig. 1. Solar assisted heat pump system configuration.

Fig. 2. Total national tolerable capital cost due to solar assisted heat pump upgrade for different interest rates and fuel cost escalation rates (Low, Medium and High as per Table 5).



Flat plate collector array
Grid
Meter
Fuse box
Appliance & lighting load
DHW use
Power supply from the fuse box
Power supply to the system components
Solar pump
Hot water tank
float tank pump
Three-way valve (evaporator side)
D.1
D.3
D.2
C.1
C.3
C.2
Power supply from the fuse box
Power supply from the fuse box
Space heating radiator
Compressor
Float tank
Auxiliary heater
A.2
A.3
A.1
B.2
B.3
B.1
Hot water pump
Three-way valve (condenser side)
Power supply from the fuse box
Power supply from the fuse box
Main water supply

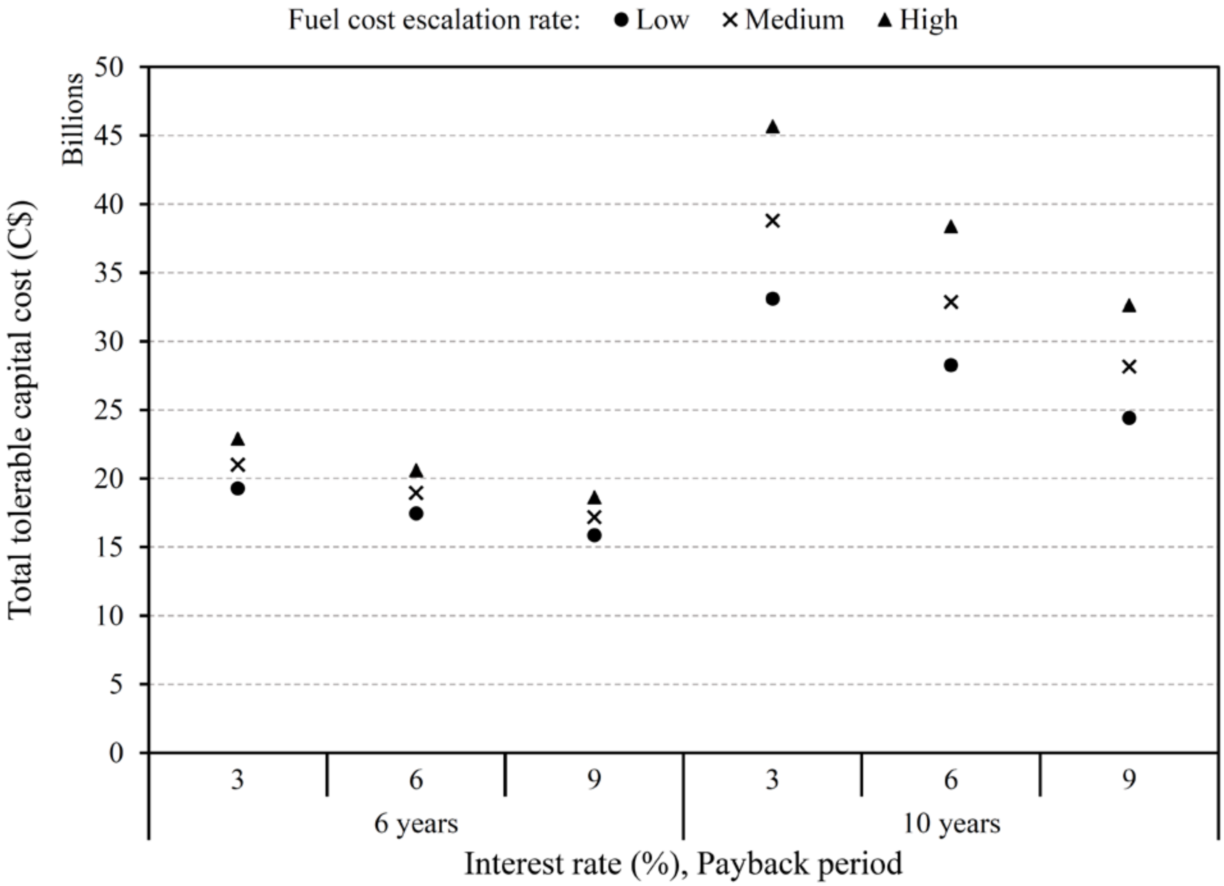

Fuel cost escalation rate: ● Low × Medium ▲ High
Billions
Total tolerable capital cost (C$)
50
45
40
35
30
25
20
15
10
5
0
3
6
9
3
6
9
6 years
10 years
Interest rate (%), Payback period

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

SAHP system components	Parameter	Unit	Value	Reference
Collector weight	M_{coll}	kg	43.5	[38]
Test flow rate	$\dot{m}$	kg/s	0.059	
Efficiency constant coefficient	$F_R(\tau\alpha)_n$	–	0.689	
Efficiency square coefficient	a	W/m^{2}K	3.8475	
Efficiency quadratic coefficient	b	W/m^{2}K^2	0.01739	
Incidence angle modifier coefficient	b_0	–	0.154	
COP	a_0	–	5.4494	[12-13, 45]
	a_1	K^{-1}	-0.0836	
	a_2	K^{-2}	9×10^{-5}	
NG fired boiler	η_{ref}	–	0.92	[41]
	T_{ref}	°C	50	
	$(\tan \varphi)_{T>50^\circ C}$	$^\circ C^{-1}$	-0.15	
	$(\tan \varphi)_{T\leq 50^\circ C}$	$^\circ C^{-1}$	-0.25	
Oil fired boiler	η_{ref}	–	0.85	[42]
	T_{ref}	°C	50	
	tan φ	$^\circ C^{-1}$	-0.15	
Radiator	M_{unit}	kg	49	[46]
	C_{avg}	J/kgK	1350	
	Q_0	W	967	
	$T_{s,0}$	°C	55	
	$T_{r,0}$	°C	35	
	$T_{env,0}$	°C	21	

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

Control stage	Actuator	Period		Sensor location	Setpoint	
		start	end		on	off
Collector loop	Solar pump	1 Jan	31 Dec	ΔT between solar floating tank & solar collector	5	1
Thermal management	Hot water pump	1 Jan	31 Dec	Thermal storage tank outlet to zone	50	55
	Three-way valve (evaporator side)	1 Jan	31 Dec	ΔT between hot water tank & float tank	1	0
	Three-way valve (condenser side)	1 Jan	31 Dec	ΔT between hot water tank & float tank	1	0
	HP	1 Jan	31 Dec	float tank	2	1
	Pump HP	1 Jan	31 Dec	float tank	2	1
	Boiler	1 Jan	31 Dec	Boiler outlet	50	55
Heat delivery	DHW Pump	1 Jan	31 Dec	DHW tank	54	56
	DHW tank	1 Jan	31 Dec	DHW draw	--	--
	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 [35]

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. 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 [50]

[2] Statistics Canada handbook [51]

[3] Statistics Canada Handbook [51]

[4] Local companies

Table 5. 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 [52]

[‡] Energy Escalation Rate Calculator (EERC) [53]

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

Table 6. 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 7. Energy savings and GHG emission reductions for the CHS due to SAHP 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	60,662	35	5.4	89	0.25	4,057
NS	131,393	44	10.7	81	0.69	5,282
PE	24,175	54	1.9	79	0.11	4,363
NB	72,060	30	7.7	107	0.22	3,036
QC	254,126	13	20.1	79	1.00	3,941
OT	1,608,866	47	131.2	82	6.63	4,120
MB	108,944	32	9.3	85	0.49	4,455
SK	148,106	47	13.8	93	0.64	4,344
AB	508,451	52	41.3	81	1.17	2,293
BC	408,534	37	26.2	64	1.40	3,428
Canada	3,325,316	37	267.6		12.59	

Table 8. CHREM estimates of annual energy consumption (PJ) with existing (Exist) and SAHP retrofit (SHPR) in houses eligible (EL) and houses not eligible (N-E) for SAHP retrofit

	Electricity			NG			Oil			Wood			Total		
	N-E	EL		N-E	EL		N-E	EL		N-E	EL		N-E	EL	
Province		Exist	SHPR		Exist	SHPR		Exist	SHPR		Exist	SHPR		Exist	SHPR
NF	12.3	2.9	2.8	0.0	0.0	0.0	2.9	6.7	3.2	1.5	1.8	0.0	16.7	11.4	6.0
NS	12.2	5.5	5.6	0.0	0.0	0.0	8.1	14.5	5.2	4.5	1.5	0.0	24.8	21.5	10.8
PE	0.9	0.9	1.0	0.0	0.0	0.0	1.7	2.3	0.8	1.0	0.5	0.0	3.6	3.7	1.8
NB	15.3	3.4	2.7	0.0	0.0	0.0	4.2	5.5	3.1	6.1	4.6	0.0	25.6	13.5	5.8
QC	189.8	15.5	8.3	0.2	0.8	9.9	9.8	20.5	0.0	8.9	1.5	0.0	208.7	38.3	18.2
OT	87.9	49.3	53.7	162.3	175.1	61.4	25.5	21.9	0.0	0.0	0.0	0.0	275.7	246.3	115.1
MB	15.8	3.1	3.4	19.4	14.2	4.6	0.0	0.0	0.0	0.0	0.0	0.0	35.2	17.3	8.0
SK	6.8	3.8	4.9	20.2	20.0	5.1	0.0	0.0	0.0	0.0	0.0	0.0	27.0	23.8	10.0
AB	13.6	14.7	19.4	57.7	62.1	16.1	0.0	0.0	0.0	0.0	0.0	0.0	71.3	76.8	35.5
BC	46.3	18.3	19.8	46.7	37.2	9.5	0.0	0.0	0.0	2.1	0.0	0.0	95.1	55.5	29.3
Canada	400.9	117.4	121.6	306.5	309.4	106.6	52.2	71.4	12.3	24.1	9.9	0.0	783.7	508.1	240.5

Table 9. Annual energy savings and GHG emission reductions due to SAHP 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	0.1	0.0	3.5	1.8	5.4	0.00	0.00	0.25	0.25
NS	-0.1	0.0	9.3	1.5	10.7	0.04	0.00	0.65	0.69
PE	-0.1	0.0	1.5	0.5	1.9	0.00	0.00	0.11	0.11
NB	0.7	0.0	2.4	4.6	7.7	0.05	0.00	0.17	0.22
QC	7.2	-9.1	20.5	1.5	20.1	0.02	-0.46	1.44	1.00
OT	-4.4	113.7	21.9	0.0	131.2	-0.66	5.75	1.54	6.63
MB	-0.3	9.6	0.0	0.0	9.3	0.00	0.49	0.00	0.49
SK	-1.1	14.9	0.0	0.0	13.8	-0.11	0.75	0.00	0.64
AB	-4.7	46.0	0.0	0.0	41.3	-1.16	2.33	0.00	1.17
BC	-1.5	27.7	0.0	0.0	26.2	0.00	1.40	0.00	1.40
Canada	-4.2	202.8	59.1	9.9	267.6	-1.82	10.25	4.16	12.59

Table 10. Average seasonal performance factor, solar fraction, fractional thermal energy saving, annual end-use energy savings and GHG emission reductions due to SAHP retrofits in the CHS

Province	Energy Savings (%)	GHG emission reductions (%)	SPF	f_{sol} (%)	Fractional thermal energy saving (%)		Extended fractional energy saving (%)	
					SAHP	SCS	SAHP	SCS
NF	19	31	1.7	34	41	34	41	34
NS	23	13	1.8	39	27	23	15	21
PE	26	28	2.9	49	36	31	22	27
NB	20	7	1.8	40	20	18	15	16
QC	8	39	1.7	38	31	23	31	23
OT	25	23	1.7	37	31	27	19	25
MB	18	27	1.6	36	29	24	29	24
SK	27	14	1.8	42	32	28	18	24
AB	28	9	1.9	43	38	33	18	28
BC	17	30	2.3	47	32	27	32	27
Canada	21	19	1.8	40	31	27	21	25

Table 11. 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	22,738	27,065	32,350	19,374	22,866	27,110	16,690	19,535	22,977
	6	12,992	14,273	15,685	11,741	12,860	14,092	10,665	11,647	12,727
NS	10	23,219	27,759	33,322	19,765	23,427	27,892	17,011	19,993	23,613
	6	13,154	14,484	15,953	11,883	13,044	14,326	10,790	11,810	12,933
PE	10	20,499	24,451	29,283	17,445	20,631	24,509	15,010	17,604	20,747
	6	11,582	12,735	14,007	10,462	11,469	12,578	9,499	10,382	11,354
NB	10	24,430	28,708	33,877	20,873	24,331	28,490	18,030	20,852	24,231
	6	14,303	15,612	17,050	12,938	14,083	15,337	11,764	12,770	13,870
QC	10	30,244	36,415	44,021	25,755	30,734	36,840	22,175	26,231	31,182
	6	17,195	19,016	21,034	15,536	17,127	18,887	14,110	15,506	17,048
OT	10	9,186	10,712	12,540	7,851	9,084	10,555	6,783	7,789	8,985
	6	5,389	5,856	6,366	4,876	5,284	5,728	4,434	4,792	5,182
MB	10	6,118	6,946	7,906	5,254	5,926	6,702	4,561	5,112	5,745
	6	3,742	4,015	4,309	3,391	3,630	3,887	3,089	3,299	3,524
SK	10	4,364	4,827	5,334	3,748	4,124	4,534	3,253	3,562	3,897
	6	2,669	2,824	2,986	2,419	2,554	2,696	2,203	2,322	2,447
AB	10	170	1	-241	146	9	-185	126	15	-142
	6	104	51	-12	94	48	-7	86	45	-3
BC	10	6,248	7,080	8,040	5,366	6,041	6,817	4,658	5,211	5,845
	6	3,822	4,096	4,391	3,463	3,703	3,961	3,155	3,366	3,592