Analysis of a Coupled Air-Based Solar Collector and Heat Pump Water Heater in Canada and the United States

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Abstract

Heat pump water heaters (HPWHs) have limited market share in Canada and the United States largely due to their space cooling effect which increases heating costs throughout winters in these countries. Coupling a HPWH with solar collectors lessens the space cooling effect during cold-climate heating seasons while also improving HPWH performance year-round in cold and moderate climates. This study experimentally and numerically examined air-based solar collectors and their impact on HPWHs with the objective of determining the feasibility of solar assisted HPWHs in Canada and the United States. An air-based solar collector was used in an experimentally validated model of the combined system, and different configurations of solar-assisted HPWH (SAHPWH) were analyzed to minimize the space cooling effect and electricity consumption. The results indicate that the space cooling effect of HPWHs can be mitigated by coupling the HPWH with a solar collector in all configurations studied. The configurations of SAHPWH which minimized water heating electricity consumption for each Canadian and American location studied were determined, and a correlation was found between climate zone and the configuration with minimum electricity consumption. The maximum electricity reductions from an electric water to a SAHPWH were realized near the Canada and US border, and with a 5% transition to SAHPWHs, Canadian residential energy for water heating can be decreased by 3.1%.

Keywords: Solar-assisted heat pump water heater, air-based solar thermal, Canadian and American feasibility, electricity reduction, TRNSYS simulation

1. Introduction

Water heating is dominated by natural gas in Canada and the United States and, as such, contributes 21.3% and 15.5% of the residential greenhouse gas (GHG) emissions by secondary energy source in these countries, respectively (NRCan, 2018) (US EIA, 2018). One alternative technology is the heat pump water heater (HPWH), which uses an electricity-driven refrigeration cycle to heat water. HPWHs achieve energy factors (energy delivered per unit of energy input) of 2 to 3, as compared to electric resistance and gas water heaters which obtain energy factors of approximately 1 and 0.67, respectively. In the United States, new regulations have mandated the use of HPWHs for domestic hot water (DHW) systems with tank sizes greater than 55 gal (US DOE, 2014), and given the historical progression of Canadian DHW regulations following those set in the United States, Canada may soon follow suit in requiring HPWHs. Despite the benefits and regulations, HPWHs presently have two major barriers: high capital costs and a secondary space cooling effect which is disadvantageous throughout the relatively long heating season in many locations across Canada and the United States. Space cooling is caused by the removal of energy from the space via the evaporator of the refrigeration cycle which relocates heat to the water. The air to water refrigeration cycle is shown in Fig. 1.

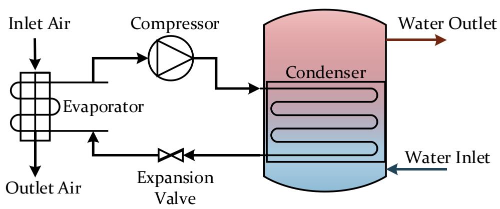

Fig. 1: Commercially available wrap-around coil heat pump water heater

For the refrigeration cycle to efficiently heat water, the inlet air temperature must be above approximately 5°C, so HPWHs are commonly supplied conditioned air from a home which causes space cooling. Alternatively, HPWHs could use outdoor air in warmer climates such as the southern United States, which have outdoor temperatures that meet the inlet HPWH air temperature requirement. In these warm locations, however,

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HPWHs are often fed conditioned air because the secondary space cooling effect of the refrigeration cycle is beneficial in reducing energy for air conditioning. In colder climates, the cooling effect increases heating costs during a large portion of the year, but using outdoor air is not an option due to cold ambient temperatures. To reduce the space cooling throughout the heating season and allow the electricity reductions of HPWHs to be realized, combining a HPWH with a solar collector may be a technologically and economically viable option.

Solar collectors are commonly coupled with HPWHs in either direct- or indirect-expansion configurations which are shown in Fig. 2. In the direct expansion configuration, the solar collector is the evaporator in the refrigeration cycle, so the HPWH refrigerant is the working fluid in the collector. In the indirect configuration, the collector and refrigeration cycle are connected via a heat exchanger, one side of which is the HPWH evaporator. Because a heat exchanger separates the solar collector system from the HPWH, the collector may have water, a glycol solution, or air as a working fluid rather than refrigerant. The indirect expansion configuration is easier and less expensive to couple with a commercially available HPWH, because no modifications to the refrigeration cycle are required.

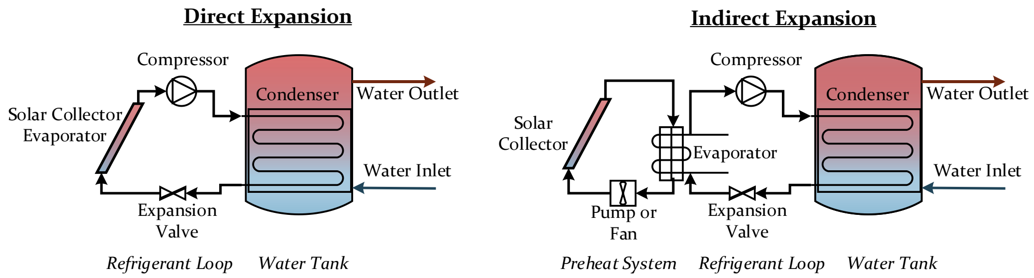

Fig. 2: Solar-assisted HPWHs in direct and indirect expansion configurations

The objective of this research was to assess the feasibility of an indirect expansion HPWH and air-based solar thermal collector system in Canada and the United States via experiments and simulation. With an air-based solar thermal collector to preheat inlet air for the HPWH, it may be possible to realize electricity reduction of HPWH systems as compared to electric resistance water heaters, without increasing space heating loads throughout cold Canadian and American winters. Additionally, coupling a solar collector with a HPWH may increase year-round operating performance compared to a HPWH alone in all climates within these countries. In this study, solar collectors coupled with a HPWH in various configurations were compared to minimize the annual electricity consumption across Canada and the United States. This paper contains a review of pertinent literature, followed by methodology which includes descriptions of the solar-assisted HPWH (SAHPWH) configurations analyzed. The experimental and simulated data are included, with a discussion of the results followed by the conclusions.

2. Literature Review

HPWHs have been studied in various locations worldwide to determine their feasibility and additional benefits or costs due to their inherent space cooling. Sparn et al. (2014) experimentally replicated US climates to show that energy reductions can be realized using HPWHs throughout the US, but recommended HPWHs not be used in conditioned spaces in cold regions with long heating seasons. This is because the cooling effect of HPWHs increases space heating costs throughout heating seasons, such as subzero Canadian winters (Khalaf, 2017; Amirirad, et al., 2018). The space cooling effect must be mitigated for HPWHs to be economically feasible in cold climates, and coupling the HPWH with solar collectors is one method to achieve this.

Significant research has been conducted to date on direct-expansion SAHPWH systems. A study by Kong et al. (2017) on a direct-expansion SAHPWH system in China concluded that the site-specific conditions of insolation and ambient temperatures had a significant effect on the overall system COP and heating time. Deng and Yu (2016) went further to show that ambient temperature had a large effect on SAHPWHs when solar insolation was low, but little effect when insolation was high. Vieira et al. (2015), however, concluded that HPWHs in warmer climates were less influenced by site-specific conditions such as insolation and temperature, thus achieving a high COP at a wide range of temperature and insolation values. The variance between the effect of insolation, temperature, and other site-specific parameters between the aforementioned studies can be partially attributed to findings in a review by Poppi et al. (2018), which indicated that existing

HPWH studies are difficult to compare due to the wide variety of boundaries, geometries, locations, and assumptions. This means detailed analysis of HPWH systems is required for each HPWH configuration and location in which they are implemented to improve and optimize performance of the systems. Despite the research on direct-expansion systems, Kamel et al. (2015) explained that direct-expansion photovoltaic-coupled SAHPWHs are inefficient, because additional controls are required for the mass flow rate to prevent refrigerant from pooling at the evaporator outlet. In addition, direct-expansion SAHPWHs are complex to fabricate from commercially available HPWHs because they require redesign of the refrigerant cycle, so indirect-expansion SAHPWHs are often preferred for aftermarket coupling of solar collectors with HPWHs.

Several studies agree that SAHPWHs improved performance compared to HPWHs alone in all climates, but most notably in cold climate regions. Carbonell et al. (2014) simulated solar thermal HPWHs and saw large electricity savings when using an air-source heat pump system, particularly in cold climates with high insolation values. This is because energy consumption for space and water heating is greater in cold climates, and systems with a higher energy demand are operational for a greater proportion of time, therefore realizing larger absolute electricity savings than those with low energy demand. Cai et al. (2017) determined that a dual source multi-functional solar HPWH system was also particularly beneficial in cold climate conditions, with significant COP increases in an optimized cold climate system, as compared to other climates. Li et al. (2014) simulated and optimized the solar collector area and storage factor for domestic hot water and space heating in Beijing, increasing the COP by 1.4 times compared to the non-optimized system. Although there are benefits and high electricity savings of solar-coupled HPWHs in cold climates, most systems analyzed in past research still have a negative impact on the space heating load throughout the heating season.

Kegel et al. (2012) compared an air-source solar collector coupled with an air-source HPWH to a water-source solar collector with a ground-source heat pump system for space and water heating in Montreal. This study concluded that the air-source solar collector and heat pump system configuration was more efficient than the water-source configuration. Despite the benefit of air-based collectors with HPWHs, a review by Kamel et al. (2015) highlighted that there is limited research on air-based solar collectors coupled indirectly with HPWHs. Past research has shown reduced performance of HPWH-only and combined HPWH-solar systems in cold climates compared to moderate climates, so new strategies and configurations of SAHPWH which prevent or reduce impact on space conditioning loads were explored in this study. This study aims to address the lack of research on air-based solar collectors coupled with HPWHs, particularly in colder climates, and analyze the energy performance of various configurations of SAHPWH in different locations in a way that is directly comparable. Different configurations of the coupled system were analyzed for Canada and the United States to determine the preferred configurations for electricity reduction.

3. Methodology

The performance of a commercially available wrap-around condenser coil HPWH coupled with an air-based solar collector to preheat inlet HPWH air was assessed in this study experimentally and via simulation using the Transient System Simulation Tool (TRNSYS) software. An experimental set-up was used to develop a performance map of the HPWH and to validate the TRNSYS model. The validated HPWH model was expanded to include a solar collector in the different solar collector and HPWH configurations studied. This section describes the configurations analyzed, followed by a description of the experimental set-up and overall procedure used.

1.1. Configurations Analysed in Study

Three configurations of SAHPWH, shown in Fig. 3, were considered in this study. The configurations differed in the location from which inlet solar collector air was drawn: the first recirculated air in a closed loop between the solar collector and HPWH, the second drew air from and exhausted to outdoors, and the third configuration drew air from and exhausted to a conditioned space.

It was found that in the closed loop configuration, closed loop circulation of air wherein the inlet to the solar collector was the outlet to the HPWH and vice versa, led to the SAHPWH system operating independently from the space conditioning system. Similarly, the outdoor air configuration which drew air from outside, heated it in the solar collector, and exhausted it to the outdoors was also independent of the space conditioning system. During periods of low insolation, HPWH inlet temperatures in these two configurations decreased below 5°C in many locations, which is the threshold under which the HPWH does not operate. If water draws occurred dropping the water tank temperature was below 45°C and the inlet air temperature was below 5°C, the water storage tank recharged with the backup electric element that is present in commercially available HPWHs, leading to increased electricity consumption.

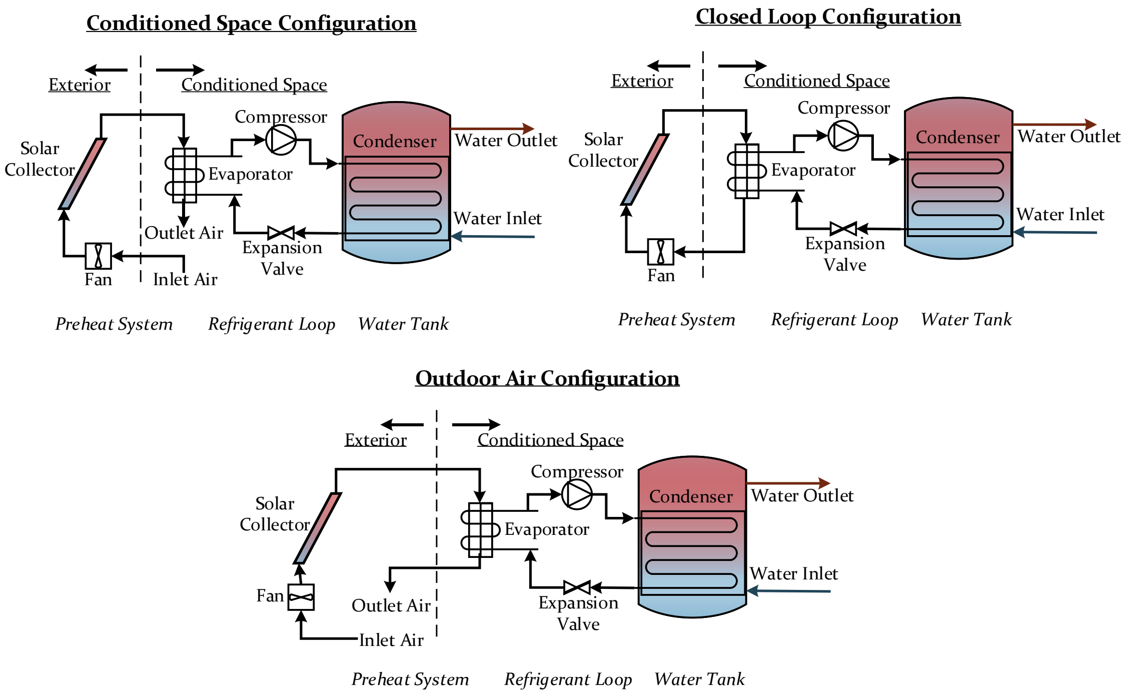

Fig. 3: Configurations of SAHPWH analyzed within the study

In the conditioned configuration, air was drawn from a conditioned space so HPWH inlet air temperatures were always at least 20°C, meaning the electric element usage was eliminated. The conditioned space configuration removed air from a conditioned space, circulated it through the solar collector to the HPWH inlet, and exhausted air to the space causing net heating or cooling, depending on the temperature differential between the inlet and exit air. During periods of high solar insolation, the exit HPWH air temperatures to the room were found to be greater than the 20°C room temperature causing a heating effect on the space, and during periods of little to no solar insolation, the HPWH exit temperatures were lower than the room temperatures causing a cooling effect on the space. In addition, when the HPWH was not in operation and it was the heating season, all solar thermal gains from the collector were used to directly heat the space. In this analysis, it was assumed that the space heating system was electric with a COP of 1, and the cooling system had a seasonal energy efficiency ratio (SEER) of 12. The SEER is the ratio of cooling energy in BTU per hour to the electrical energy in Watts. The space heating and cooling seasons were assumed based on ASHRAE climate zones, shown in Tab. 1. The cities analyzed in this study and their climate zones are shown in Fig. 4.

Tab. 1: ASHRAE Climate Zone numbers and corresponding assumed heating and cooling seasons

Climate Zone	Heating Season	Cooling Season
1, 2, 3	-	Always
4, 5	December, January, February	March, April, May, June, July, August, September, October, November
6	November, December, January, February, March	April, May, June, July, August, September, October
7	October, November, December, January, February, March, April	May, June, July, August, September
8	Always	-

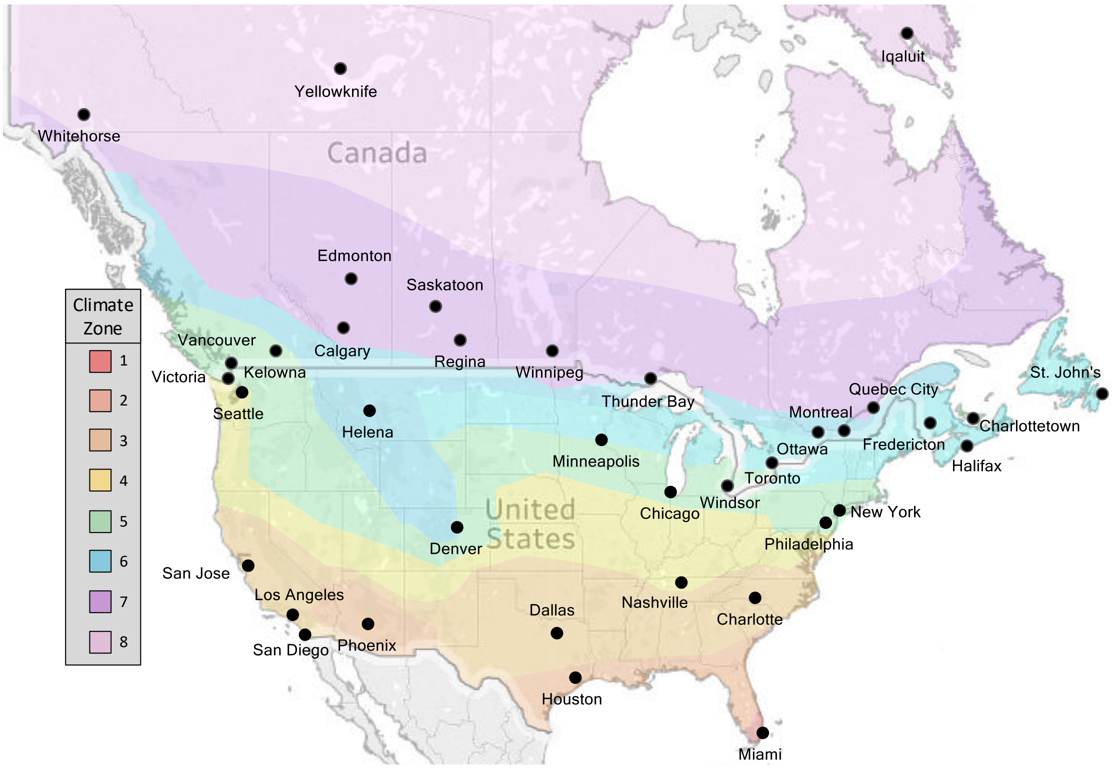

Fig. 4: ASHRAE Climate zones for Canadian and American cities studied

1.2. Experimental Setup

The solar collector in the system was simulated in TRNSYS and the output temperatures were the inlet conditions for the experimental HPWH. The experimental HPWH results were then used to validate a TRNSYS model of the HPWH, which was combined with the solar collector model and used for the detailed analysis of the SAHPWH configurations. In this section, the experimental system and experimental methods used are described.

The experimental system included a commercially available HPWH, air-handling unit (AHU), water draw system, and mains water cooling system. The solar collector was simulated based on a commercially available air-based solar collector, and the AHU reproduced the simulated solar collector outlet temperatures for the inlet HPWH temperatures in the experimental system. The specifications of the HPWH and solar collector studied are shown in Tab. 2. Because the heating season is the largest barrier for HPWHs, the solar collector was analyzed at an angle of 15° greater than latitude for each location, which is optimal for winter conditions. The experimental system was evaluated in a conditioned room under CSA-F379.1 Schedule A 150 L hot water draws, in day-long tests. During hot water draws, 60°C water in the HPWH tank was replenished with mains water which was chilled by the mains water cooling system to replicate mains water conditions for Canadian locations in winter. A schematic diagram and image of the experimental system are shown in Fig. 5.

Tab. 2: HPWH and solar collector specifications (GE Appliances, 2012) (Fraunhofer ISE, 2013)

HPWH Property	Value	Solar Collector Property	Value
Tank Volume (L)	189	Area (m^2)	1.26
Refrigerant	R-134a	Absorber Material	Polyester Felt
Compressor Power (W)	600	Working Fluid	Air
Upper Heating Element Power (W)	4500		

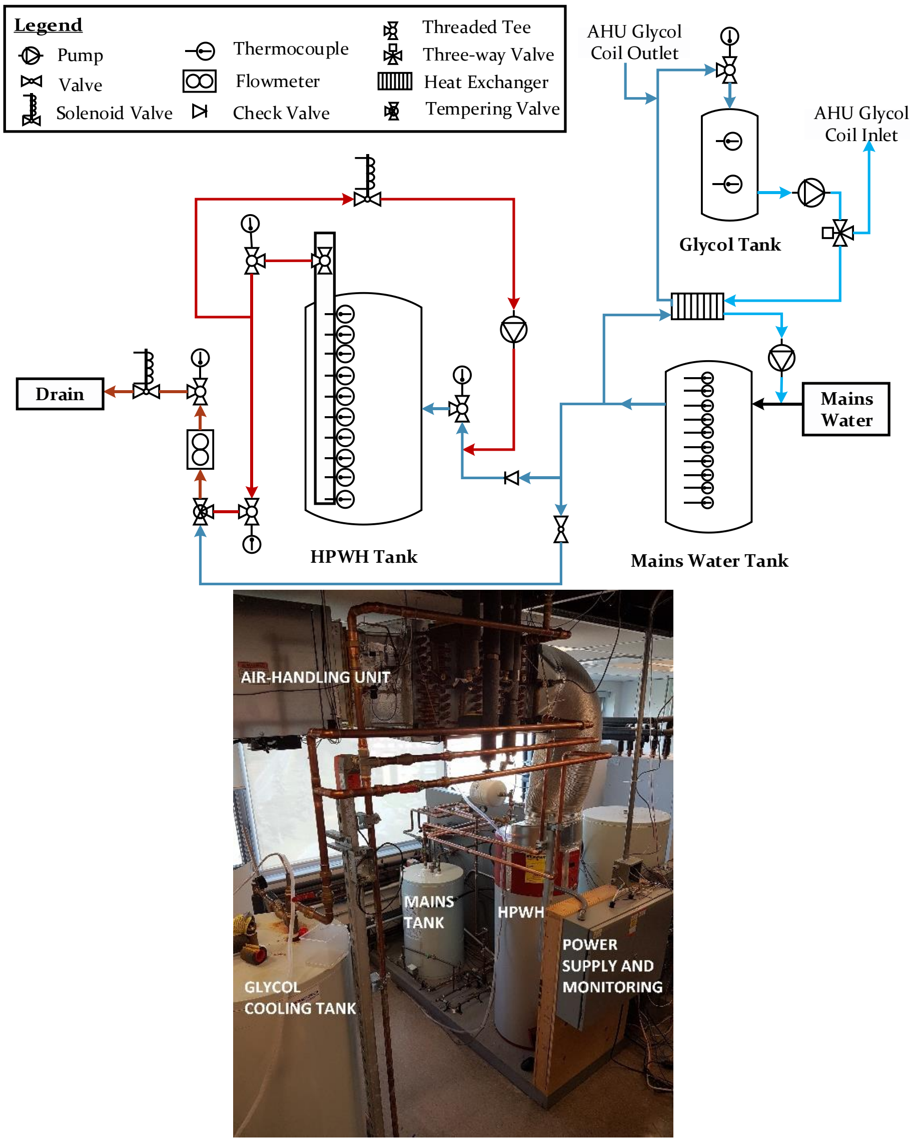

Fig. 5: Schematic of experimental water supply, water draw, and glycol systems (top) and image of experimental set-up (bottom)

The experimental setup included ten Type T thermocouples in both the HPWH tank and the mains water tank which had equal vertical spacing. Based on the work by Cruickshank and Harrison (2010), the tank temperatures at each node in the tanks were assumed to be well mixed in the horizontal direction, and thus were not monitored for horizontal temperature differences. The water draw system consisted of a turbine-type flowmeter to measure draw volumes, an on/off solenoid valve to control draws, and a tempering valve to mix the 60°C water from the HPWH tank with mains water to supply 55°C water. The mains water was circulated through a glycol to water heat exchanger which cooled the water, and the cooled water was stored in a mains water tank, from which water was removed to fill the HPWH water during water draw events. The conditioning equipment for the air in the air-handling unit (AHU) included a fan, a humidifier, and three air tempering coils: a water-based cooling coil, a water-based heating coil, and a glycol/water-mixture in a super-cooling coil. The instrumentation for the AHU included Type T thermocouples, an air flowmeter, and relative humidity sensors at the air inlet and exit of the HPWH. The full control and instrumentation of the experimental setup was used to generate a performance map of the HPWH system for use in the TRNSYS model.

1.3. TRNSYS Model

The experimental HPWH had condenser coils wrapped around the water storage tank, which are not represented by existing HPWH TRNSYS models. To address this, Khalaf (2017) developed a refrigeration cycle for a HPWH with wrap-around condenser model for use within TRNSYS. The refrigeration cycle determined power and heat rejection to a storage tank (kJ/h), based upon the inlet air conditions which are the outputs from the Type 539 solar collector. The HPWH storage tank, modelled using Type 534, took the heat rejection from the refrigeration cycle and determined the HPWH tank temperatures at each of the ten nodal positions. Based on the tank temperatures, a controller determined an on/off signal for the refrigeration cycle. When the refrigeration cycle could not keep up with draws, the controller also turned on an electric element to provide supplemental heat rejection to the storage tank. Daily draws from the storage tank were imposed by Type 1243a. During draw events from the storage tank, a Type 953 tempering valve was used to determine the proportion of mains water and hot water from the storage tank were required to achieve a DHW distribution temperature of 55°C.

The TRNSYS model used an experimental performance map for the compressor power, heat rejection to the water, and sensible and latent heat transfer from the air at different operating conditions. The experimental and TRNSYS systems were run under day-long draw tests having the same inlet conditions and the experimental and simulated behavior were compared as shown in Fig. 6.

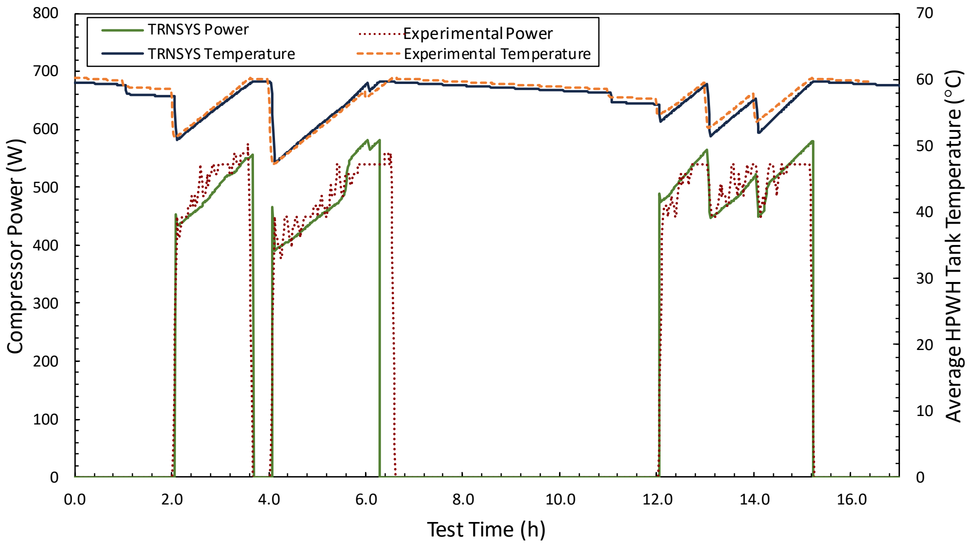

Fig. 6: Experimental validation results for HPWH compressor power and average water storage tank temperature

The validation sample was the result for a one-day test operating with a 150 L total draw volume, with inlet HPWH air conditions representative of solar collector outlet temperatures on a day of average insolation in January in Ottawa, Canada. In the validation process for this sample, the mean average error (MAE) of the average HPWH tank temperature was 0.6°C, while the MAE of the compressor power was 28 W or 6%. The error was within the experimental error determined during the previous error analysis of the experimental system (Khalaf, 2017).

4. Results and Discussion

The validated TRNSYS model of the HPWH was expanded to include solar thermal collectors and was used to simulate SAHPWH performance in various locations across Canada and the United States. In each location, the performance of a SAHPWH in each conditioned space, closed loop, and outdoor air configurations was analyzed, in addition to a HPWH-only system.

The main challenge of HPWH only systems in cold climates is secondary space cooling which increases space heating throughout winter. The HPWH only system drew 207-244 kWh per month from the space throughout winter in various Canadian cities, as shown in Fig. 7. The slight variation in HPWH only cooling among the Canadian cities was the result of variations in the mains water temperature which caused the HPWH to operate for different total durations in each of the cities. Cities with cooler mains water temperatures such as Winnipeg required a greater amount of HPWH operating time to heat the water, during which time the space cooling occurred. To combat the space cooling in cold regions, the closed loop and outdoor air configurations were designed to operate independently of the space conditioning systems. The conditioned space configuration of SAHPWH was not independent of the space conditioning systems but had net heating for the space throughout winter in the Canadian cities, as opposed to the HPWH alone which had significant space cooling, as shown in Fig. 7. When the HPWH was coupled with a solar collector in conditioned configuration, the cooling was fully offset and 20-54 kWh per month of additional heat was provided to the space in locations across Canada, with the exception of Vancouver in November which reduced the space cooling from that of the HPWH only system, but still saw a net cooling load. The low insolation in Vancouver in November led to 1 kWh of space cooling despite the coupled solar collector. Vancouver had the least space heating benefits throughout winter from the conditioned configuration due to the relatively low solar insolation, and conversely, Winnipeg realized the greatest space heating benefits due to highest solar insolation.

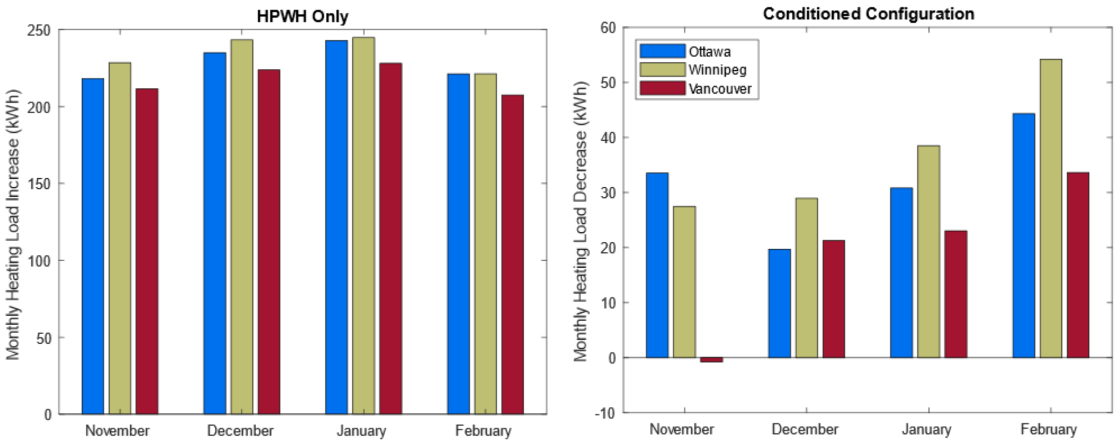

Fig. 7: Cooling by HPWH only (left) and heating by conditioned configuration (right) during winter in Canadian cities

The conditioned space, closed loop, outdoor air, and HPWH only systems were analyzed and compared in terms of annual water heating electricity consumption across Canada and the United States. Various tank volumes and daily draw volumes were examined to illustrate trends caused by variations in system design and performance. In this analysis, all input parameters were maintained constant, except the daily draw or tank volumes studied. Annual electricity trends in Ottawa, which are representative of major cities across Canada, and Dallas, which are representative of the southern United States are shown in Fig. 8.

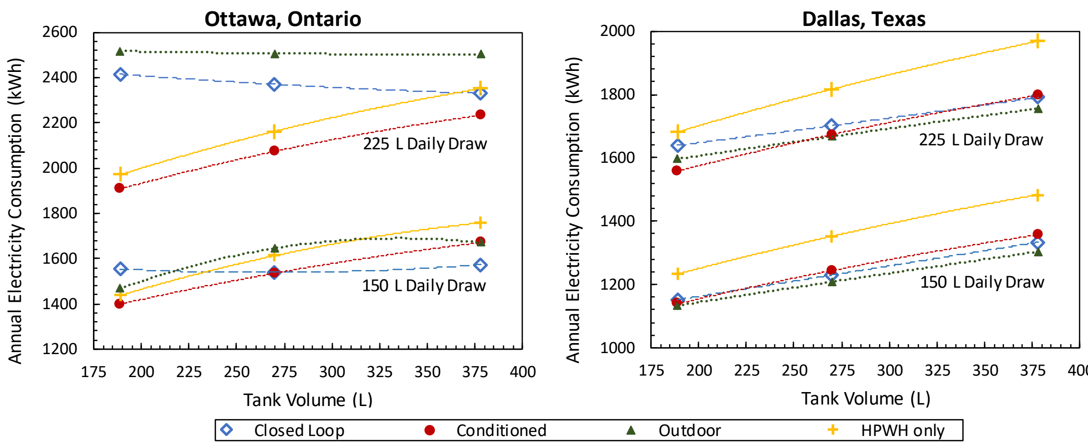

Fig. 8: Variation in annual electricity consumption for daily draw volumes, tank sizes, and configurations in Ottawa, Ontario (left) and Dallas, Texas (right)

In Ottawa, the conditioned configuration had lowest electricity consumption in most cases, because relatively low winter air temperatures and insolation levels limited the performance of the outdoor and closed loop configurations. In the conditioned configuration, inlet HPWH air temperatures were at least 20°C, whereas the closed loop and outdoor configurations inlet temperatures reached as low as 5°C during periods of low insolation and temperature. Below 5°C inlet air temperatures, which were common in the closed loop and outdoor air configurations in Ottawa, an electric backup element heated the water, significantly increasing electricity consumption. The outdoor configuration had a high proportion of time during which the electric element operated and thus often had greatest annual electricity consumption. The closed loop configuration only had least electricity consumption in Ottawa when the storage tank size was relatively large compared to the daily draw volume. This is because at larger tank volumes with relatively small draws, less variation in tank temperature occurred, limiting the fraction of time the electric backup element operated for the closed loop configuration, thus reducing overall electricity consumption.

For all configurations in both locations, electricity consumption increased for larger tank sizes that were oversized for the draw volume, due to two main factors: greater losses from the tank occur at larger tank volumes, and more energy is consumed to heat water at higher temperatures which occur for a larger portion of time with larger tank sizes. This indicates the importance of properly sizing storage tanks to hot water demand in reduction of electricity. Although the closed loop configuration had lower electricity consumption in larger tank volume cases, it is impractical to design a system with these characteristics.

In Dallas, ambient temperatures and solar insolation are high so there was more time during which the inlet temperatures to the HPWH were above 5°C in closed loop and outdoor configurations, meaning the HPWHs could operate without the electric backup element for significantly more time throughout the year. As such, there is little variation in electricity consumption between the three solar assisted configurations in Dallas. The slight variations in annual electricity consumption can be partially attributed to differences in the inlet temperatures of the HPWH air, because greater inlet temperatures improve HPWH performance. The closed loop and outdoor configurations had higher inlet temperatures than the conditioned configuration for a larger portion of the year, which lead to lower electricity consumption. In addition, the overall electricity consumption for all configurations including the HPWH-only scenario is lower in the southern United States than Canada due to warmer mains water temperatures.

Comparison of the two graphs in Fig. 8 shows that for different draw volumes, tank sizes, and locations, different configurations of SAHPWH minimized electricity consumption. The configuration which resulted in lowest annual electricity consumption for each location in Canada and the United States under a 150 L daily draw with a 189 L tank volume is shown in Fig. 9, along with the corresponding annual electricity consumption.

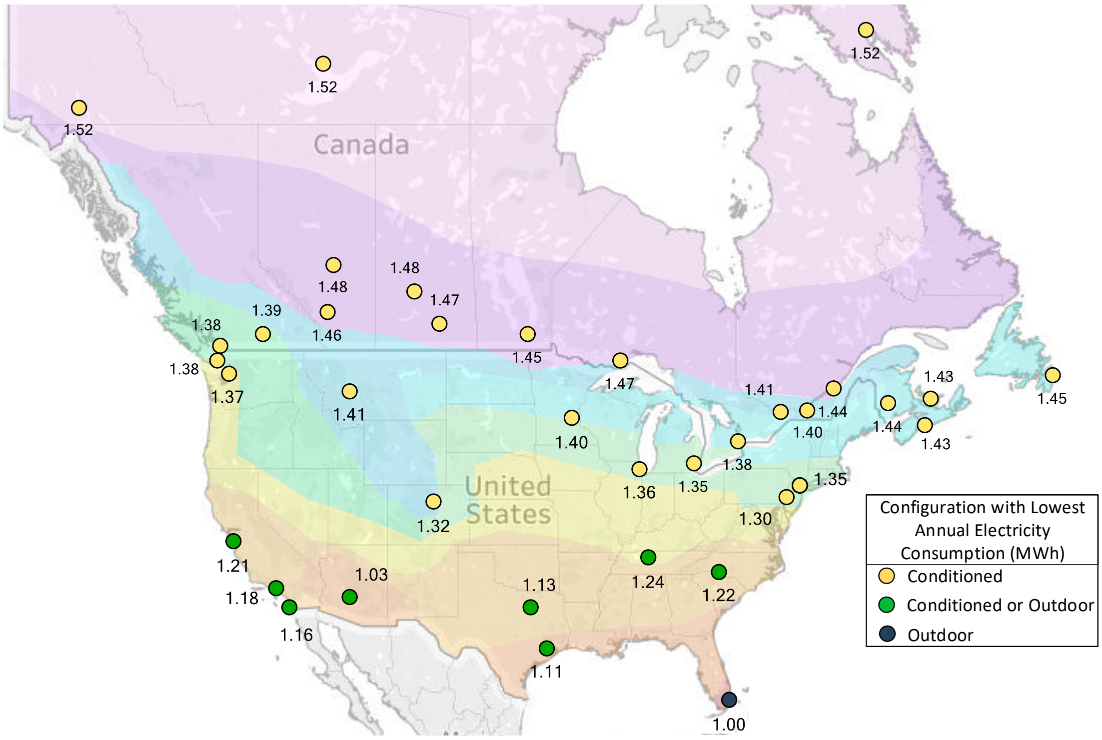

Fig. 9: SAHPWH configurations resulting in lowest annual electricity consumption

There is a correlation between the climate zone in which a city is located and the configuration(s) which minimized electricity consumption. In climate zone 1 (red), the outdoor configuration was preferred; in climate zones 2 and 3 (orange), there was less than 5% difference in electricity consumption between the outdoor and conditioned configurations; in climate zones 4 and above (yellow to purple), the conditioned configuration had minimum energy consumption. The colder climate zones had lowest electricity consumption with the conditioned space configuration because this configuration had highest inlet air temperatures for the HPWH thus increasing HPWH performance, while the outdoor and closed loop configurations relied heavily on the electric backup element. Although the greatest electricity is consumed for SAHPWHs in northern regions, the greatest electricity savings can be realized when transitioning from an electric water heater to a SAHPWH in locations near the Canada and United States border in climate zones 6 and 7, as shown in Fig. 10.

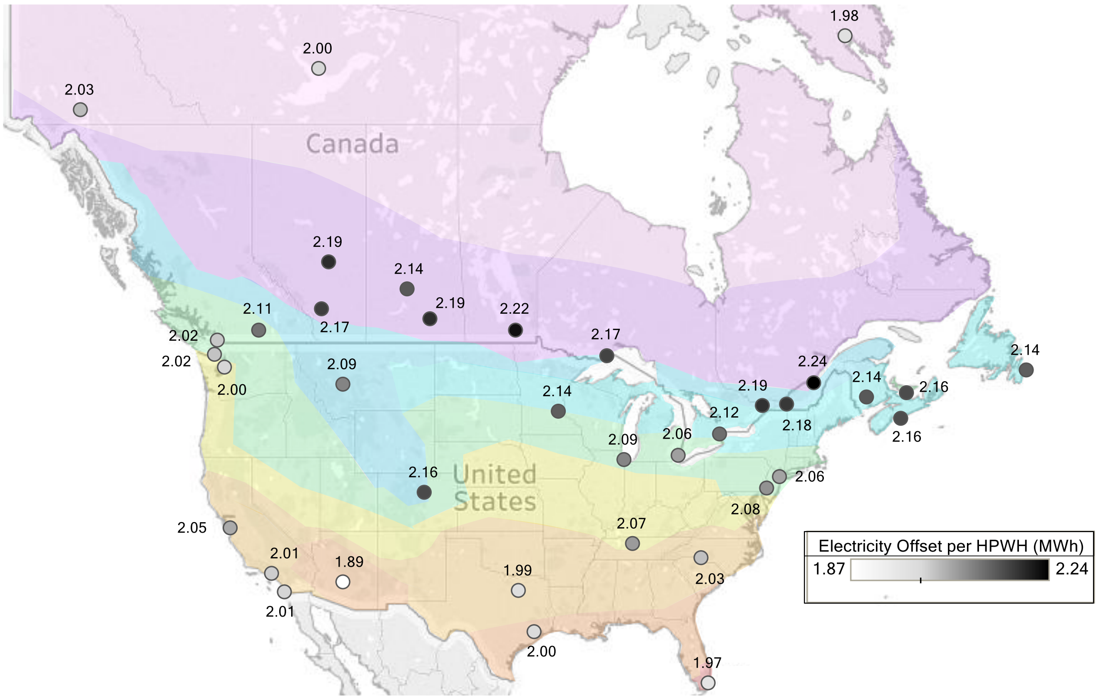

Fig. 10: Electricity offset from electric resistance water heater to solar assisted HPWH

There is a correlation between the climate zone in which a city is located and the electricity offset. Near the Canada and US border, greatest savings were realized due to the balance of low mains water temperatures and high solar insolation. In cooler mains temperature regions, the greatest amount of energy was required for water heating, so implementing a HPWH alone with a COP of 2-3 has a relatively large absolute energy reduction in northern locations than southern locations which required lower amounts of energy to heat water. Locations in the far north did not have the greatest electricity savings, however, due to low inlet HPWH air temperatures from the solar collector which reduced HPWH performance as compared to higher insolation regions. The balance of sufficiently high solar insolation to improve HPWH performance with low mains water temperature to increase base electricity consumption occurred near the Canada and United States border, where electricity savings are maximized.

The SAHPWH electricity savings in each location were also analyzed based on 5% adoption of SAHPWH technology, scaled by population of each location (US Census Bureau, 2018) (Statistics Canada, 2019). This represents the electricity reduction possible if 5% of households with an average occupancy of 2.7 persons per dwelling transitioned to a SAHPWH. When scaled by population, large cities such as New York, Toronto, and Los Angeles achieved the largest energy savings due to large populations, whereas northern Canada had the least savings due to the relatively lower populations. If 5% of households across Canada switched from an electric or natural gas water heater to a SAHPWH, the nationwide energy reduction would be 2.46 TWh, which translates to a relative energy reduction of 3.1% of the national residential water heating energy consumption. With widespread adoption of SAHPWHs in Canada, the energy consumption for water heating in the residential sector could be halved from the current 79 TWh annual consumption.

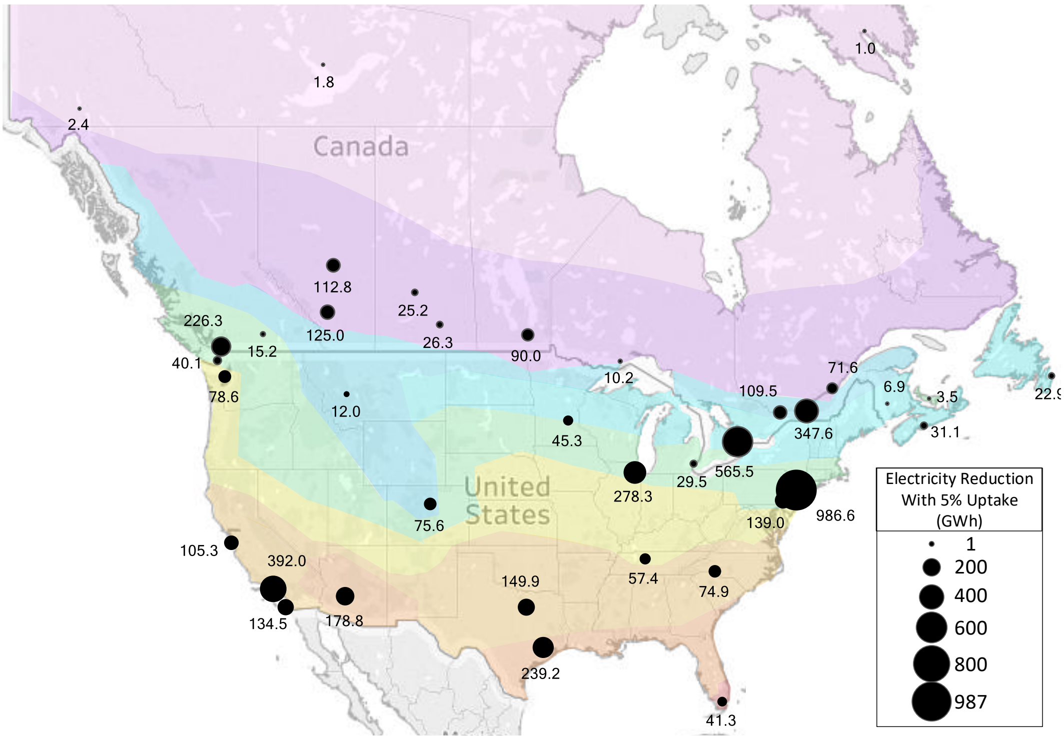

Fig. 11: Electricity reductions with 5% technology uptake in Canadian and American cities

5. Conclusions

SAHPWHs were analyzed across Canada and the United States to determine the technological feasibility of various configurations of the combined system. The major issue associated with HPWHs in Canadian and American climates, space cooling during winters, was mitigated with all configurations of solar assisted HPWH. The configurations which resulted in lowest annual water heating electricity consumption were correlated to the climate zone in which the system was implemented. In climate zone 1, the outdoor configuration had lowest electricity consumption; in climate zone 2 and 3, outdoor and conditioned configurations had less than 5% difference in electricity consumption; and in cooler climate zones, conditioned configuration had lowest electricity consumption. The greatest electricity reductions can be realized when implementing a SAHPWH near the Canada and United States border in climate zones 6 and 7, and with 5% adoption of SAHPWH technology across Canada, a 3.1% reduction in residential water heating energy consumption could occur. Residential water heating energy consumption could be halved with widespread use of SAHPWHs across Canada, indicating the national advantage of significant technology uptake in reducing energy consumption and greenhouse gas emissions alike, while simultaneously providing residential consumers with added space heating and cooling benefits.

6. Acknowledgements

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