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# Assessing the potential of air-source heat pumps in the Canadian residential sector

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## Abstract

Air-source (air-air) heat pumps can play a critical role in driving an efficient electrification of space heating in Canadian buildings. However, the deployment of these systems is often challenging in Canada, complicated by large variations in climate, utility rates and structures, and existing heating energy sources. This paper uses a simulation-based approach, driven by an enhanced data-driven model, to develop a more comprehensive overview of the technical and economic potential of heat pumps as replacements for current common heating systems (natural gas furnace, oil furnace, electric baseboards) in Canadian residential buildings. Results highlight the economic value in transitioning from electric baseboards or oil furnaces to heat pump systems in each of the four regions examined (Halifax, Toronto, Winnipeg, Vancouver), and note the growing potential of heat pumps as replacements for natural gas furnaces, with planned carbon pricing resulting in lifecycle cost savings vs. gas furnaces by 2030 in all regions. Findings can be used to better understand the current and future context for heat pumps to support R&D, policy, and market development.

*Keywords: Air-source heat pumps;electrification;residential sector;techno-economic analysis*

## 1. Introduction

The *Canadian Net Zero Emissions Accountability Act* outlines Canada's commitment to achieving carbon neutrality by 2050 [1]. The built environment must play a key role in this transition: Canadian buildings account for 17% of national greenhouse gas (GHG) emissions, with nearly 80% of this total directed towards space heating, cooling, and hot water preparation [2]. Heat pumps are critical in driving decarbonization of the built environment via their ability to efficiently electrify space conditioning. However, supporting greater adoption requires an appropriate understanding of system selection and economics.

The Canadian context represents a particularly challenging set of circumstances for heat pump integration. Wide variations in both climates (mild maritime, to extreme cold) and utility rates and structures (vast differences in prices of natural gas vs. electricity) mean that the impact of heat pumps (e.g., on energy savings, utility costs, greenhouse gas (GHG) emissions) can differ greatly in a given region. Quantifying these impacts is a critical step in driving the policy and R&D required to facilitate a greater uptake of heat pumps in Canada.

Air-source (air-air) heat pumps are a popular choice of heat pump integration in Canadian homes, driven by their relative lower cost and ease of installation. Previous efforts have examined the role and impacts of these systems in Canada [3,4], but often focus on assessing heat pumps in a single building archetype or as a replacement for a single type of existing heating technology (e.g., natural gas furnaces). Recent studies [5] have attempted to present a more complete outlook but employ simplified heat pump models to facilitate analysis, limiting the ability to compare different heat pump technologies or assess the impact of system sizing.

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This paper uses a simulation-based approach, supported by extensive testing and measured data, to examine the energy, GHG, and economic impacts of electrifying building thermal loads via the implementation of air-source heat pumps. A detailed, data-driven heat pump model is used to represent two common air-source heat pump integrations: A conventional variable capacity unit, and a cold climate (variable capacity) unit aimed at maintaining heating performance in the cold Canadian climate. Each heat pump integration is used to examine the impact of replacing three common heating systems (natural gas furnace, electric baseboards, oil furnace) in three types of typical single family Canadian housing. Results are used to examine the short- and medium-term role of air-source heat pumps in driving an effective, economic decarbonization of Canadian homes.

## 2. Definition of Base Cases for Heat Pump Integration

Climate, utility rates, and electricity generation methods (and associated GHG emissions) can vary greatly across Canada. Four Canadian regions are selected for this analysis, each representing a unique context for system integration. Table 1 summarizes key parameters for each region [2,6].

Table 1: Summary of Climate and Electricity Generation Methods for Selected Canadian Regions [2,6]

| **Characteristic** | **Halifax** | **Toronto** | **Winnipeg** | **Vancouver** |
|---|---|---|---|---|
| Climate Type | Cold-Humid | Cold-Humid | Very Cold | Marine |
| Heating Degree Days (18°C) | 4000 | 3520 | 5670 | 2825 |
| Cooling Degree Days (18°C) | 100 | 280 | 170 | 40 |
| Heating Design Temperature (°C) | -16 | -18 | -33 | -7 |
| Cooling Design Temperature (°C) | 26 | 31 | 30 | 28 |
| Main Electricity Generation Method(s) | Coal, Fuel Oil | Nuclear, Nat. Gas, Hydro | Hydro | Hydro |
| GHG Emission Factor, Electricity (g $CO_2$/kWh) | 760 | 30 | 1.3 | 20 |

Three separate building archetypes are developed to better understand the impact of building size, construction, and heat pump integration method on energy and economic performance. These archetypes have been developed to represent specific segments of the residential building stock, with geometry and floor area derived from available literature and databases [7,8,9]. Each archetype also uses a different base case heating system to examine the impact of heat pumps replacing different common heating technologies. The most common residential heating energy system is highly region-dependent: Natural gas heating is prevalent from Western through Central Canada (Vancouver, Winnipeg, Toronto), while electrical or oil-based heating is more common in the Atlantic provinces (Halifax) [2]. To develop a more comprehensive understanding of the transition to heat pumps, all three of these heating base cases (Natural gas, oil, electricity) are examined in each region, even in situations where particular systems have smaller uptake. This can provide policy makers with information to better tailor potential incentive programs and identify situations where transitioning to a heat pump offers immediate energy and economic benefits. A summary of relevant parameters for each building archetype is presented in Table 2. Where possible, archetype performance has been validated using data from test homes (for L2S [3]) or compared with available literature [2].

Table 2: Summary of Archetype Parameters [7,8,9]

| | | **Archetype** | |
|---|---|---|---|
| **Characteristic** | **Small Bungalow (SB)** | **Medium Two-Storey (M2S)** | **Large Two-Storey (L2S)** |
| Heated Floor Area | 110 $m^2$ | 190 $m^2$ | 280 $m^2$ |
| Number of Floors | 1 | 2 | 2 |
| Basement | No, slab on grade | Yes | Yes |
| Construction Vintage | 1960s | New Build | New Build |
| Primary Heating Fuel & System | Heating Oil<br>Forced Air Furnace | Electric<br>Baseboard Heaters | Natural Gas<br>Forced Air Furnace |
| Heating Efficiency | 71% | 100% | 95% |
| Cooling System | Central AC<br>COP = 3.5* | Split AC Unit<br>COP = 3.3* | Central AC<br>COP = 3.5* |
| DHW Fuel | Heating Oil | Electric | Natural Gas |
| Heat Recovery Ventilator | No | Yes | Yes |

For each archetype, building envelope performance is modified to represent region specific construction for the four selected cities in Table 1. For the M2S and L2S archetypes, envelope performance was selected based on the National Building Code of Canada (NBC) minimum requirements for the selected climate zones [6]. For the SB archetype, envelope performance was derived from the *Canadian Single-Detached & Double/Row Housing Database* (CSDDRD) [8] for the appropriate regions and 1960s vintage, with this archetype and construction period selected to represent the smaller, older homes where oil systems are typically still seen. A summary of envelope parameters for the SB archetype is provided in Table 3.

Table 3: Summary of Envelope Construction for SB Archetype

| | City | | | |
|---|---|---|---|---|
| **Characteristic** | **Halifax** | **Toronto** | **Winnipeg** | **Vancouver** |
| Wall RSI ($m^2$°C/W) | 1.8 | 1.7 | 1.9 | 1.9 |
| Roof RSI ($m^2$°C/W) | 3.3 | 3.9 | 4.6 | 3.1 |
| Window U Value (W/$m^2$°C) | 2.9 | 2.9 | 2.9 | 5.5 |
| Infiltration ($ach_{50}$) | 7.4 | 6.7 | 3.4 | 9.8 |

## 3. Heat Pump System Integrations

The developed housing archetypes serve as a basis to examine three different heating system transitions:

I. Natural Gas Furnaces to Air-Source Heat Pumps
II. Oil Furnaces to Air-Source Heat Pumps
III. Electric Baseboards to Air-Source Heat Pumps

Each transition is selected due to the unique economic boundary conditions imposed, and its relevance and potential impacts in supporting a decarbonization of Canadian residential buildings. In cases that involve a transition from fossil fuels, it is assumed that homeowners will proceed with a complete electrification of space and water heating, including the introduction of an electric (non-heat pump) hot water tank.

### Heat Pump Integration and Sizing Methods

The base case mechanical systems for each archetype play a critical role in defining the form of heat pump integration. In cases where central ducted is available (replacing oil or natural gas furnaces), a ducted heat pump configuration is proposed, with the indoor coil of the heat pump integrated into a central air handling unit. For homes without central ducting (replacing electric baseboards), a ductless configuration is used, with the indoor unit of the heat pump integrated into the stairwell linking the first and second floors of the home. In this integration, the basement of the home is heating only using electric baseboards, as per the base case.

Heat pump sizing also has an important impact on system performance and economics. Given the cold Canadian climate, all heat pump systems are sized with a focus on space heating using Option C of NRCan's *Air-Source Heat Pumps Sizing and Selection Guide* [10].

### Heat Pump Technologies

Two market available air-source heat pump technologies are assessed to examine their economic and energy savings potential in each of the defined transition cases:

Conventional Variable Capacity Air-Source Heat Pump (**VCHP**): Variable capacity units are an increasingly popular option in the Canadian residential heat pump market. Unlike single stage heat pumps, variable speed systems are able to efficiently modulate their capacity to better match heating or cooling demand. However, these systems are not necessarily well adapted to cold climates, with many market-available options suffering significant performance degradations at the colder ambient temperatures common in Canadian winters. This integration focuses on these more conventional variable capacity systems in each region and transition case.

The performance of variable capacity systems is closely linked both to their rated performance and their ability to modulate their capacity to meet lower heating or cooling loads. Key parameters used in the analysis are provided below in Table 4, and are the same for all sizes of heat pumps used in the simulations.

Table 4: Variable Capacity Heat Pump Parameters [11,12]

| | HP Configuration | |
|---|---|---|
| | Ductless | Ducted |
| Heating COP* | 3.3 (All) | 3.7 (All) |
| Cooling COP* | 4.1 (All) | 3.9 (All) |
| Min. Outdoor Operating Temperature, Heating Mode (°C) | -17 | -23 |
| % Capacity at Cut-Off Temperature (Max Speed) | 51% | 38% |
| Average Min: Max Capacity Ratio | 0.32 | 0.30 |

*At AHRI Rating Conditions

Cold Climate Variable Capacity Heat Pumps (**CCHP**): Cold climate heat pumps combine variable speed compressor technologies with other cycle upgrades (e.g., larger outdoor heat exchangers, vapour injection cycles) to maintain a higher portion of heating capacity at low outdoor temperatures. Although multiple definitions of cold climate heat pumps exist in the literature [13,14], they are classified in this paper as systems operating to an outdoor temperature of -25°C and maintaining at least 65% of their rated heating capacity.

Figure 1 compares the normalized capacity of the ducted CCHP and VCHP systems used in this study. The CCHP unit maintains a much larger portion of its heating capacity at low ambient temperatures, while also operating to a lower minimum outdoor temperature. These characteristics have important implications for system efficiency and peak electrical demand.

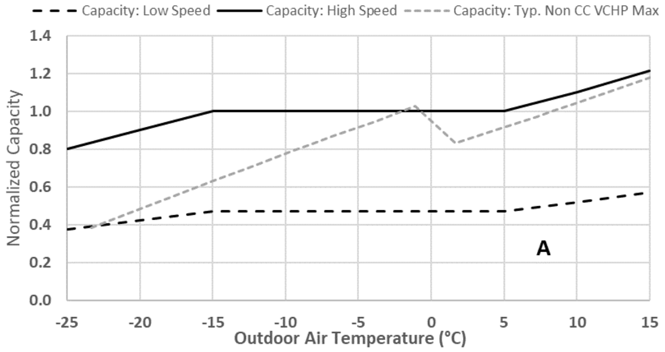

Figure 1: Comparison of CCHP and VCHP Normalized Heating Capacity [12,15]

Table 5 summarizes key parameters for the CCHP systems examined in this study. Variations in rated COP are due to the differences in manufacturer listed performance among units of the same model line.

Table 5: Cold Climate Heat Pump Parameters [15,16]

| | HP Configuration | |
|---|---|---|
| | Ductless | Ducted |
| Heating COP* | 4.4 (0.75 Ton)<br>4.2 (1 Ton)<br>4.1 (1.5 Ton) | 3.6 (1.5 Ton)<br>3.8 (2 Ton) |
| Cooling COP* | 4.5 (0.75 Ton)<br>3.8 (1 Ton)<br>4.2 (1.5 Ton) | 3.3 (All) |
| Min. Outdoor Operating Temperature, Heating Mode (°C) | -25 | -25 |
| % Capacity at Cut-Off Temperature (Max Speed) | 66% | 80% |
| Average Min: Max Capacity Ratio | 0.33 | 0.30 |

*At AHRI Rating Conditions

## 4. Modelling Methodology

Appropriately modelling the performance of each heat pump system is critical to properly assess its energy and economic benefits. All system models were developed in TRNSYS v.18 using the appropriate Canadian Weather for Energy Calculations (CWEC) weather file (2020 version). Simulations were run using a time step of 2.5 minutes in order to properly represent the control logic of the heat pump and its interaction with any auxiliary heating systems.

### Heat Pump Performance Modelling

Examining the potential of variable and cold climate heat pump systems requires a simulation model capable of capturing their unique performance characteristics. In this study, all heat pump systems are simulated using a new enhanced heat pump model (TRNSYS Type 3255). This model has been developed based on extensive test experience at the CanmetENERGY in Varennes facility and integrates a series of new capabilities including performance variations with compressor speed, and key short term transients including startup, defrost, and cycling. Further details on this model are provided in Breton *et al.* [17].

Type 3255 employs a data-driven approach, using performance maps supplied as inputs to the model to represent variations in heat pump capacity and power as a function of temperature and compressor speed. Where possible, this study uses performance maps derived from detailed testing to drive simulations. In cases where this data is not available, performance data has been derived from manufacturer data sheets and information available in the open literature. For the ductless VCHP system, performance curves are derived from a database of variable capacity heat pump performance [18]. Data sources are summarized in Table 6.

Table 6: Summary of data sources for heat pump modelling

| | Ductless Systems | | Ducted Systems | |
|---|---|---|---|---|
| Heat Pump System | Rated Performance | Part Load Performance | Rated Performance | Part Load Performance |
| VCHP | Literature [18] | Literature [18] | Manufacturer [12] | Manufacturer [12] |
| CCHP | Test [19] | Test [19] | Manufacturer [15] | Manufacturer [15] |

**Heat Pump Control**

A PID controller is used to vary the heat pump compressor speed to maintain 21°C in heating mode, and 23°C in cooling. The simulated controller also contains a threshold minimum operating frequency, below which the heat pump turns off. This feature enables the model to capture on/off cycling when building loads fall below the minimum capacity of the heat pump. Additional controls ensure that the heat pump only operates within its intended range of outdoor temperatures.

While heat pump systems are sized to cover the majority of annual heating demands, they are not selected to meet the full heating demands of the home at design conditions. As such, electric auxiliary systems are included to supplement heat pump operations as needed. When ambient temperatures are above the minimum operating temperature for the heat pump, auxiliary heaters use a slightly lower setpoint (20°C vs. 21°C for the heat pump) to prioritize heat pump operations while ensuring thermal comfort in the space. When ambient temperatures fall below the minimum heat pump operating temperature, auxiliary heaters maintain 21°C.

## 5. Economic Analysis

System economics play an important role in defining the pace of heat pump adoption in Canada. In this study, each system integration is evaluated over a 20-year lifespan, with a focus on capital, maintenance and operating costs (replacement costs are neglected). Lifecyle calculations use an inflation rate of 1.8% and a discount rate of 3.3%, based on current Canadian financial markets. Given current economic volatility, these values represent a conservative approach over the defined 20-year analysis period.

System capital costs are based on a component level analysis, and include all required equipment, controls, and ducting (for centrally ducted systems). Included components are summarized in Table 7. Given the focus on decarbonization in this paper, all transitions from fossil fuel heating systems also include replacing the base case hot water tank with an electric resistance equivalent storage tank. Heat pump costs do not include modifications to the electrical service of the home, which can significantly increase overall system costs.

Table 7: Components included in calculation of system capital costs

| Category | Components |
|---|---|
| Equipment | Heat Pump (Both Indoor & Outdoor Sections) |
| | Auxiliary Electric Baseboards (Ductless Cases) |
| | Auxiliary Electric Duct Heaters (Ducted Cases) |
| | Hot Water Storage Tank |
| Controls | Thermostat |
| Distribution | Ductwork (Ducted Cases) |

System costs are derived via RS Means [20] and available online suppliers [21], and include both material and labour. All costs were adjusted for the appropriate region using factors from RS Means. For clarity, system costs are summarized by integration case in the *Results* section of this paper.

Utility rates and structures also play a critical role in defining the operating costs of the systems. This study uses current rates and structures in each region [22-28]. Rates include both fixed and energy charges, tiered/time of use structures, rate riders, and provincial or federal carbon pricing for 2022. Energy escalation rates were estimated using information from the National Energy Board of Canada [29]. Given the volatility in current (2022) energy markets, escalation rates can be considered a conservative estimate over the system lifespan. A summary of utility rates used in the analysis is provided in Table 8.

Table 8: Summary of utility rates and structures used

| **Utility** | **Charge** | **Halifax** | **Toronto** | **Winnipeg** | **Vancouver** |
|---|---|---|---|---|---|
| Electricity | Fixed Charge | \$10.83/month | \$40.10/month | \$6.64/month | \$8.86/month |
| | Energy Charge | \$0.1841/kWh | \$0.1132/kWh (Off-peak)<br>\$0.1508/kWh (Mid-peak)<br>\$0.2152/kWh (On-peak) | \$0.1015/kWh | \$0.111/kWh<br>(First 1,350 kWh/2 Month)<br>\$0.166/kWh<br>(> 1,350 kWh/2 Month) |
| | Escalation Rate | 0.10% | 0.60% | 0.30% | 0.30% |
| Nat. Gas | Fixed Charge | \$21.87/month | \$22.12/month | \$14/month | \$12.82/month |
| | Energy Charge | \$0.7658/m$^3$ | \$0.563/m3<br>(First 30 m$^3$/Month)<br>\$0.556/m3<br>(Next 55 m$^3$/Month)<br>\$0.551/m3<br>(Next 85 m$^3$/Month)<br>\$0.547/m3<br>(Above 170 m$^3$/Month) | \$0.4571/m$^3$ | \$0.5713/m$^3$ |
| | Escalation Rate | 1.00% | 0.70% | 1.00% | 0.20% |
| Fuel Oil | Energy Charge | \$1.80/L | \$2.14/L | \$1.89/L | \$1.89/L |
| | Escalation Rate | 3% | 3% | 3% | 3% |

## 6. Results and Discussion

The developed methodology provides a basis to explore the energy and economic implications of air-source heat pump adoption across Canada. Results are presented by heating system transition below.

### Transitioning from Natural Gas Furnaces to Air-Source Heat Pumps in Large Two-Storey Homes

Table 9 summarizes the energy performance of both heat pump systems as gas furnace replacements in large two-storey homes in Halifax and Toronto. Each system demonstrates a clear reduction in annual energy use, with savings for space heating and cooling ranging from 53% to 60%. Despite the colder climate and higher number of heating degree days in Halifax, annual savings are greater vs. Toronto because of a reduced need for auxiliary heating (Halifax has a smaller number of operating hours below -20°C). It is also interesting to note that the predominance of coal-fired electricity in Atlantic Canada yields an *increase* in GHG emissions with each heat pump case, although this is expected to change as the grid undergoes further decarbonisation.

Table 9: Summary of heat pump energy performance replacing natural gas furnaces in Halifax and Toronto

| | | Halifax | | | Toronto | |
|---|---|---|---|---|---|---|
| End Use | Base Case | VCHP | CCHP | Base Case | VCHP | CCHP |
| Total Heating (kWh) | 11,910 | 5,310 | 4,570 | 13,300 | 5,950 | 5,290 |
| Furnace | 11,910 | -- | -- | 13,300 | -- | -- |
| Heat Pump | -- | 4,780 | 4,300 | -- | 5,090 | 4,900 |
| Aux: Elec Duct Heater | -- | 530 | 270 | -- | 860 | 400 |
| Cooling (kWh) | 260 | 250 | 250 | 620 | 550 | 570 |
| Fans (kWh) | 760 | 1,110 | 1,010 | 860 | 1,230 | 1,120 |
| DHW (kWh) | 7,080 | 5,650 | 5,650 | 6,650 | 5,310 | 5,310 |
| Lighting/Equip. (kWh) | 6,930 | 6,930 | 6,930 | 7,020 | 7,020 | 7,020 |
| Total Energy Use (kWh) | 26,940 | 19,250 | 18,410 | 28,450 | 20,060 | 19,310 |
| Total Savings (kWh) | -- | 7,700 | 8,540 | -- | 8,400 | 9,130 |
| % Savings for Htg&Clg* | -- | 54% | 60% | -- | 53% | 58% |
| Seasonal Heating COP | 0.97 | 2.20 | 2.57 | 0.97 | 2.19 | 2.47 |
| GHG Emissions (tn $CO_2$ eq) | 9.5 | 14.6 | 14 | 3.8 | 0.6 | 0.6 |
| GHG Emissions (%) | -- | +54% | +47% | -- | -84% | -85% |

*Seasonal Heating COP for whole home, inc. HP & aux.

Table 10 summarizes the energy performance of each heat pump system in Winnipeg and Vancouver. The impact of the different climates is immediately clear: The colder climate in Winnipeg reduces energy savings due to a greater reliance on auxiliary energy use, while the milder Vancouver climate yields higher operating efficiencies and greater energy use reductions (aux. heating is only used in Vancouver when the heat pump is in defrost). It is important to note that the savings associated with the CCHP in Vancouver are related to the operating efficiency of this unit across the most common winter temperatures (-5°C to +5°C), rather than a strong need for cold climate performance – This result may change if other VCHP or CCHP units are examined in the analysis, and is not a definitive reflection of VCHP vs. CCHP systems in this area. Future work is needed to investigate the sensitivity of results to the heat pump performance curve used, especially in milder regions where the cold climate capacity of the CCHP may be used less. The value of cold climate performance is evident however in Winnipeg, where the CCHP reduces auxiliary energy use by nearly 1,000 kWh. GHG emissions are nearly eliminated in both cities due to the relatively clean electricity grids.

Table 10: Summary of heat pump energy performance replacing natural gas furnaces in Winnipeg and Vancouver

| | Winnipeg | | | Vancouver | | |
|---|---|---|---|---|---|---|
| End Use | Base Case | VCHP | CCHP | Base Case | VCHP | CCHP |
| Total Heating (kWh) | 20,420 | 10,940 | 10,370 | 8,460 | 3,580 | 2,410 |
| Furnace | 20,420 | -- | -- | 8,460 | -- | -- |
| Heat Pump | -- | 6,960 | 7,370 | -- | 3,490 | 2,320 |
| Aux: Elec Duct Heater | -- | 3,970 | 3,000 | -- | 80 | 90 |
| Cooling (kWh) | 410 | 360 | 350 | 140 | 140 | 130 |
| Fans (kWh) | 850 | 1,610 | 1,500 | 670 | 910 | 870 |
| DHW (kWh) | 8,160 | 6,500 | 6,500 | 6,390 | 2,790 | 2,790 |
| Lighting/Equip. (kWh) | 6,890 | 6,890 | 6,890 | 6,990 | 6,990 | 6,990 |
| Total Energy Use (kWh) | 36,730 | 26,300 | 25,610 | 22,650 | 14,410 | 13,190 |
| Total Savings (kWh) | -- | 10,420 | 11,100 | -- | 8,240 | 9,460 |
| % Savings for Htg&Clg | -- | 46% | 49% | -- | 57% | 71% |
| Seasonal Heating COP* | 0.97 | 1.86 | 1.97 | 0.97 | 2.26 | 3.38 |
| GHG Emissions (tn $CO_2$ eq) | 5.2 | 0.03 | 0.03 | 2.9 | 0.3 | 0.3 |
| GHG Emissions (%) | -- | -99% | -99% | -- | -90% | -91% |

*Seasonal Heating COP for whole home, inc. HP & aux.

Table 11 summarizes the economic performance of each system in all four regions. Except in Halifax, all heat pump integrations result in higher lifecycle costs, primarily due to the increased cost of the heat pump systems vs. base case (natural gas furnace + air conditioner) that they are replacing. Interestingly, some form of utility cost savings is achieved using the CCHP in two of the four regions examined (Halifax, Vancouver), suggesting that an economic incentive to cover a portion of the heat pump system costs could shift the economic balance in favor of these systems (This result assumes a complete shift to electricity for all end uses and a removal of the gas connection). In this context, choosing the appropriate systems to incentivize (i.e., those that achieve the greatest utility cost savings) is of critical importance given the current marginal utility cost savings vs. the base case system.

Table 11: Summary of lifecycle costs for VCHP and CCHP systems as gas furnace system replacements

| City | System | Capital Cost ($) | Lifecycle Utility Cost ($) | Lifecycle Maintenance Cost ($) | Total Lifecycle Cost ($) |
|---|---|---|---|---|---|
| Halifax | Base | $19,500 | $64,200 | $3,000 | $86,700 |
| | VCHP | $21,200 | $54,100 | $1,500 | $76,800 |
| | CCHP | $25,100 | $51,800 | $1,500 | **$78,400** |
| Toronto | Base | $21,500 | $46,400 | $3,700 | **$71,600** |
| | VCHP | $23,500 | $50,400 | $1,900 | $75,800 |
| | CCHP | $27,100 | $48,800 | $1,900 | $77,800 |
| Winnipeg | Base | $21,800 | $36,500 | $3,400 | **$61,700** |
| | VCHP | $26,600 | $41,600 | $1,800 | $70,000 |
| | CCHP | $28,800 | $40,600 | $1,800 | $71,200 |
| Vancouver | Base | $20,200 | $28,400 | $3,100 | **$51,700** |
| | VCHP | $21,400 | $30,300 | $1,600 | $53,300 |
| | CCHP | $25,500 | $27,300 | $1,600 | $54,400 |

A major factor impacting natural gas rates in Canada is the implementation of carbon pricing. Carbon prices evolve according a schedule defined by the federal government, ranging from a current surcharge of \$0.0979/m$^3$ of natural gas, to a value of \$0.1860/m$^3$ in 2025 and a final price of \$0.3389/m$^3$ by 2030 [30]. Table 12 summarizes the impact of 2025 and 2030 carbon pricing on the above results. Increases in carbon pricing allow CCHP systems to achieve operating cost parity with natural gas furnaces by 2025 in nearly all locations except Winnipeg, where CCHP operating costs are slightly higher vs. the base case. Using the 2030 carbon pricing, operating cost savings are enough in all regions to outweigh the higher capital costs associated with the heat pump integrations, although economic incentives may be needed to achieve the shorter-term payback periods (<10 years) often desired by homeowners.

Table 12: Lifecyle cost variation with carbon pricing

| | | 2025 Carbon Pricing | | 2030 Carbon Pricing | |
|---|---|---:|---:|---:|---:|
| City | System | Lifecycle Utility ($) | Total Lifecycle ($) | Lifecycle Maintenance ($) | Total Lifecycle ($) |
| Halifax | Base | $66,700 | $89,200 | $71,000 | $93,500 |
| | VCHP | $54,100 | **$76,800** | $54,100 | **$76,800** |
| | CCHP | $51,800 | $78,400 | $51,800 | $78,400 |
| Toronto | Base | $49,000 | **$74,200** | $53,300 | $78,500 |
| | VCHP | $50,400 | $75,800 | $50,400 | **$75,800** |
| | CCHP | $48,800 | $77,800 | $48,800 | $77,800 |
| Winnipeg | Base | $40,400 | **$65,600** | $46,700 | $71,900 |
| | VCHP | $41,600 | $70,000 | $41,600 | **$70,000** |
| | CCHP | $40,600 | $71,200 | $40,600 | $71,200 |
| Vancouver | Base | $29,600 | **$52,900** | $33,400 | $56,700 |
| | VCHP | $30,300 | $53,300 | $30,300 | **$53,300** |
| | CCHP | $27,300 | $54,400 | $27,300 | $54,400 |

**Transitioning from Oil Furnaces to Air-Source Heat Pumps in Small Bungalows**

Table 13 summarizes the energy performance of both heat pump technologies as replacements for oil furnaces in 1960s vintage small bungalows located in Halifax and Toronto. Results also reflect a transition from oil-fired hot water tanks to electrically heated tanks in each heat pump case. Compared to the natural gas cases, energy use reductions are even larger due to the lower efficiency of the oil-fired heating equipment in the base cases. In Halifax, GHG emissions still increase with each heat pump integration due to the carbon intensive nature of electricity generation. As noted previously, emissions associated with electricity are expected to fall in future years as electricity grids undergo further decarbonization.

Table 13: Summary of heat pump energy performance replacing oil furnaces in Halifax and Toronto

| | Halifax | | | Toronto | | |
|---|---|---|---|---|---|---|
| End Use | Base Case | VCHP | CCHP | Base Case | VCHP | CCHP |
| Total Heating (kWh) | 17,750 | 6,480 | 4,950 | 14,740 | 5,690 | 4,470 |
| Furnace | 17,750 | -- | -- | 14,740 | -- | -- |
| Heat Pump | -- | 5,920 | 4,650 | -- | 5,150 | 4,200 |
| Aux: Elec Duct Heater | -- | 560 | 300 | -- | 540 | 270 |
| Cooling (kWh) | 340 | 140 | 130 | 950 | 510 | 430 |
| Fans (kWh) | 470 | 1,240 | 1,140 | 530 | 1,260 | 1,120 |
| DHW (kWh) | 8,200 | 4,450 | 4,450 | 7,770 | 4,200 | 4,200 |
| Lighting/Equip. (kWh) | 4,920 | 4,920 | 4,920 | 5,020 | 5,020 | 5,020 |
| Total Energy Use (kWh) | 31,680 | 17,230 | 15,590 | 29,010 | 16,680 | 15,240 |
| Total Savings (kWh) | -- | 14,450 | 16,100 | -- | 12,320 | 13,770 |
| % Savings for Htg&Clg | -- | 63% | 72% | -- | 60% | 69% |
| Seasonal Heating COP* | 0.58 | 2.09 | 2.75 | 0.59 | 2.02 | 2.58 |
| GHG Emissions (tn $CO_2$ eq) | 11.40 | 13.10 | 11.90 | 6.30 | 0.50 | 0.50 |
| GHG Emissions (%) | -- | +15% | +4% | -- | -92% | -93% |

*Seasonal Heating COP for whole home, inc. HP & aux.

Energy performance results for heat pump system integrations in Winnipeg and Vancouver are provided in Table 14. Each heat pump system offers strong heating and cooling energy use reductions, ranging from 55% to 80% depending on the region and heat pump technology. Heat pump seasonal performance is lower in Winnipeg, due to the colder climate and extended period of time when outdoor temperatures are below the minimum operating limit for the heat pump. Users may also note the higher annual heating energy use for the base case in Vancouver vs. Winnipeg, which relates to higher infiltration and poor envelope performance associated with 1960s construction in this region. As with the natural gas cases, the improved performance of the CCHP vs. the VCHP in Vancouver relates to its higher operating COP over the most common winter temperatures. This result is not suggesting cold climate performance is needed in Vancouver and should not be considered a definitive statement on VCHP vs. CCHP technology in this region. Instead, it highlights the importance of selecting systems that optimize operating efficiency over the most common winter temperatures.

Table 14: Summary of heat pump energy performance replacing oil furnaces in Winnipeg and Vancouver

| | | Winnipeg | | | Vancouver | |
|---|---|---|---|---|---|---|
| End Use | Base Case | VCHP | CCHP | Base Case | VCHP | CCHP |
| Total Heating (kWh) | 19,110 | 8,670 | 8,100 | 20,090 | 6,040 | 3,990 |
| Furnace | 19,110 | -- | -- | 20,090 | -- | -- |
| Heat Pump | -- | 6,100 | 5,950 | -- | 5,900 | 3,840 |
| Aux: Elec Duct Heater | -- | 2,570 | 2,150 | -- | 140 | 150 |
| Cooling (kWh) | 680 | 320 | 300 | 350 | 150 | 130 |
| Fans (kWh) | 590 | 1,500 | 1,190 | 530 | 1,980 | 1,170 |
| DHW (kWh) | 9,210 | 5,050 | 5,050 | 7,520 | 4,060 | 4,060 |
| Lighting/Equip. (kWh) | 4,870 | 4,870 | 4,870 | 4,910 | 4,910 | 4,910 |
| Total Energy Use (kWh) | 34,460 | 20,410 | 19,510 | 33,400 | 17,140 | 14,260 |
| Total Savings (kWh) | -- | 14,050 | 900 | -- | 16,260 | 19,140 |
| % Savings for Htg&Clg | -- | 55% | 58% | -- | 70% | 80% |
| Seasonal Heating COP* | 0.59 | 1.76 | 1.88 | 0.60 | 2.39 | 3.63 |
| GHG Emissions (tn $CO_2$ eq) | 7.70 | 0.03 | 0.03 | 7.60 | 0.34 | 0.29 |
| GHG Emissions (%) | -- | -99% | -99% | -- | -95% | -96% |

*Seasonal Heating COP for whole home, inc. HP & aux.

Table 15 summarizes the lifecycle economics of each heat pump system replacing the oil-fired base cases. The high cost of heating oil means that all heat pump integrations offer strong utility cost savings vs. the base case, demonstrating the value to homeowners in transitioning from heating oil to heat pump systems. In most regions, the CCHP is the preferred option despite its higher initial cost, primarily because of the larger magnitude of energy use reductions it achieves vs. the VCHP. In Vancouver, the CCHP is preferred only because of its improved performance vs. the VCHP over the most common winter temperatures. This result may change when examining a different VCHP unit, and is not a definitive statement on the suitability of the CCHP vs. the VCHP in Vancouver. One challenge for homeowners is the higher cost of heat pump systems, which can be significant vs. furnace systems. Although not examined in this study, the Government of Canada has recently launched an incentive program to support homeowners in the transition from oil-fired to heat pump systems by covering a portion of capital and installation costs [31]. This program further increases the value proposition for heat pumps and will drive uptake in coming years.

Table 15: Summary of lifecycle costs for VCHP and CCHP systems as oil furnace system replacements

| City | System | Capital Cost ($) | Lifecycle Utility Cost ($) | Lifecycle Maintenance Cost ($) | Total Lifecycle Cost ($) |
|---|---|---:|---:|---:|---:|
| Halifax | Base | $19,800 | $101,700 | $3,800 | $125,300 |
| | VCHP | $21,200 | $48,600 | $1,500 | $71,300 |
| | CCHP | $24,600 | $44,200 | $1,500 | **$70,300** |
| Toronto | Base | $21,900 | $109,500 | $4,700 | $136,100 |
| | VCHP | $22,900 | $43,000 | $1,900 | **$67,800** |
| | CCHP | $26,600 | $39,900 | $1,900 | $68,400 |
| Winnipeg | Base | $21,400 | $107,700 | $4,300 | $133,400 |
| | VCHP | $26,600 | $32,800 | $1,800 | **$61,200** |
| | CCHP | $28,700 | $31,300 | $1,800 | $61,800 |
| Vancouver | Base | $20,500 | $105,200 | $3,900 | $129,600 |
| | VCHP | $21,400 | $37,100 | $1,600 | $60,100 |
| | CCHP | $25,500 | $29,900 | $1,600 | **$57,000** |

### Transitioning from Electric Baseboards to Air-Source Heat Pumps in Medium Two-Storey Homes

The final system transition examined is the replacement of electric baseboards with heat pump systems. As mentioned earlier, this integration varies from the two previous cases in that ductless heat pumps are used, which serve only the first two floors of the home. Table 16 summarizes the energy performance for this system transition in medium two-storey housing in Halifax and Toronto. It is clear that heating and cooling energy use reductions appear to be less than for the previous cases, primarily because the heat pump is no longer serving the whole home. When comparing only the energy used to heat the two above ground floors, energy use reductions are significantly higher, approaching 54% in each heat pump integration. VCHP and CCHP performance is also very close in both cities: Both systems maintain a similar portion of capacity at colder ambient temperatures and are sized using the same objectives.

Table 16: Summary of heat pump energy performance replacing electric baseboards in Halifax and Toronto

| | Halifax | | | Toronto | | |
|---|---|---|---|---|---|---|
| End Use | Base Case | VCHP | CCHP | Base Case | VCHP | CCHP |
| Total Heating (kWh) | 6,760 | 3,860 | 3,840 | 7,720 | 4,470 | 4,430 |
| Heat Pump | -- | 2,044 | 2,072 | -- | 2,383 | 2,426 |
| Aux: Elec BB (1st, 2nd) | 5,470 | 460 | 400 | 6,230 | 530 | 440 |
| Aux: Elec BB Basement | 1,280 | 1,360 | 1,360 | 1,490 | 1,560 | 1,560 |
| Cooling (kWh) | 490 | 290 | 340 | 970 | 530 | 670 |
| Fans (kWh) | 480 | 620 | 530 | 490 | 670 | 560 |
| DHW (kWh) | 5,640 | 5,640 | 5,640 | 5,300 | 5,300 | 5,300 |
| Lighting/Equip. (kWh) | 5,250 | 5,250 | 5,250 | 5,280 | 5,280 | 5,280 |
| Total Energy Use (kWh) | 18,620 | 15,660 | 15,600 | 19,760 | 16,250 | 16,240 |
| Total Savings (kWh) | -- | 2,960 | 3,020 | -- | 3,510 | 3,520 |
| % Savings for Htg&Clg | -- | 43% | 42% | -- | 42% | 41% |
| Seasonal Heating COP* | 1.00 | 1.77 | 1.74 | 1.00 | 1.75 | 1.73 |
| GHG Emissions (tn $CO_2$ eq) | 14.10 | 11.90 | 11.90 | 0.60 | 0.49 | 0.50 |
| GHG Emissions (%) | -- | -16% | -16% | -- | -18% | -18% |

*Seasonal Heating COP for whole home, inc. HP & aux. COP higher when considering only zones served by HP

Table 17 summarizes the energy performance of each heat pump integration in Winnipeg and Vancouver. The value of the CCHP is immediately clear in Winnipeg, with the extended operating range of this unit providing a strong reduction in baseboard energy use on the first and second floors of the home. Results in Vancouver follow a similar trend to Halifax and Toronto, with both the VCHP and CCHP offering similar performance over the heating season. Given the relatively clean electricity grids in Winnipeg and Vancouver, some readers may question the importance of transitioning from baseboards to heat pumps in the overall context of decarbonization. While the magnitude of GHG emission reductions is quite small in these two regions, transitioning to more efficient heat pump systems also frees up additional generating capacity to meet increased demand driven by population growth and a greater electrification of other sectors (e.g., transport).

Table 17: Summary of heat pump energy performance replacing electric baseboards in Winnipeg and Vancouver

| | Winnipeg | | | Vancouver | | |
|---|---|---|---|---|---|---|
| End Use | Base Case | VCHP | CCHP | Base Case | VCHP | CCHP |
| Total Heating (kWh) | 12,490 | 9,480 | 8,750 | 6,100 | 3,510 | 3,300 |
| Heat Pump | -- | 2,940 | 3,840 | -- | 1,620 | 1,330 |
| Aux: Elec BB (1st, 2nd) | 9,430 | 3,400 | 1,760 | 4,580 | 320 | 370 |
| Aux: Elec BB Basement | 3,060 | 3,130 | 3,150 | 1,520 | 1,580 | 1,590 |
| Cooling (kWh) | 680 | 460 | 380 | 420 | 280 | 220 |
| Fans (kWh) | 480 | 630 | 640 | 480 | 540 | 510 |
| DHW (kWh) | 6,490 | 6,490 | 6,490 | 5,090 | 5,090 | 5,090 |
| Lighting/Equip. (kWh) | 5,220 | 5,220 | 5,220 | 5,280 | 5,280 | 5,280 |
| Total Energy Use (kWh) | 25,360 | 22,280 | 21,480 | 17,370 | 14,700 | 14,400 |
| Total Savings (kWh) | -- | 3,080 | 800 | -- | 2,670 | 2,970 |
| % Savings for Htg&Clg | -- | 25% | 31% | -- | 42% | 46% |
| Seasonal Heating COP* | 1.00 | 1.33 | 1.44 | 1.00 | 1.71 | 1.81 |
| GHG Emissions (tn $CO_2$ eq) | 0.033 | 0.029 | 0.028 | 0.35 | 0.29 | 0.29 |
| GHG Emissions (%) | -- | -12% | -15% | -- | -15% | -17% |

*Seasonal Heating COP for whole home, inc. HP & aux. COP higher when considering only zones served by HP

Table 18 summarizes the economic performance of the heat pump systems replacing electric baseboard heating. Smaller capital costs for most CCHPs vs. VCHPs relates to the unit sizes: Given their improved capacity, smaller CCHPs were integrated while meeting the same sizing objective. Heat pump systems offer utility cost reductions in all cities, as would be expected given they are replacing a less efficient base case system using the same energy source. All heat pump systems achieve lifecycle cost savings over the 20-year analysis period, with the VCHP and CCHP systems offering relatively similar total costs. These overall savings tend to be limited somewhat by the higher cost of the heat pump systems vs. inexpensive electric resistance heating. As with the previous transitions examined, it is likely that incentives covering first costs may be needed to drive greater uptake and ensure payback periods fall within the expected range for homeowners.

Table 18: Summary of lifecycle costs for VCHP and CCHP systems as electric baseboard system replacements

| City | System | Capital Cost ($) | Lifecycle Utility Cost ($) | Lifecycle Maintenance Cost ($) | Total Lifecycle Cost ($) |
|---|---|---|---|---|---|
| Halifax | Base | $6,700 | $52,300 | $1,500 | $60,500 |
| | VCHP | $8,500 | $44,300 | $1,500 | $54,300 |
| | CCHP | $8,300 | $44,200 | $1,500 | **$54,000** |
| Toronto | Base | $7,700 | $50,000 | $1,900 | $59,600 |
| | VCHP | $9,200 | $42,500 | $1,900 | $53,600 |
| | CCHP | $9,000 | $42,400 | $1,900 | **$53,300** |
| Winnipeg | Base | $8,100 | $40,200 | $1,800 | $50,100 |
| | VCHP | $10,400 | $35,500 | $1,800 | $47,700 |
| | CCHP | $10,500 | $34,300 | $1,800 | **$46,600** |
| Vancouver | Base | $6,600 | $37,700 | $1,600 | $45,900 |
| | VCHP | $7,800 | $31,100 | $1,600 | $40,500 |
| | CCHP | $7,900 | $30,300 | $1,600 | **$39,800** |

## 7. Conclusions and Future Work

This study has examined the techno-economic impacts of heat pump adoption in single family Canadian housing. Using an enhanced, data-driven heat pump model, both variable capacity and cold climate variable capacity systems were simulated over a full year as replacements for (i) natural gas furnaces, (ii) oil furnaces, and (iii) electric baseboards. While simulations show the strong energy savings benefits of heat pumps, the economics of these systems are highly dependent on the regional climate, local utility rates and heating energy source being displaced. Integrating heat pumps as replacements for natural gas furnaces represents the most challenging current context, with heat pumps currently offering utility cost savings in only two of the four regions assessed (Vancouver, Halifax), with lifecycle costs higher in all regions. Heat pumps as replacements for oil and electric baseboard systems present a stronger value proposition in the current economic climate, offering both utility and lifecycle cost savings in all cases. An additional analysis using planned carbon pricing shows that by 2030 heat pumps will offer both utility and lifecycle cost savings vs. all three systems examined in this paper (natural gas furnaces, oil furnaces, electric baseboards), representing a significant improvement in system economics vs. the current context. Even when lifecycle cost savings are achieved, the adoption of heat pumps may be challenged by the higher first cost of these systems vs. those they are replacing. Results from this study can be used as a starting point to support the future policy and incentive programs needed to drive decarbonization of Canadian residential buildings.

Heat pump adoption is likely to rise significantly in the coming years as efforts to decarbonize space heating gain momentum. Although not examined in this study, understanding the electrical demand implications associated with this increased uptake is critical to ensure that local electricity grids have the capacity and infrastructure to support a greater electrification of building systems. CanmetENERGY in Varennes has previously used its simulation capabilities to examine the peak demand implications of air-source heat pumps in residential buildings, and will continue this work to complement the energy and economic impacts presented in this article. These peak demand implications also necessitate a new generation of heat pump systems that combine efficient heating and cooling with energy storage to increase flexibility and demand response capabilities. Ongoing research at CanmetENERGY in Varennes has identified novel combinations of heat pumps and thermal storage for the Canadian context, with planned work furthering this research through additional development and a small-scale proof of concept. This work is intended to further compliment the information presented in this paper and support the efficient electrification of Canadian residential buildings.

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