Heat Pump Water Heaters in the Canadian Residential Market

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Abstract

This paper presents a techno-economic analysis of heat pump water heaters (HPWH) in new-construction Canadian housing, identifying challenges and potential solutions to efficiently meet domestic hot water heating loads. The analysis is conducted in six Canadian regions (Maritime, Quebec, Ontario, Prairies, Pacific and sub-Arctic) encompassing different climates, utility rates and structures, and typical space heating equipment. Housing energy models developed in the TRNSYS simulation tool are used to perform an analysis comparing annual energy use, utility costs and greenhouse gas emissions to typical base case systems. Parametric studies are conducted to evaluate the impact of evaporator location, and hot water draw profiles on the overall energy saving potential. Overall, HPWHs in the Canadian residential sector demonstrates some potential, resulting in annual energy savings in all regions assessed. From an economic perspective however, these systems are challenged by the current low utility rates.

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1. Introduction

Canada is one of the highest per capita consumers of energy in the world [1]. The residential sector accounts for approximately 17% of national secondary energy use, with nearly 20% of this total directed towards domestic hot water (DHW) [2]. The share of DHW energy use is likely to rise in the future, as improved building insulation levels and highly efficient mechanical systems reduce the energy required for space heating and cooling.

Heat pump (HP) systems are an ideal technology to reduce energy consumption in buildings. In addition to their high efficiencies, HPs also facilitate the integration of renewable energy with building systems. To date, however, the majority of the HP market has been focussed on efficiently meeting space heating and cooling requirements. Applying heat pump technologies to DHW production offers the potential to efficiently address a major energy end use while at the same time opening a significant new market for heat pump manufacturers.

Despite strong energy savings potential, the integration of HP water heaters (HPWH) into buildings is far from straightforward. The most common HPWH systems currently available use the indoor air as a thermal source for the HP, cooling the space while providing hot water. While this is ideal in warmer climates, it can increase heating loads and overall building energy use in heating-dominated regions such as Canada. As such, these systems require a careful whole-building analysis to ensure that they improve overall energy efficiency.

The impact of HPWHs in Canada has been previously examined by several authors. Biaou and Bernier [3] used simulation to demonstrate the energy savings potential of a HPWH for a net-zero energy home in Montreal. The Canadian Mortgage and Housing Council [4] examined the in-field performance of a HPWH integrated into a typical single family home in Ottawa. Bursill [5] performed laboratory tests on a HPWH, using the experimental

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data to develop a simulation model of the HPWH and test several control parameters. However, despite this research, there is still a lack of information regarding the potential of HPWHs across Canada, and the impact that the DHW consumption and HP thermal source can have on building energy use.

The objective of this paper is to identify the impact of HPWHs on the annual energy performance of newly constructed homes in Canada. First, representative housing models are developed for six regions across Canada. The models are then used as a base for several system integrations examining the impact of using different thermal sources for the HPWH as well as three different daily hot water consumption profiles. A simple payback period and life cycle cost analysis is also performed to evaluate the economic viability.

2. Overview of Canada's Residential DHW Market

From the survey of household energy use [6], the majority of Canadian dwellings use a standard tank to meet their hot water heating needs. The predominant fuel source varies depending on the region: Electric hot water heaters dominate in the Maritimes and Quebec, natural gas fired systems are more common in Ontario and the Prairies, while British Columbia is evenly split between electricity and natural gas. Canada wide, 52% of residential hot water heaters are heated using natural gas and 44% through electricity. Oil and propane make up the remaining 4%. Of the households that know the age of their hot water heater, 48% are 5 years old or less, 38% are between 6 to 10 years old, 9% between the age of 11 and 15 years and the remaining 5% are older than 15 years. With a recommended replacement age of 13 years [7] it can be expected that over the next 7 years over 50% of Canadian households will be replacing their hot water heater. Thus, with increased interest in introducing HPWHs into the Canadian market, it is important to evaluate the anticipated impact these systems can have and identify improvements to better adapt HPWHs in the Canadian climate.

3. Base Case Housing Models

To evaluate the energy savings, greenhouse gas (GHG) emission reduction potential and economic viability of HPWHs in the Canadian residential market, base case housing energy models were created for six Canadian regions representing different climate zones and utility rate structures. TRNSYS v. 17 was used to perform the analysis due to its flexibility in modelling non-standard heating and cooling systems. The housing energy models were based on the Canadian Centre for Housing Technologies research houses, which represent typical tract-built models available in the Canadian housing market [8]. The housing model was updated for each selected region to meet the National Building Code of Canada (NBC) minimum energy efficiency performance requirements for residential housing [9].

Base electric load profiles were assumed to follow those developed for Annex 42 of the International Energy Agency Energy Conservation in Buildings and Community Systems Programme [10] and the Building Technologies Office [11]. The electrical load profiles were developed to provide a realistic representation of household electricity use when assessing and comparing economic, carbon and energy performance of residential systems. Annually, each household was modelled with a lighting and receptacle load of 9,150 kWh.

Representative DHW draw profiles were taken from a Carleton University study where the DHW consumption was monitored in 73 houses in the province of Quebec, Canada [12]. The annual DHW draw profiles were developed with a time-resolution of 5 minutes and divided into 4 consumption levels (low, average, median, high) and three consumption patterns (morning, evening and dispersed). The dispersed and average DHW profile was used in the initial simulations (180.6 L/day normalized). Hot water draw profiles were adjusted according to the incoming mains temperatures for each region.

Utility rates were obtained from each city's power and energy provider. For regions where utility rates are based on the current market cost of energy the historical rates over the past year were used. GHG emission factors vary depending on the location and fuel source for electricity production [13]. Respective GHG emission factors used for natural gas was 1,900 g CO2 eq./m³ and 2,715 g CO2 eq./L for fuel oil. Table 1 summarizes the six selected regions for analysis, utility rates, GHG emission factors and the respective key housing characteristics. Additional housing characteristics can be found in the NBC [9].

Table 1. Selected regions and respective key housing characteristics

Characteristic	Halifax, NS	Montreal, QC	Toronto, ON	Edmonton, AB	Vancouver, BC	Whitehorse, YK
HDD below 18°C	4,000	4,200	3,520	5,120	2,825	6,580
Electricity GHG Emission Factor (g CO_2/kWh)	733	6	199	921	22	50

Fixed Utility Costs ($/year)	$130	$148	$529	$715	$212	$208
Electricity Rate ($/GJ)	$32.42	$21.35	$42.70	$22.78	$29.03	$40.27
Natural Gas Rate ($/GJ)	--	--	$6.78	$3.95	$6.99	--
Fuel Oil Rate ($/GJ)	--	--	--	--	--	$23.95
Heat Recovery Ventilator	Yes	Yes	Yes	Yes	Yes	Yes
Primary Heating Fuel	Electric	Electric	Natural Gas	Natural Gas	Natural Gas	Oil
Heating Efficiency	100%	100%	92.1%	92.1%	92.1%	85%
Space Cooling System	Yes	Yes	Yes	Yes	Yes	No
DHW Fuel	Electric	Electric	Natural Gas	Natural Gas	Natural Gas	Electric
DHW Tank Volume (L)	189	189	189	189	189	189
DHW Standby Loss/ EF	73 W	73 W	0.58	0.58	0.58	73 W

Using part load performance curves outlined by the National Energy Code for Buildings [14] for the space heating and cooling equipment, the housing model in each region was simulated with the respective CWEC weather-file and a 2 ½ minute timestep. The annual energy consumption, utility costs and GHG emissions are summarized in Table 2 along with the percentage of energy end use for DHW heating.

Table 2. Annual energy consumption, utility costs and GHG emissions for base case housing model in each region

Characteristic	Halifax	Montreal	Toronto	Edmonton	Vancouver	Whitehorse
Electricity Consumption (GJ)	101.2	117.8	52.7	50.3	48.7	64.6
Natural Gas Consumption (GJ)	0.0	0.0	70.5	85.9	58.2	0.0
Fuel Oil Consumption (GJ)	0.0	0.0	0.0	0.0	0.0	105.7
Total Energy Consumption (GJ)	101.2	117.8	123.2	136.2	106.9	170.3
Utility Costs ($, CDN)	$4,292	$2,664	$3,255	$2,199	$2,034	$5,343
GHG Emissions (ton CO2 eq.)	22.7	0.2	7.1	19.0	3.6	9.0
% Energy End Use for DHW	15.0%	13.1%	18.6%	19.8%	19.8%	11.4%

4. Heat Pump Water Heater Energy Model

To assess the potential of HPWHs in the Canadian residential sector, the conventional DHW heating system in each base case model was replaced with a HPWH designed to operate in heat pump mode at ambient temperatures above 7.2°C (i.e. not a cold climate HPWH). The validated HPWH model proposed by Maguire [7] was used for this study. The model is data-driven, and is based on a market available HPWH system. The examined HPWH has a nominal 50 gallon tank volume and a rated energy factor of 2.35. Compressor power is rated at 700 W, while the unit also contains two 4.5 kW electric auxiliary elements, located in the upper and lower portions of the tank, to provide auxiliary water heating capacity.

4.1. HPWH Operational Modes

HPWH control follows the operational modes observed during the in-lab testing described by Maguire [7]. Only the two primary modes of operation are simulated within this study, as these cover the vast majority of typical DHW operations. For each mode, it is important to note that only one heating element operates at a single time (i.e. heat pump, upper element, or lower element). All control decisions are based on the average tank fluid temperature, T_{tank}.

Hybrid Mode: Available when HP evaporator air inlet temperatures are between 7.2°C and 48.9°C. Priority is given to heat pump operations, followed by the resistance elements if necessary. Table 3 summarizes the hybrid mode controls.

Table 3. Hybrid mode control sequence

Element	On Condition	Off Condition

Heat Pump	$T_{tank}<T_{set}$-0.8°C	Activation of either element, or T_{set} met
Lower Element	$T_{tank}<T_{set}$-13.9°C <u>or</u> $T_{tank}<T_{set}$ (if upper element previously on)	Activation of upper element, or T_{set} met
Upper Element	$T_{tank}<T_{set}$-25.0°C	$T_{tank}>T_{set}$-8.3°C

Electric Mode: Used when heat pump evaporator air inlet temperatures are out of the range for hybrid mode. In this mode, only the resistance elements are used. Table 4 summarizes the electric mode controls.

Table 4. Electric mode control sequence

Element	On Condition	Off Condition
Lower Element	$T_{tank}<T_{set}$-0.8°C <u>or</u> $T_{tank}<T_{set}$ (if upper element previously on)	Activation of upper element, or T_{set} met
Upper Element	$T_{tank}<T_{set}$-25.0°C	$T_{tank}>T_{set}$-8.3°C

5. Heat Pump Water Heater Techno-economic Results Summary and Analysis

To perform the HPWH analysis, it is assumed that the HPWH is installed in the basement with the evaporator using the basement air as the evaporator source temperature to produce hot water (Scenario 1). The basement is typically maintained between 15°C to 18°C depending on the space heating system, with space conditioning met using either electric baseboard heaters (Halifax and Montreal) or a central furnace (Toronto, Edmonton, Vancouver, Whitehorse).

To evaluate the economic suitability of a HPWH, the simple payback period was calculated and a life cycle cost analysis was conducted for each region. The lifecycle cost analysis included estimated capital, installation and maintenance costs evaluated over a 13 year period [15]. An annual inflation rate of 1.5% and a discount rate of 4% were assumed for the analysis based on the current Canadian financial market. Energy escalation rates varied with each region and were taken from the National Energy Board [16], as summarized in Table 5.

Table 5. Energy escalation rates used for life cycle cost analysis

Annual escalation rate	Halifax	Montreal	Toronto	Edmonton	Vancouver	Whitehorse
Electricity	0.1%	0.1%	0.6%	2.8%	0.3%	3.0%
Natural Gas/Fuel Oil	--	--	0.7%	1.0%	0.2%	3.0%

The life cycle cost analysis assumed that the selected system was installed in a newly constructed house (i.e. no replacement). Estimated equipment costs, installation costs and annual maintenance costs are summarized in Table 6 [15]. Average costs were adjusted for each selected region using RSMeans location factors [17].

Table 6. Capital, installation and annual maintenance costs assumed for life cycle cost analysis

Equipment	Capital Cost ($, CDN)	Installation Cost ($, CDN)	Annual Maintenance Cost ($ CDN)
Electric DHW tank	$386	$637	$168
Natural gas DHW tank	$614	$1,812	$170
Heat pump water heater	$1,594	$1,928	$188

5.1. HPWH Evaporator Location Parametric Analysis

To evaluate the impact of the HPWH evaporator inlet and outlet temperature locations, a parametric analysis was conducted on different ducting strategies within the household. In all cases the HPWH tank is assumed to be located in the basement. Table 7summarizes the four HPWH evaporator locations considered.

Table 7. HPWH evaporator inlet and outlet temperature location parametric analysis

Scenario	Evaporator Location	Additional Notes
Scenario 1	Basement	Basement maintained between 15°C and 18°C.
Scenario 2	Ducted to main floor	Main floor maintained at 21°C during heating season and 23°C during cooling season. HPWH will operate at warmer temperature and help meet cooling load.
Scenario 3	Ducted to unheated garage	No additional space heating is required to compensate for energy extracted. Unheated garage may not always be above 7.2°C requiring the use of auxiliary heating system.
Scenario 4	Ducted to unheated garage and HRV exhaust	Some warmer air from HRV exhaust helps compensate the colder garage temperature. The HRV is sized to bring 31L/s of fresh air, approximately 40% of the required evaporator airflow.

The predicted annual energy consumption, utility costs and GHG emissions are summarized in Tables 8 to 13 for the respective regions. The simple payback period and 13 year life cycle cost is also calculated for each scenario. It is important to note that Halifax and Montreal use all electric space heating systems, and thus have no natural gas or fuel oil consumption.

Table 8. Techno-economic results for HPWH in Halifax with different evaporator locations

Halifax, Nova Scotia	Base Case	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Electricity Consumption (GJ)	101.2	98.2	98.0	97.2	96.7
Total Energy Savings (GJ)	--	3.0	3.2	4.0	4.5
Utility Costs ($, CDN)	$4,292	$4,166	$4,158	$4,126	$4,106
Utility Cost Savings ($, CDN)	--	$126	$134	$166	$186
GHG Emissions (ton CO2 eq.)	22.7	22.0	22.0	21.8	21.8
GHG Emission savings (ton CO2 eq.)	--	0.7	0.7	0.9	0.9
Simple payback period (years)	--	19.8	19.2	15.5	13.9
13 year life cycle cost ($, CDN)	45.7k	47.0k	47.0k	46.7k	46.5k

Table 9. Techno-economic results for HPWH in Montreal with different evaporator locations

Montreal, Quebec	Base Case	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Electricity Consumption (GJ)	117.8	114.5	114.2	113.7	113.2
Total Energy Savings (GJ)	--	3.3	3.6	4.1	4.6
Utility Costs ($, CDN)	$2,664	$2,584	$2,576	$2,565	$2,553
Utility Cost Savings ($, CDN)	--	$80	$88	$99	$111
GHG Emissions (ton CO2 eq.)	0.2	0.2	0.2	0.2	0.2
GHG Emission savings (ton CO2 eq.)	--	0.0	0.0	0.0	0.0
Simple payback period (years)	--	> 30	> 30	28.2	25.1
13 year life cycle cost ($, CDN)	29.5k	30.1k	30.1k	30.0k	29.9k

Table 10. Techno-economic results for HPWH in Toronto with different evaporator locations

Toronto, Ontario	Base Case	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Electricity Consumption (GJ)	52.7	61.8	61.5	62.5	62.2
Natural Gas Consumption (GJ)	70.5	49.2	50.7	48.3	48.2
Total Energy Consumption (GJ)	123.2	111.0	112.1	110.8	110.4
Total Energy Savings (GJ)	--	12.2	11.1	12.4	12.6
Utility Costs ($, CDN)	$3,255	$3,455	$3,452	$3,468	$3,459
Utility Cost Savings ($, CDN)	--	($200)	($197)	($213)	($204)
GHG Emissions (ton CO2 eq.)	7.1	6.5	6.6	6.5	6.5
GHG Emission savings (ton CO2 eq.)	--	0.6	0.5	0.6	0.6
Simple payback period (years)	--	> 30	> 30	> 30	> 30
13 year life cycle cost ($, CDN)	38.0k	41.6k	41.6k	41.8k	41.7k

Table 11. Techno-economic results for HPWH in Edmonton with different evaporator locations

Edmonton, Alberta	Base Case	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Electricity Consumption (GJ)	50.3	62.1	61.7	62.9	62.5
Natural Gas Consumption (GJ)	85.8	60.3	61.6	59.7	59.5
Total Energy Consumption (GJ)	136.2	122.4	123.3	122.6	122.0
Total Energy Savings (GJ)	--	13.8	12.9	13.6	14.2
Utility Costs ($, CDN)	$2,199	$2,372	$2,367	$2,387	$2,379
Utility Cost Savings ($, CDN)	--	($173)	($168)	($188)	($180)
GHG Emissions (ton CO2 eq.)	19.0	20.9	20.9	21.1	21.0
GHG Emission savings (ton CO2 eq.)	--	(1.9)	(1.9)	(2.1)	(1.0)
Simple payback period (years)	--	> 30	> 30	> 30	> 30
13 year life cycle cost ($, CDN)	28.7k	32.5k	32.5k	32.8k	32.7k

Table 12. Techno-economic results for HPWH in Vancouver with different evaporator locations

Vancouver, BC	Base Case	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Electricity Consumption (GJ)	48.7	56.7	56.5	57.0	56.9
Natural Gas Consumption (GJ)	58.2	37.6	37.6	37.6	37.6
Total Energy Consumption (GJ)	106.9	94.3	94.1	94.6	94.5
Total Energy Savings (GJ)	--	12.6	12.8	12.3	12.4
Utility Costs ($, CDN)	$2,034	$2,180	$2,171	$2,191	$2,187
Utility Cost Savings ($, CDN)	--	($146)	($135)	($155)	($151)
GHG Emissions (ton CO2 eq.)	3.6	2.5	2.5	2.5	2.5
GHG Emission savings (ton CO2 eq.)	--	1.1	1.1	1.1	1.1
Simple payback period (years)	--	> 30	> 30	> 30	> 30
13 year life cycle cost ($, CDN)	24.7k	27.7k	27.7k	27.9k	27.9k

Table 13. Techno-economic results for HPWH in Whitehorse with different evaporator locations

Whitehorse, Yukon	Base Case	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Electricity Consumption (GJ)	64.6	59.0	58.7	59.7	59.4
Fuel Oil Consumption (GJ)	105.7	107.6	109.7	106.6	106.3
Total Energy Consumption (GJ)	170.3	166.6	168.4	166.3	165.7
Total Energy Savings (GJ)	--	3.7	1.9	4.0	4.6
Utility Costs ($, CDN)	$5,343	$5,154	$5,189	$5,157	$5,139
Utility Cost Savings ($, CDN)	--	$189	$154	$186	$204
GHG Emissions (ton CO2 eq.)	9.0	9.1	9.2	9.0	8.9
GHG Emission savings (ton CO2 eq.)	--	(0.1)	(0.2)	0.0	0.1
Simple payback period (years)	--	12.4	15.6	12.9	11.8
13 year life cycle cost ($, CDN)	66.7k	66.8k	67.3k	66.9k	66.7k

From the analysis, the HPWH reduced the annual energy consumption in all the regions assessed. More energy savings are seen in the regions where the natural gas fired conventional hot water heater was replaced with the HPWH. This is not surprising, as the 65% efficient natural gas system is replaced with a HPWH with a seasonal COP of 2.35. For the regions where the electric hot water heater was replaced with the HPWH, the savings were less evident, as the energy extracted by the HPWH to heat the DHW tank reduced space temperatures and increased the energy use of the space heating system.

In comparing the various evaporator air inlet and outlet locations (ambient temperature) of the HPWH, the annual energy savings in all regions were very similar to when the HPWH was located in the basement. For the regions where electric baseboards were used to meet the household space heating loads (Halifax and Montreal), using the garage as the ambient temperature for the HPWH generated more energy savings than using the conditioned space. This indicates that using an inefficient space heating system to supplement the energy for the HPWH is not beneficial in this instance. The energy savings to help cool the space during the summer could not outweigh the additional space heating requirements during the winter and shoulder seasons.

For Toronto, Edmonton and Whitehorse, using the 1st floor as the ambient temperature for the HPWH did not generate any energy savings over using the basement. With the thermostat for the furnace located on the main floor, this highlights that although a slightly warmer source temperature is available to the HPWH, the incremental energy savings for DHW could not outweigh the increased use of the space heating system. In Vancouver the opposite was noticed. This is attributed to the warmer climate (less demand for space heating).

In Toronto and Whitehorse, using the garage as the ambient temperature for the HPWH demonstrated energy savings from the basement scenario. In Whitehorse, with no space cooling system, the reduced space heating load offered in this configuration generates more energy savings than the increased electricity use for DHW production. In Toronto, where only minimal savings were obtained for space cooling by placing the evaporator in the basement in Scenario 1, the increased energy use by the HPWH in Scenario 2 was offset by reduced use of the space heating. For Edmonton and Vancouver, the opposite was noticed when using the garage as the evaporator source. Here, the reduced seasonal COP of the HPWH was not offset by the performance of the furnace system operating at a lower part-load.

In all cases, with exception of the Vancouver, supplementing the unheated garage source temperature with the HRV exhaust for the HPWH generated the most annual energy savings over all locations considered. This is expected as the HRV exhaust uses a portion of the household conditioned return air to supplement the HPWH evaporator. In Vancouver, no benefit was seen as it was still more beneficial to use the conditioned 1st floor temperature to improve HPWH performance, rather than a portion of unheated air from the garage.

Utility cost savings were only seen in regions where an electric hot water tank was replaced with a HPWH. With the low natural gas rates in Toronto, Edmonton and Vancouver, even with the improved annual efficiency to produce hot water, the system would need to have a seasonal COP of 3.0 or more to overcome natural gas costs that are 6 times cheaper per unit of energy than electricity. Furthermore, none of the regions demonstrated a beneficial 13 year life cycle cost over a conventional system. Simple payback periods ranged from 11.8 years in Whitehorse to above 30 years in the Montreal region when utility cost savings were achieved. The Whitehorse region demonstrated the best economic viability due to the high utility rates.

GHG emission reductions can be anticipated in all regions with exception of Edmonton, which has very energy intensive electricity production. In Halifax, also with an energy intensive electricity generation process, GHG emission reductions are seen as the electric hot water tank is replaced with an efficient HPWH.

5.2. HPWH Hot Water Draw Parametric Analysis

An additional parametric analysis was conducted to assess the impact on the energy savings, utility cost savings and GHG emission reduction potential of the HPWH under different hot water draw profiles. This parametric analysis simulated a low and high hot water consumption using a dispersed profile. Similar to the average hot water draw profile used, both hot water draw profiles were adjusted according to the incoming mains temperatures for each region. The normalized daily hot water consumption was 123.6 L/day (low) and 238.8 L/day (high). The evaporator of the HPWH was assumed to be located in the basement for this analysis. Results including Simple payback periods and 13 year life cycle costs are summarized below (Tables 14 to 19).

Table 14. Techno-economic results for HPWH in Halifax with different hot water draw profiles

Halifax, Nova Scotia	Base Case (Low)	HPWH (Low)	Base Case (High)	HPWH (High)
Electricity Consumption (GJ)	97.1	94.5	105.8	101.2
Total Energy Savings (GJ)	--	2.6	--	4.6
Utility Costs ($, CDN)	$4,123	$4,015	$4,480	$4,290
Utility Cost Savings ($, CDN)	--	$108	--	$190
GHG Emissions (ton CO2 eq.)	21.8	21.2	23.7	22.7
GHG Emission savings (ton CO2 eq.)	--	0.6	--	1.0
Simple payback period (years)	--	23.2	--	13.2
13 year life cycle cost ($, CDN)	44.1k	45.5k	47.7k	48.3k

Table 15. Annual energy consumption, utility costs and GHG emissions for HPWH in Montreal with different hot water draw profiles

Montreal, Quebec	Base Case (Low)	HPWH (Low)	Base Case (High)	HPWH (High)
Electricity Consumption (GJ)	113.6	110.8	122.5	117.6
Total Energy Savings (GJ)	--	2.8	--	4.9
Utility Costs ($, CDN)	$2,563	$2,495	$2,777	$2,658
Utility Cost Savings ($, CDN)	--	$68	--	$119
GHG Emissions (ton CO2 eq.)	0.2	0.2	0.2	0.2
GHG Emission savings (ton CO2 eq.)	--	0.0	--	0.0
Simple payback period (years)	--	> 30	--	22.7
13 year life cycle cost ($, CDN)	26.9k	29.2k	29.1k	30.9k

Table 16. Annual energy consumption, utility costs and GHG emissions for HPWH in Toronto with different hot water draw profiles

Toronto, Ontario	Base Case (Low)	HPWH (Low)	Base Case (High)	HPWH (High)
Electricity Consumption (GJ)	52.6	56.9	52.7	62.8
Natural Gas Consumption (GJ)	64.3	50.2	77.3	50.2
Total Energy Consumption (GJ)	116.9	107.1	130.0	113.0
Total Energy Savings (GJ)	--	9.8	--	17.0
Utility Costs ($, CDN)	$3,206	$3,303	$3,302	$3,542
Utility Cost Savings ($, CDN)	--	($97)	--	($240)
GHG Emissions (ton CO2 eq.)	6.8	6.3	7.5	6.6
GHG Emission savings (ton CO2 eq.)	--	0.5	--	0.9
Simple payback period (years)	--	> 30	--	> 30

13 year life cycle cost ($, CDN)	37.5k	40.0k	38.5k	42.5k

Table 17. Annual energy consumption, utility costs and GHG emissions for HPWH in Edmonton with different hot water draw profiles

Edmonton, Alberta	Base Case (Low)	HPWH (Low)	Base Case (High)	HPWH (High)
Electricity Consumption (GJ)	50.2	56.4	50.3	64.4
Natural Gas Consumption (GJ)	78.7	61.3	94.3	61.1
Total Energy Consumption (GJ)	128.9	117.7	144.6	125.5
Total Energy Savings (GJ)	--	11.2	--	21.6
Utility Costs ($, CDN)	$2,172	$2,246	$2,199	$2,428
Utility Cost Savings ($, CDN)	--	($74)	--	($229)
GHG Emissions (ton CO2 eq.)	18.6	19.4	19.5	21.6
GHG Emission savings (ton CO2 eq.)	--	(0.8)	--	(2.1)
Simple payback period (years)	--	> 30	--	> 30
13 year life cycle cost ($, CDN)	28.5k	31.0k	28.8k	33.2k

Table 18. Annual energy consumption, utility costs and GHG emissions for HPWH in Vancouver with different hot water draw profiles

Vancouver, BC	Base Case (Low)	HPWH (Low)	Base Case (High)	HPWH (High)
Electricity Consumption (GJ)	48.7	52.3	48.7	57.3
Natural Gas Consumption (GJ)	52.6	37.8	64.3	37.4
Total Energy Consumption (GJ)	101.3	90.1	113.0	94.7
Total Energy Savings (GJ)	--	11.2	--	18.3
Utility Costs ($, CDN)	$1,994	$2,022	$2,077	$2,199
Utility Cost Savings ($, CDN)	--	($28)	--	($122)
GHG Emissions (ton CO2 eq.)	3.3	2.5	4.0	2.5
GHG Emission savings (ton CO2 eq.)	--	0.8	--	1.5
Simple payback period (years)	--	> 30	--	> 30
13 year life cycle cost ($, CDN)	20.6k	26.1k	21.5k	27.9k

Table 19. Annual energy consumption, utility costs and GHG emissions for HPWH in Whitehorse with different hot water draw profiles

Whitehorse, Yukon	Base Case (Low)	HPWH (Low)	Base Case (High)	HPWH (High)
Electricity Consumption (GJ)	59.3	52.7	71.2	62.3
Fuel Oil Consumption (GJ)	106.1	109.4	105.4	108.8
Total Energy Consumption (GJ)	165.4	162.1	176.6	171.1
Total Energy Savings (GJ)	--	3.3	--	5.5
Utility Costs ($, CDN)	$5,129	$4,931	$5,607	$5,317
Utility Cost Savings ($, CDN)	--	$198	--	$290
GHG Emissions (ton CO2 eq.)	8.9	9.1	9.1	9.2
GHG Emission savings (ton CO2 eq.)	--	(0.2)	--	(0.1)
Simple payback period (years)	--	11.8	--	8.1
13 year life cycle cost ($, CDN)	64.1k	64.1k	69.9k	68.8k

Similar to the HPWH evaporator location analysis, all regions demonstrated energy savings regardless of the actual hot water (HW) draw profile. More energy savings are seen with a larger HW draw profile because of the increased amount of DHW heating required. Interestingly however, the low and high HW draw profiles resulted in an increase in space heating energy consumption over the average HW draw profile. For the high HW draw profile, this can be expected as more energy from the basement is used to meet the higher DHW load. For the low

DHW profile, the increased heating demand is associated with the less heat and humidity gain in the actual household. Also, although the low HW draw profile is approximately 33% less than the average HW draw profile, a 66% reduction in DHW energy is seen, highlighting that the HPWH operates more often in heat pump mode under this profile. This also contributes to increasing the space heating demand.

From an economic perspective, utility cost savings were obtained in regions where a conventional electric hot water tank was replaced with the HPWH. For the regions where a natural gas fired system was replaced, the conversion from natural gas to electricity, regardless of the HW draw profile, did not result in any savings. Similar to the conclusion drawn from the average HW profile, the low cost of natural gas requires a HPWH to have a seasonal COP of 3.0 or higher in order to become economically viable in these regions. Only the Whitehorse region demonstrated equal or a slightly shorter 13 year life cycle cost in comparison to the conventional system, mainly due to higher annual utility costs. Whitehorse also achieved the lowest simple payback period at 8.1 years, under the high DHW profile.

From a GHG emission reduction perspective, conclusions are similar to the average DHW profile analysis. With the exception of Edmonton and Whitehorse, all regions can expect to see a GHG emission reduction when switching from an electric or natural gas system to the HPWH. In Edmonton the carbon intensive electricity production increases GHG emissions while in Whitehorse the fuel oil required to compensate for the increased heating loads results in a slight increase in emissions.

6. Conclusion and Future Work

A techno-economic analysis was presented on the impact that heat pump water heaters (HPWH) can have in the Canadian residential sector. The majority of hot water heating in the residential sector is met through either conventional electrically heated or natural gas fired systems. To perform the techno-economic analysis a newly constructed housing energy model designed to meet current minimum energy efficiency levels was developed for six Canadian regions with varying climates and utility rate structures. The conventional hot water tank was replaced with a HPWH and several parametric studies were conducted to assess alternative HPWH evaporator locations and different hot water draw profiles. The results highlighted that the evaporator location had little impact on the overall energy consumption of the building. However, the greatest energy savings were typically achieved when ducting the exhaust of the household heat recovery ventilator through the evaporator of the HPWH. It was also interesting to note that the majority of regions demonstrated greater energy savings using the unheated garage as the source and sink rather than the basement or 1st floor, as this configuration assisted in reducing cross-effects on the space heating load. For houses with a heat pump space heating system, it may be more beneficial to use the indoor conditioned space as the source/sink temperature for the HPWH, as the household heating load can be efficiently met. Three different hot water draw profiles were also assessed. As anticipated, the greatest energy savings were achieved using a high hot water draw profile. The HPWH operated most efficiently under the low hot water draw profile, as the system was given enough time to operate in heat pump mode to meet the DHW requirements. Interestingly, operating longer in heat pump mode resulted in an increased space heating demand compared to the average and high hot water draw profile, minimizing the global energy savings achieved using a HPWH.

Form a greenhouse gas (GHG) emissions perspective, the results varied depending on the region and type of conventional domestic hot water (DHW) system being replaced. In regions where an electric hot water tank is replaced, the HPWH always resulted in GHG emission reductions, even with the increased space heating demand. In regions with carbon intensive electricity generation, where a natural gas DHW system is replaced, the HPWH increased overall GHG emissions. In very cold regions, GHG emission reductions achieved with the HPWH were negated by increased heating loads placed on the inefficient fuel-based space heating system.

A simple payback period was calculated and a 13 year life cycle cost analysis was performed to evaluate the economic viability of HPWHs in the Canadian residential market. For the regions where natural gas is inexpensive, the HPWH never demonstrated economic benefits. For the regions where an electric hot water tank was replaced with the HPWH, annual utility cost savings were realized, but high first costs rarely resulted in a viable simple payback period under the estimated lifetime of the HPWH (> 13 years). Similarly, the 13 year life cycle cost analysis consistently concluded that, from a solely economic perspective, it is better for the end-user to install a conventional hot water heating system instead of a HPWH, as high initial costs combined with low utility rates are difficult to overcome. Only in Whitehorse did it make financial sense to install a HPWH, where a simple payback period of just over 8 years was estimated under a high hot water draw profile.

Future work will look to evaluate the potential of replacing conventional electric hot water heaters in regions where natural gas is not accessible. Additional hot water draw profiles will be assessed, as well as different HPWHs suitable for colder climates (evaporator can be located outdoors). Testing of these systems is also planned to get a better understanding of system operations and performance, while additional studies will be conducted to determine how to better adapt HPWHs to the Canadian climate.

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