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## A Techno-Economic Assessment of Air-Source Heat Pumping Technologies in the Canadian Residential Sector

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### Abstract

While heat pump systems have strong potential to reduce energy use in the Canadian residential sector, the optimal system type and configuration can vary greatly depending on local climate and economic conditions. This paper applies techno-economic analysis to compare three market available air-to-air heat pumps (single stage, conventional variable capacity, and cold climate variable capacity) and examine their relative potential under different climate and utility rate structures. Using an improved, data-driven heat pump model, the economic and energy performance of each system is assessed for new construction housing in three Canadian regions. Results demonstrate the energy savings benefit of cold climate heat pumps in harsher winter climates, and the challenging economic context faced by heat pumps under current low natural gas rates in some Canadian regions. Key design concepts, including the sensitivity of the results to changes in estimated operating COP, and the strong link between peak loads and the combined control of the heat pump and auxiliary systems, are also discussed in order to promote an improved integration of heat pumps in Canada.

*Keywords:* Variable capacity heat pumps; Cold climate heat pumps; Techno-economic analysis; Canadian residential sector

### 1. Introduction

As the world transitions towards a decarbonized economy and infrastructure, efficient renewable energy technologies are of great importance. In recognition of this context, the Government of Canada has developed a Market Transformation Roadmap [1], which presents a framework for an increased adoption of the high efficiency mechanical systems needed to drive decarbonisation of the built environment. Heat pumps play an important role within the Roadmap, responding to key aspirational goals regarding future high efficiency space heating systems (Target energy performance<sup>1</sup> >100%) and the integration of renewable energy. However, to fully capitalize on this strong potential, appropriate heat pump system selection is of critical importance.

The Canadian context represents a particularly challenging set of circumstances for heat pump integration. Significant variations in both climate (mild maritime to extreme cold) and utility rate structures (vast differences in natural gas vs. electricity rates) often mean that the optimal system choice is highly dependent on local climate and economic conditions. Selection can be further complicated when considering the peak load impacts of heat pumps, an aspect of growing importance given the increasing electrification of building systems and more widespread heat pump adoption.

The current Canadian residential heat pump market is dominated by air-source (air-to-air) heat pumps, driven by their lower costs and relative ease of installation [2]. However, traditional single stage systems suffer significant performance degradations at colder temperatures while cycling frequently at milder conditions, making it difficult to meet comfort needs in Canadian climates. The last decade has seen important technological advances in the market, including the increased availability of inverter-driven variable speed compressors, and the introduction of cold climate air-source heat pumps, which combine variable capacity

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<sup>1</sup> Energy performance here refers to how efficiently a selected technology delivers space heating, quantified using the COP and Heating Season Performance Factor (HSPF) (heat pumps) or annual fuel utilization efficiency (AFUE) (gas and oil-fired equipment) [1]. These targets provide important motivation for increased heat pump adoption in Canada.

technology with larger outdoor coils and other cycle improvements such as vapour injection [3,4]. These advancements allow the heat pump to provide increased heating capacities at lower ambient temperatures, while still efficiently modulating at milder conditions. While previous studies have examined the energy performance of these systems and their economics in isolation [5,6], there is little information available regarding when the added investment for cold climate and variable capacity technologies is most appropriate, or how the economics of different air-source heat pump technologies compare across Canada.

This paper presents a simulation-based approach, driven by extensive testing and measured data, to assess the relative benefits of three types of market available air-source heat pumps: conventional single speed systems, conventional variable capacity units, and cold climate (variable capacity) heat pumps. A new data-driven heat pump model, capable of appropriately capturing the unique performance characteristics of variable capacity heat pumps, is used as a base for system assessment. Each heat pump integration is examined for newly constructed housing in three Canadian regions (Montreal, Edmonton, and Vancouver) to identify the potential for energy and lifecycle cost savings. A grid interaction analysis is also performed to more fully understand the implications of a given system selection.

## 2. Development of Base Case Housing Models

Climate, utility rate structure, and the type of heat pump integration (ducted or ductless) can vary greatly across Canada. In order to highlight these effects, three Canadian regions were selected, each representing a unique set of boundary conditions. Key climate parameters for each region are provided in Table 1 [7].

Table 1 Summary of climate characteristics

Characteristic	Montreal	Edmonton	Vancouver
Heating Design Temperature (°C)	-23	-30	-7
Heating Degree Days Below 18°C	4,200	5,120	2,825
Climate Type	Cold & Humid	Cold & Dry	Cool & Humid

Housing models used in the analysis were selected to be representative of typical single family housing, with building geometry based on the Canadian Centre for Housing Technology (CCHT) test homes located in Ottawa, Canada [8]. The modelled home included two above ground floors and a finished basement, with a total heated floor area of 284 m<sup>2</sup>. The building envelope was modified to represent new construction housing in each region using National Building Code of Canada (NBC) minimum requirements for the appropriate climate zone [7]. Building mechanical systems were based on typical configurations in each region, and included both centrally ducted systems (Edmonton, Vancouver) and non-ducted configurations (Montreal). It is important to note that Montreal does include small flexible ducting to distribute a low volume (65 CFM) of ventilation air from the HRV, with a small electric duct heater used to ensure a suitable ventilation supply air temperature. A summary of key housing characteristics for each base case is provided in Table 2, with further details available in Kegel *et al.* [9].

Table 2 Key housing characteristics for base case models

Characteristic	Montreal	Edmonton	Vancouver
Central Air Distribution	No	Yes	Yes
Primary Heat Fuel & System	Electric Baseboard Heaters	Natural Gas Forced Air Furnace	Natural Gas Forced Air Furnace
Heating Efficiency	100%	92%	92%
Space Cooling System	Split AC Unit COP = 3.3*	Central AC COP = 3.5*	Central AC COP = 3.5*
DHW Fuel	Electric	Natural Gas	Natural Gas
Heat Recovery Ventilator (HRV)	Yes	Yes	Yes

\*At AHRI rating conditions

## 3. Heat Pump System Integrations

Each base case model serves as a platform to assess three different heat pump technologies:

- I. Conventional Single Stage Air-Source Heat Pump (SSHP)
- II. Conventional Variable Capacity Air-Source Heat Pump (VCHP)
- III. Cold Climate (Variable Capacity) Air-Source Heat Pump (CCHP)

It is important to note that the method of heat distribution within the home can vary depending on whether central ducting is available. As such, for each system type listed above (SSHP, VCHP, CCHP), both ducted and non-ducted configurations were examined. For locations with existing central ducting (Edmonton, Vancouver), 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 (Montreal), a ductless configuration is proposed, with a wall mounted indoor unit located in the stairwell connecting the first and second floors of the home. In this configuration, the basement is heated only using electric baseboards, as per the base case.

For all heat pump cases, system sizing was chosen to match the capacity used in the CCHP analysis. This decision was made to provide a common base of comparison for all systems, and to avoid cross-effects from different sizing methodologies. System sizing for the CCHP case was based on the heat pump acting as the primary source of heating for the building, supplemented by limited auxiliary heating operations if needed.

System sizing in Montreal is limited to 1.5 tons, the largest market available system size for the ductless CCHP used in the simulations. As outlined later in this paper, the simulation model for this heat pump was based on extensive test data, with the tested model not available in sizes > 1.5 tons. This limitation is better understood by noting the type of ductless system used: A single-split (one indoor unit, one outdoor unit) ductless configuration. Although a multi-split unit (multiple indoor units, one outdoor unit) is a more likely choice given the size of the home in this study, the single-split unit is modelled due to the availability of extensive performance data derived from detailed testing at the CanmetENERGY facility. Given that similar data was not available for multi-split systems, the single-split was used instead to avoid employing additional modelling assumptions, while more closely representing as-installed performance.

**Single Stage Air-Source Heat Pump**

The single stage heat pump represents the most basic system available in the current market, and is included in the analysis to provide a point of reference for the other technologies.

Single stage heat pumps encounter two significant challenges when operating in many Canadian climates:

- I. Heating capacity drops drastically at colder ambient temperatures, increasing auxiliary energy use
- II. Available capacity at milder conditions is often far greater than the building heating load, leading to frequent and inefficient on/off cycling.

Given the reduced heating performance at colder ambient temperatures, fully sized auxiliary systems (sized to meet the peak heating loads) are required. For ductless configurations, auxiliary heating is achieved using electric baseboards located in each thermal zone, while for centrally ducted configurations, an electric duct heater is used to supplement heat pump operations as required. Key SSHP parameters are provided in Table 3.

Table 3 Performance characteristics for single stage heat pump

	Montreal	Edmonton	Vancouver
HP Size	1.5 Ton	3 Ton	2 Ton
HP Configuration	Ductless	Ducted	Ducted
Heating COP*	3.2	3.7	3.7
Cooling COP*	3.5	3.4	3.4
Min. Outdoor Operating Temperature, Heating Mode (°C)	-8	-20	-20
% of Rated Capacity @ Cut-Off	62%	27%	27%

\*At AHRI Rating Conditions

**Conventional Variable Capacity Air-Source Heat Pump**

Variable capacity units account for a growing share of the Canadian market, driven by increased energy savings resulting from the ability to efficiently modulate the capacity of the unit to match heating or cooling demand. However, variable capacity technology alone does not necessarily constitute a cold climate heat pump: Many market available units provide less than 50% of rated capacity at outdoor air temperatures of -20°C or -25°C. This integration examines these more conventional variable capacity systems in each region.

Variable capacity heat pumps are defined both by their full capacity at maximum speed, and their ability to modulate to meet reduced loads. Fig. 1 presents the heating capacity and COP as a function of outdoor air temperature for a representative ducted variable capacity heat pump [10]. Capacity curves are normalized based on AHRI rating conditions (i.e. capacity at 47°F (8.3°C)). It is important to note the increase in COP at lower compressor speeds, which allows this type of heat pump to operate at improved efficiencies during times of lower heating demand while also limiting on/off cycling.

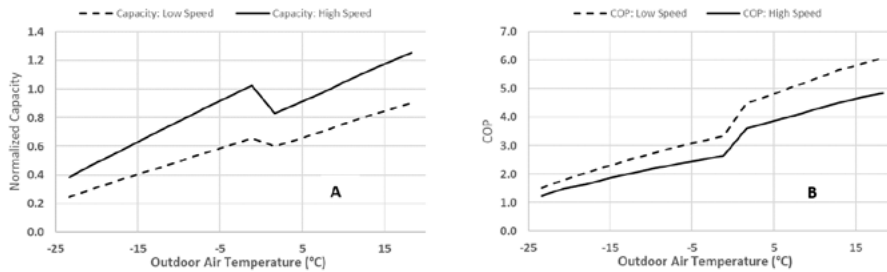


Fig. 1. Variation of (A) heating capacity and (B) COP at minimum and maximum capacity for a typical VCHP [10]

A summary of key variable speed heat pump parameters for each region is provided in Table 4.

	Montreal	Edmonton	Vancouver
HP Size	1.5 Ton	3 Ton	2.5 Ton
HP Configuration	Ductless	Ducted	Ducted
Heating COP*	3.3	4.1	3.7
Cooling COP*	4.1	4.1	3.9
Min. Outdoor Operating Temperature, Heating Mode (°C)	-17	-23	-23
% Capacity at Cut-Off Temperature (Max Speed)	51%	38%	38%
Average Min: Max Capacity Ratio	0.32	0.30	0.30

\*At AHRI Rating Conditions

### Cold Climate Variable Capacity Air-Source Heat Pump

Cold climate heat pumps combine variable capacity technologies with other cycle improvements (e.g., larger outdoor coils, vapour injection cycles) to maintain a larger portion of heating capacity at low outdoor air temperatures. While several definitions for cold climate heat pumps are available in the literature [11,12], in this study they have been classified based on an ability to operate to a minimum outdoor air temperature of -25°C, while still maintaining over 65% of their rated capacity. These performance characteristics make cold climate units well suited to space heating in many Canadian regions, albeit at added initial investment.

Fig. 2 (A) shows a representative normalized heating curve for a ducted cold climate heat pump at minimum and maximum speed [13]. A representative curve for a non-cold climate variable capacity unit at maximum speed is also presented. It is clear that the cold climate unit is able to maintain a far greater percentage of its heating capacity, reducing the amount of auxiliary energy input required. Fig. 2(B) shows the COP of the same representative cold climate unit over its range of operating conditions.

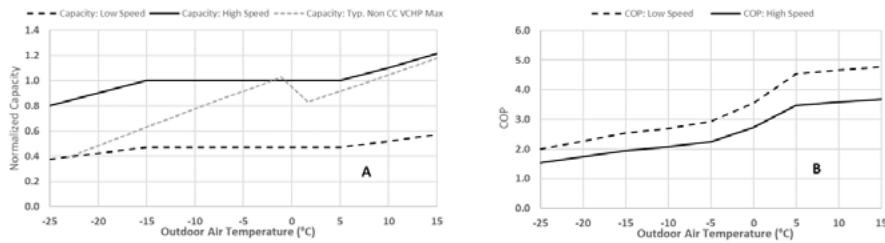


Fig. 2. Summary of (A) heating capacity and (B) COP for cold climate variable capacity heat pump [13]

A summary of key cold climate heat pump characteristics is provided below in Table 5.

Table 5 Key performance characteristics for cold climate variable capacity heat pumps

	Montreal	Edmonton	Vancouver
HP Size	1.5 Ton	3 Ton	2.5 Ton
HP Configuration	Ductless	Ducted	Ducted
Heating COP*	4.1	3.7	3.6
Cooling COP*	4.2	3.7	3.7
Min. Operating Temperature, Heating Mode (°C)	-25	-25	-25
% Capacity at Cut-Off Temperature (Max Speed)	66%	80%	80%
Average Min: Max Capacity Ratio	0.33	0.47	0.56

\*At AHRI Rating Conditions

#### 4. Heat Pump System Energy Models

Accurately modelling each heat pump system is critical in order to properly estimate the energy and economic benefits of each integration. In this study, all systems were modelled with TRNSYS v.17 using the appropriate Canadian Weather for Energy Calculations (CWEC) weather file. Each simulation was run with a time step of 2.5 minutes to better simulate the control logic of the heat pump and auxiliary systems.

##### Heat Pump Performance Modelling

One of the main strengths of TRNSYS is its ability to support the development and integration of custom components models for different HVAC equipment. This capability was leveraged to develop a new variable capacity heat pump model, Type 3255 [6], which was designed to more closely represent variable capacity performance in system level simulations. The component model is based on extensive experience with a heat pump test bench at the CanmetENERGY facility in Varennes, and integrates a number of new capabilities including performance variation with compressor speed, and short term characteristics such as defrost and compressor behaviour during start up. Further details regarding model development and capabilities can be found in Breton *et al.* [6].

Type 3255 uses a data driven approach to heat pump simulation, requiring the user to provide a detailed map of how capacity and power consumption vary with compressor speed. Wherever possible, systems simulated in this paper use experimental data to inform heat pump simulations. However, given the variety of systems examined in this study, certain models have been developed using manufacturer data at rated conditions, with performance at lower compressor speeds estimated using typical curves relating heat pump power to the ratio of delivered and rated heating capacities [14, 15]. A summary of the data sources used for each heat pump integration is summarized in Table 6.

Table 6 Summary of data sources for heat pump modelling

Heat Pump System	Ductless Systems		Ducted Systems	
	Rated Performance	Part Load Performance	Rated Performance	Part Load Performance
SSHP	Manufacturer [16]	Literature [15]	Manufacturer [17]	Literature [15]
VCHP	Manufacturer [18]	Literature [14]	Test [3]	Test [3]
CCHP	Test [19]	Test [19]	Manufacturer [13]	Literature [14]

### Representing Heat Pump Control

Heat pump control was simulated using a PID controller, which estimated the required compressor frequency (or heat pump capacity, for SSHP) to maintain the desired temperature setpoint of 21°C in heating, or 23°C in cooling. Additional controls ensure that the heat pump only operates within its intended range of outdoor temperatures. Compressor frequency spikes to maximum during start up after a defrost or shutdown event when in heating mode, based on observations noted during testing at the CanmetENERGY facility.

Auxiliary heating elements (electric baseboards for ductless cases, electric duct heater for central systems) are a key component of each heat pump integration, and play an important role in defining the peak loads of the system. Auxiliary systems have three operating modes, depending on heat pump operations:

- I. Heat pump is defrosting: For central systems, the auxiliary duct heater turns on at a constant, fixed, limited capacity to minimize occupant discomfort during defrost. No special control is used for the ductless system, as the system modelled is not equipped with internal heating elements. Defrost length is fixed at 5 minutes in the current model (future work will add varying defrost lengths).
- II. Heat pump is operating: Auxiliary heaters operate with a slightly lower setpoint (20°C vs. 21°C for the heat pump) to ensure space temperatures are maintained within an acceptable range while still prioritizing heat pump operations. The heat pump and auxiliary system may operate in parallel.
- III. Heat pump is unable to operate: When ambient temperatures are too cold for the heat pump to operate, auxiliary heating maintains the desired setpoint of 21°C.

### 5. Lifecycle Cost Analysis

In addition to examining energy performance, it is also important to understand the economics of each system to fully assess their potential in the Canadian market. With this in mind, each system integration has been assessed over a 20 year lifespan, with a focus on the associated capital, maintenance, and operational costs. No replacement costs are included. All lifecycle calculations were performed using an inflation rate of 1.8% and a discount rate of 3.3%, based on current Canadian financial markets.

System capital costs were estimated at the component level, and included all required equipment, controls, and ducting. A listing of all equipment included in the cost analysis is provided in Table 7.

Table 7 Summary of components included in capital cost calculations

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

Component costs were derived from available suppliers [20-22], and RS Means [23], and included both material and labor. Wherever possible, prices were compared from the same source for all three system integrations to ensure that relative pricing between each remained consistent. Equipment and labour costs were adjusted for each region using factors presented in RS Means [23]. Capital costs for each integration and region are presented in Table 8, with values in Canadian Dollars. Annual maintenance includes typical tasks (inspection, coil & filter cleaning), but not replacement of major components (e.g. refrigerants or compressors).

Table 8 Summary of capital and maintenance costs for each system integration by region

System	Cost	Montreal	Edmonton	Vancouver
Base Case	System	\$8,400	\$12,300	\$11,600
	Annual Maintenance	\$114	\$237	\$225
SSHP	System	\$8,500	\$12,400	\$10,900
	Annual Maintenance	\$114	\$123	\$117
VCHP	System	\$9,200	\$17,200	\$14,200
	Annual Maintenance	\$114	\$123	\$117
CCHP	System	\$10,100	\$19,800	\$16,000
	Annual Maintenance	\$114	\$123	\$117

Utility rates used in the study were based on current rates and structures for each selected region [24-28]. This included all daily/monthly fixed charges, tiered rate structures, and appropriate rate riders. Energy escalation rates were estimated using information from the National Energy Board of Canada [29]. A summary of utility rates used in the analysis are provided in Table 9. Natural gas rates are not presented for Montreal, as this source of energy is not used in the base case or any heat pump integration.

Table 9 Summary of utility rate structures in each selected region [24-29]

Utility	Charge	Montreal	Edmonton	Vancouver
Electricity	Daily Charge	\$0.4064/day	\$0.8283/day	\$0.205/day
	Energy Charge	\$0.0591/kWh (First 36 kWh/day) \$0.0912/kWh (> 36 kWh/day)	\$0.1132/kWh	\$0.0928/kWh (First 1,350 kWh/2 Month) \$0.1392 (> 1,350 kWh/2 Month)
	Escalation Rate	0.1%	2.8%	0.3%
Nat. Gas	Daily Charge	--	\$0.965/day	\$0.409/day
	Energy Charge	--	\$4.23/GJ (\$0.015/kWh <sub>Eq</sub> )	\$7.36/GJ (\$0.026/kWh <sub>Eq</sub> )
	Escalation Rate	--	1.0%	0.2%

## 6. Results and Discussion

The developed models provide an important base to assess the energy and economic performance of each system, and to study the peak load implications of the three selected technologies.

### Energy Performance

Table 10 summarizes the annual energy performance of each ductless heat pump integration in Montreal. Integrating a heat pump system results in a notable reduction in the energy used for heating and cooling, with savings ranging from 19% to 31%. While these savings represent an important reduction in energy use, the total energy required for heating still remains quite high in all cases. This can be attributed to the fact that, in the ductless system configuration, the heat pump only serves the first and second floors of the home, with the basement still heated using electric baseboards (Elec. BB). Comparing the energy used to heat the two above ground floors, each heat pump system is able to demonstrate heating energy use reductions of greater than 32%. The CCHP unit in particular demonstrates strong performance, reducing heating energy use for the first and second floors by nearly 50% while almost completely eliminating operations of the electric baseboards. Energy use reductions are more limited for the SSHP and VCHP cases, primarily due to reduced heating capacities and inefficient cycling of the SSHP at milder ambient conditions.

Readers may note the significant decrease in cooling energy use for the CCHP and VCHP cases, which can be attributed to the higher sensible heat factor (SHF) and the improved operating COPs of these two units in cooling. Given that cooling control in the model is based on the dry bulb space temperature, a system with a higher SHF is able to more rapidly reach the setpoint temperature, reducing system operations and energy use.

Table 10 Summary of annual energy performance for each ductless heat pump system in Montreal

End Use	Base Case	SSHP	VCHP	CCHP
Total Heating (kWh)	16,090	12,910	11,850	11,200
Heat Pump	--	2,500	3,960	4,790
Aux: Elec BB (1st, 2nd)	10,000	4,300	1,690	220
Other: Elec. BB Basement + HRV Elec. Duct Heater	6,090	6,110	6,200	6,190
Cooling (kWh)	1,050	1,030	630	600
Fans (kWh)	490	690	700	670
DHW (kWh)	4,270	4,270	4,270	4,270
Lighting/Equip. (kWh)	9,520	9,520	9,520	9,520
Total Energy Use (kWh)	31,420	28,420	26,970	26,260
Total Savings (kWh)	--	3,000	4,450	5,160
% Savings for Htg&Clg	--	19%	27%	31%
Seasonal Heating COP*	1.0	1.25	1.35	1.44

\*Seasonal Heating COP for whole home. Seasonal COP higher when considering only zones served by HP

Table 11 summarizes the energy performance of the ducted heat pump systems in Edmonton and Vancouver. Energy savings are noticeably larger than in Montreal, given that each heat pump is now integrated into a ducting network serving all three levels of the home and sized to meet a larger portion of the heating load. In both cities, the CCHP offers the strongest energy savings, driven by greater available heating capacity at colder outdoor temperatures, and improved operating efficiencies over the most common winter temperatures (-10°C to +5°C). Cooling energy use is higher in all heat pump cases, as the selected heat pumps are able to provide cooling over a larger operating window (down to ambient temperatures of 18°C vs. 24°C for the base cases), a capability which is used primarily during the shoulder seasons.

Table 11 Annual energy performance for each ducted heat pump system in Edmonton and Vancouver

End Use	Edmonton				Vancouver			
	Base Case	SSHP	VCHP	CCHP	Base Case	SSHP	VCHP	CCHP
Total Heating (kWh)	19,310	10,600	10,340	8,590	12,690	4,500	4,740	3,830
Heat Pump	--	6,190	8,060	7,220	--	4,330	4,570	3,680
Aux: Elec. Duct Heater	--	4,410	2,280	1,370	--	170	170	140
Cooling (kWh)	280	370	320	320	260	350	320	340
Fans (kWh)	3,970	4,180	3,000	3,500	3,640	2,770	2,090	2,140
DHW (kWh)	7,490	7,490	7,490	7,490	5,870	5,870	5,870	5,870
Lighting/Equip. (kWh)	9,520	9,520	9,520	9,520	9,520	9,520	9,520	9,520
Total Energy Use (kWh)	40,570	32,160	30,670	29,420	31,980	23,010	22,540	21,700
Total Savings (kWh)	--	8,420	9,900	11,150	--	8,970	9,440	10,280
% Savings for Htg&Clg	--	44%	46%	55%	--	63%	61%	68%
Seasonal Heating COP	0.9	1.7	1.8	2.1	0.9	2.7	2.5	3.1

It is interesting to note that VCHP and SSHP performance is similar in both regions, with the VCHP actually consuming more energy for heating in Vancouver. This result is not related to the impact of variable capacity technology, but instead to the operating COP of the VCHP used in this analysis over the most common winter temperatures. To illustrate this point, Table 12 summarizes the operating COP of each heat pump integration by ambient temperature in Vancouver. Even when including cycling losses, the SSHP offers improved COPs for outdoor air temperatures from -10°C to +5°C in comparison to the VCHP. This result highlights the importance of examining not only the rated COP of the unit, but, wherever possible, the estimated operating COP at various points along the heating load line. Further details regarding the impact of these performance curves and operating COPs is presented later in this section.

Table 12: Operating COP of heat pump systems by temperature in Vancouver

Temperature Range	SSHP COP	VCHP COP	CCHP COP
-10°C to -5°C	2.8	2.0	2.6
-5°C to 0°C	2.9	2.3	2.9
0°C to 5°C	3.0	2.8	3.5
5°C to 10°C	3.0	3.5	4.6
10°C+	2.6	4.0	4.9

**Techno-Economic Performance**

Table 13 summarizes the economic performance of each system in Montreal. All three heat pump systems offer lifecycle utility and total cost reductions, with total lifecycle cost savings ranging from 8% for the SSHP to 11% for the CCHP unit. Results in Montreal are aided by (1) the fact that heat pumps are replacing a less efficient base case system using the same energy source, and (2) the relatively small incremental cost between ductless split system air-conditioners and heat pumps of the same capacity. Relatively low electricity costs and higher capital costs mean that the added energy savings provided by the CCHP yield marginal total cost savings vs. the VCHP, although both systems offer strong lifecycle cost reductions vs. the base and SSHP cases.

Table 13 Summary of lifecycle economic performance in Montreal

	Base	SSHP	VCHP	CCHP
Capital Cost	\$8,350	\$8,490	\$9,240	\$10,090
Lifecycle Utility Cost	\$38,150	\$34,120	\$32,170	\$31,220
Lifecycle Maintenance Cost	\$1,670	\$1,670	\$1,670	\$1,670
Total Lifecycle Cost	\$48,170	\$44,270	\$43,080	\$42,980

Table 14 summarizes the economic performance of each system in Edmonton and Vancouver. Results for these two regions are significantly different than those presented for Montreal, primarily because heat pumps are now replacing less expensive natural gas-based heating. Despite the much higher efficiency of the heat pumps in comparison to the furnaces used in the base cases, all heat pump cases still result in increases in total lifecycle utility costs. In Edmonton, for example, the ratio of electricity to natural gas rates (per unit of energy) is so high (> 7:1) that a seasonal COP of more than 7 is needed just to achieve *any* utility cost savings.

When comparing only the heat pump systems, it is evident that VCHP and CCHP systems are challenged by their higher capital costs. Although energy savings can significantly reduce annual electricity costs vs. the SSHP case (e.g., *annual* savings of over \$300 CAD for the CCHP in Edmonton), this is not enough to outweigh the large increase in capital costs for these systems. Despite these currently challenging conditions, it is likely that increased market adoption of higher efficiency systems will gradually reduce initial costs and make these system integrations more financially viable in the coming years. The implementation of carbon pricing may also increase fuel-based utility costs, and further improve the economics of heat pumps systems.

Table 14 Summary of lifecycle economic performance in Edmonton and Vancouver

	Edmonton				Vancouver			
	Base	SSHP	VCHP	CCHP	Base	SSHP	VCHP	CCHP
Capital Cost	\$12,290	\$12,410	\$17,220	\$19,810	\$11,630	\$10,870	\$14,170	\$16,030
Lifecycle Utility Cost (incl. N.G & elec.)	\$44,710	\$63,520	\$60,310	\$57,610	\$33,010	\$35,750	\$34,800	\$33,040
Lifecycle Maintenance Cost	\$3,450	\$1,800	\$1,800	\$1,800	\$3,280	\$1,710	\$1,710	\$1,710
Total Lifecycle Cost	\$60,450	\$77,730	\$79,330	\$79,220	\$47,920	\$48,330	\$50,680	\$50,780

**Grid Interaction**

With increased adoption of onsite renewable energy generation and electrification of building systems, it is becoming important to assess not only energy and economic performance, but also the impact that each system integration can have on the local electricity grid. This is particularly important in many areas of Canada, where displacing current fossil fuel furnace systems with heat pumps can have significant peak demand implications.

In order to illustrate this aspect of system performance, the electrical load of the HVAC system (heat pump, auxiliary heaters, and fans) is examined for the first 60 days of the year (starting Jan. 1), representing the coldest winter conditions. Results are provided as a box plot in Fig. 3. The edges of each box denote the 25<sup>th</sup> and 75<sup>th</sup> percentiles, providing an idea of the variation in loading. The line across each box shows the median value. Whiskers in each plot show the maximum and minimum HVAC electrical load.

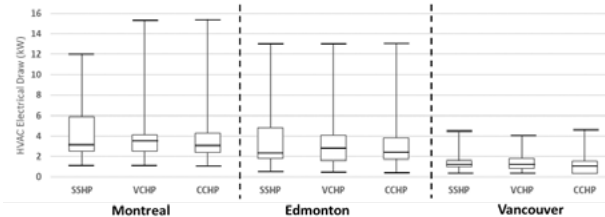


Fig. 3. Box plot of HVAC system power for each heat pump integration and region

An initial examination of the results shows median loads tend to be similar across all system types for a given region, which can be expected given the similar system sizing and operating efficiencies used in the study. However, a closer examination of the results by region reveals some key details regarding the impact of each heat pump configuration on the electricity grid. In Edmonton, the SSHP case shows a larger spread of data between the median and 75<sup>th</sup> percentile, meaning that this system spends a greater portion of time at a higher electrical draw in comparison to the other two heat pump systems. This increased draw is related to the reduced heating capacity of the SSHP at lower ambient temperatures in comparison to the CCHP, and the higher minimum operating temperature in comparison with the VCHP case (-20°C vs. -23°C). Maximum loads are identical for all three heat pumps, as these peak demands occur during the coldest winter days when outdoor air temperatures are below the minimum operating temperature of each heat pump.

Milder winter conditions in Vancouver present differing performance trends vs. the Edmonton case. These milder conditions result in similar HVAC electrical demands for all three heat pump systems, as the extra capacity and extended operating range of the CCHP and VCHP systems are not required. Peak loads in Vancouver are driven by the defrost process, when the auxiliary duct heaters (all sized identically) turn on to limit temperature drops in the conditioned space. Loading is reduced for the SSHP and VCHP cases due to their lower estimated heat pump power draws during this defrost process.

Results for Montreal underline important considerations regarding the control of the heat pump and auxiliary units. Similar to Edmonton, the SSHP shows greater variation between the median and 75<sup>th</sup> percentile, due to its reduced heating capacity and operating range. However, the VCHP and CCHP units actually have higher peak loads, due to the combined control of the heat pump and electric auxiliary.

The higher peaks for the VCHP and CCHP systems are best explained with the aid of Fig. 4, which shows several key performance criteria for the CCHP case over a four hour window starting at 3:00 AM Jan. 26<sup>th</sup> (day of maximum loading). Although the heat pump operates continuously until 5:20AM, its reduced capacity during this cold day means that it is unable to meet the setpoint temperature of 21°C. While auxiliary heating is still available during this portion of heat pump operations, the auxiliary system operates with a setpoint of 20°C to prioritize use of the heat pump. However, when outdoor air temperatures fall below the minimum cut-off for the heat pump (at 5:20 AM), the auxiliary then becomes the sole source of heating. Now operating with a new setpoint of 21°C, the auxiliary system attempts to rapidly raise the indoor temperature, causing the peak loads seen for the CCHP and VCHP cases. This behavior is not seen for the SSHP case due to its higher cut-off (i.e., minimum operating) temperature.

In addition to this peak loading, it is also interesting to note the potential issues caused by parallel heat pump/auxiliary operations. Just past 4:00 AM, the heat pump goes into defrost, cooling the space down to around 19.5°C. This translates into a strong increase in baseboard power demand, which, when combined with the heat pump operating at maximum frequency after the defrost event, also causes an unintendedly high peak power draw. In regions where the heat pump always operates above its minimum cut-off temperature, this behavior could become a major driver of peak electrical loading for the system, especially if backup baseboard temperatures setpoints are close to the temperature setpoint of the heat pump.

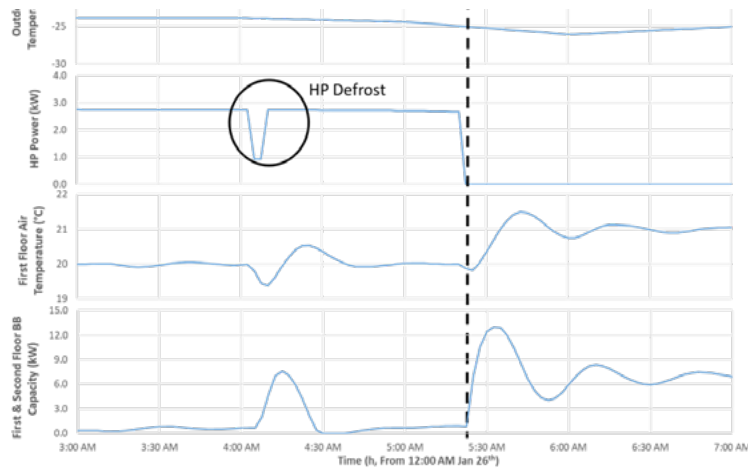


Fig. 4. Summary of key performance indicators for CCHP case in Montreal during peak load event

The importance of considering the interaction of the heat pump and auxiliary systems is clearly evident from the analysis. As demonstrated above, unforeseen operation of these two sub-systems can cause a significant increase in the peak electrical demand, and pose potential issues for the electrical grid in regions with more widespread heat pump adoption. Several simple workarounds can help facilitate a smoother interaction between these two system components, including limiting available auxiliary capacity to a reasonable amount when the heat pump is in operation (e.g., the difference between heat pump capacity and building load at the heat pump cut-off temperature), and using a ramped setpoint change when the system transitions from parallel heat pump/auxiliary operations to solely using auxiliary heating. In any case, more sophisticated controls should be carefully considered to optimize heat pump interaction with the grid. The integration of thermal storage could also afford an increased degree of flexibility by decoupling thermal supply and demand, allowing for peak shifting and demand reduction capabilities.

### Sensitivity Analysis

While the above results show the potential of heat pump systems, it is clear that the conclusions are highly dependent on the performance data and control strategies used in the analysis. An appropriate selection of the heat pump is vital in order to maximize the energy savings potential of the system. In order to better illustrate this point, two additional cases were run in Edmonton:

- (1) VCHP from Literature: A VCHP (with very similar SEER and HSPF ratings to the previously presented VCHP case) modelled using performance curves developed from manufacturer data [9]
- (2) VCHP from SSHP: A variable capacity unit, with maximum performance derived from the ducted SSHP [17], and power consumption at lower compressor speeds estimated with typical part load equations for VCHPs [14]. Capacity modulation ratios were based on the original VCHP case.

Simulation results for each case, along with the original SSHP and VCHP simulations, are compared in Table 15. By replacing the original VCHP performance curves (while keeping all other simulation settings the same), annual heating energy use was reduced by between 6% and 12%, primarily driven by higher COPs between outdoor air temperatures from  $-10^{\circ}\text{C}$  to  $+5^{\circ}\text{C}$ . The *VCHP From SSHP* case is particularly interesting, as it demonstrates the isolated impact of adding variable capacity technology to a single stage heat pump (a reduction in heating energy use of 9%). Given the significant development work in the field of variable speed drives and heat pump technologies, it is likely that the performance benefits of variable capacity units will continue to grow in the coming years, and may even be underestimated in the current analysis.

Table 15 Sensitivity analysis for VCHP systems in Edmonton

End Use	SSHP	VCHP	VCHP Lit.	VCHP From SSHP
Total Heating (kWh)	10,600	10,340	9,110	9,680
Heat Pump	6,190	8,060	6,780	5,390
Aux: Duct Heater	4,410	2,280	2,330	4,290

## 7. Conclusions

This study has examined the techno-economic potential of three market available heat pump technologies in new construction Canadian housing. Using an improved, data-driven component model, single stage, variable capacity, and cold climate variable capacity systems were simulated over a full year in the Canadian cities of Montreal, Edmonton, and Vancouver. Cold climate heat pumps offered the strongest energy savings in all three regions, with heating/cooling energy use reductions ranging from 31% in Montreal to 68% in Vancouver. Despite these energy savings, higher capital costs and low natural gas rates made it difficult to achieve lifecycle cost savings for heat pumps in all regions except Montreal. An assessment of the distribution of HVAC electrical demand showed the potential of cold climate systems to reduce electrical loads by mitigating auxiliary energy use, but also highlighted the critical importance of appropriately considering the interaction between the heat pump and any auxiliary heating systems, and the value of more sophisticated controls. While the information presented in this study offers insight into the Canadian market, it is important to be aware of the sensitivity of the results to the economic parameters and performance characteristics used. Future work will explore the economics and grid impacts of these systems in other Canadian regions and housing vintages, and obtain additional test data to more accurately represent the heat pump technologies presented in this study.

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