A Simulation-Based Exploration of Air-Source Heat Pump Sizing in Canada

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Abstract

Appropriate system sizing is critical in order to maximize the vast energy savings potential of air-source heat pump systems. However, proper system sizing is often highly dependent on a number of factors, including climate, building loads, and the performance characteristics of the heat pump.

Using Natural Resources Canada's *Air-Source Heat Pump Sizing and Selection Guide*, this paper presents a simulation-based approach to explore the energy performance impacts of four different sizing methods in 1990s single-family Canadian housing. An enhanced data-driven heat pump model, capturing performance variations with compressor speed and key short-term characteristics such as defrost, is used as a base for analysis. Annual simulation results demonstrate the strong energy savings potential of heat pumps, and the performance pitfalls of oversizing. The impact of key assumptions, including performance data and load calculations, are also discussed.

Introduction

The built environment accounts for nearly 22% of Canada's greenhouse gas emissions (NRCan, 2020a), and has a critical role to play in any national strategy to reduce carbon emissions. In recognition of the need for strong action, the Government of Canada has developed a *Market Transformation Roadmap*, which presents a framework to drastically reduce building-related emissions via the adoption of energy efficient technologies (NRCan, 2018). Space heating is a major focus of the *Roadmap*, with a series of goals and supporting initiatives outlining a market transition towards highly efficient (>100% seasonal efficiency) space systems by 2035. While this context provides a strong opportunity to increase adoption of heat pump (HP) systems, appropriate guidance on system sizing and integration is critical in order to capitalize on the energy savings potential of this technology.

Air-source heat pumps (ASHPs) dominate the Canadian heat pump market, driven by lower initial costs and relative ease of installation. However, the cold Canadian climate poses a challenge, with heating capacity decreasing at colder ambient temperatures when building heating demand is highest. In this context, properly sizing heat pump systems can be challenging: System sizing is often dependent on a number of factors, including local climate, building loads, heat pump technology, and objective (i.e., portion of heating load covered by HP) (NRCan, 2020b). This challenge is further complicated when considering the energy efficiency impacts of heat pump cycling and part load performance, which can vary significantly depending on whether single-stage or variable capacity technology is used. It is clear that a framework is needed to provide system designers with the tools and knowledge needed to maximize system performance in Canada.

In response to this need, Natural Resources Canada (NRCan) has developed an *Air-Source Heat Pump Sizing and Selection Guide*, which provides users with a detailed methodology for system sizing depending on the building loads, climate, sizing objectives, and heat pump technology (NRCan, in publication). This paper applies a simulation-based approach, driven by an improved quasi-transient heat pump model, to explore the energy performance implications of different sizing options presented in the *Guide* for four Canadian cities. First, detailed housing models in each city are presented, followed by a discussion of the various sizing approaches considered. Then, a new data-driven heat pump model is introduced, capturing key performance characteristics associated with cycling, part load, and defrost operations. Finally, relative performance is compared in each city based on annual energy and utility cost savings versus typical base case systems.

Development of base case housing models

Heat pump sizing and performance can vary greatly across Canada depending on local climate and building construction. In order to examine these impacts, four Canadian cities (Halifax, Montreal, Vancouver, and Winnipeg) have been selected for analysis, with key climate data summarized in Table 1 (CCBFC, 2010).

Table 1: Selected details for each climate zone

	HLX	MTL	VAN	WPG
Heating Design Temperature (°C)	-16	-23	-7	-33
Heating Degree Days Below 18°C	4000	4200	2950	5670
NECB Climate Zone	Zone 6	Zone 6	Zone 4	Zone 7A

As discussed in the following sections, each region represents a unique combination of system integration and climate. Homes in Montreal and Halifax are typically electrically heated, while Vancouver and Winnipeg primarily use natural-gas based heating. For both integrations, the cities selected also provide the opportunity to examine the impact of different climates on sizing.

To support the analysis, housing models representative of each cities were developed in TRNSYS v.17, using the multizone building component Type56. In all cases, building geometry was defined using information from the Canadian Centre for Housing Technology (CCHT) test homes located in Ottawa, ON (Swinton, 2003). The CCHT homes represent typical single-family Canadian housing and consist of two above-ground floors and a finished basement, with a total heated floor area of 284 m^2. The TRNSYS building model is divided into three occupied zones (basement, first and second floors) in order to capture the impact of different gains, occupancy, and thermal loads on the heating, ventilation and air conditioning (HVAC) system. The developed model has been validated with measured data, with further details provided in Kegel *et al.* (2012). The modelled building construction was then modified to represent typical 1990s construction practices using city-specific information from the Canadian Single-Detached and Double/Row Housing Database (CSDDRD) (Swan, 2009). Such vintage housing presents a key opportunity for ASHP integration as a replacement of aging HVAC systems. A summary of key housing parameters by city is provided in Table 2.

Base case heating and cooling systems were modelled in order to assess the energy savings potential of different heat pump sizing options. Building HVAC systems were based on typical configurations in each city identified via the CSDDRD. While an analysis of 1990s housing reveals that a majority of homes are not equipped with space cooling, air conditioning (AC) systems have been included in the base case models to provide a base of comparison to heat pump systems. A summary of key HVAC parameters used in the base case scenarios is provided in

Table 3.

Table 2: Housing parameters for each city

	HLX	MTL	VAN	WPG
Wall RSI (m^2°C/W)	3.1	3.1	2.2	3.0
Roof RSI (m^2°C/W)	5.5	4.8	4.5	5.5
Window U Value (W/m^2)	2.9	2.9	2.9	2.3
Infiltration (ACH_{50})	3.6	4.3	7.5	2.3

VCHP technology and modelling

In this study, all heat pump integrations were based on the use of variable capacity technology. This recent advancement in heat pump systems allows these units to vary their cooling and heating capacity to better match space conditioning loads. This results in less frequent on/off cycling compared to single-speed heat pumps, leading to more efficient operation.

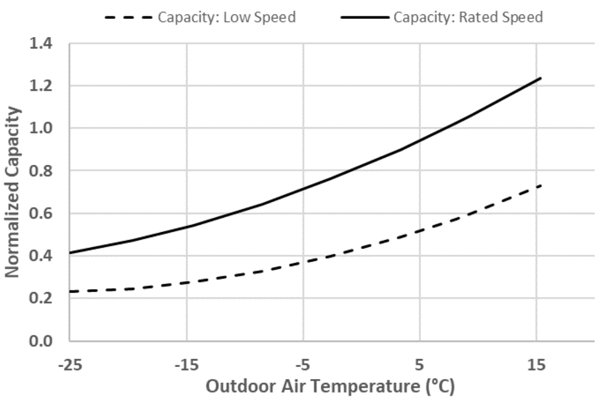
Most models of air-source heat pumps available in simulation tools represent conventional single-speed units unable to fully capture the performance of variable capacity heat pumps. An enhanced VCHP component model developed in TRNSYS (Type 3255) is used in this study to better estimate the performance and the energy use of such units (Breton *et al.*, 2019; St-Onge, 2018). Type 3255 is a data-driven model that reproduces the load-matching behaviour of variable capacity heat pumps by using a performance map that includes the capacity and power at different compressor frequencies. The model also characterizes key short-term features of heat pumps that are typically not included in simpler models, such as defrost cycles and start-up behaviour. Reverse-cycle defrost is applied at regular intervals, during which the heat pump temporarily operates in cooling mode. When exiting a defrost cycle, the heat pump capacity follows an exponential curve over a recovery period (St-Onge, 2018). Similar behaviour (power spike and derated capacity) is characteristic of VCHP start-up and is also reproduced with the modelling strategy used. This VCHP model provides an enhanced ability to capture the impact of on/off cycling, and to explore the energy performance implications of various sizing options. Further modelling details are provided in Breton *et al.* (2019).

Table 3: Summary of base case heating and cooling systems

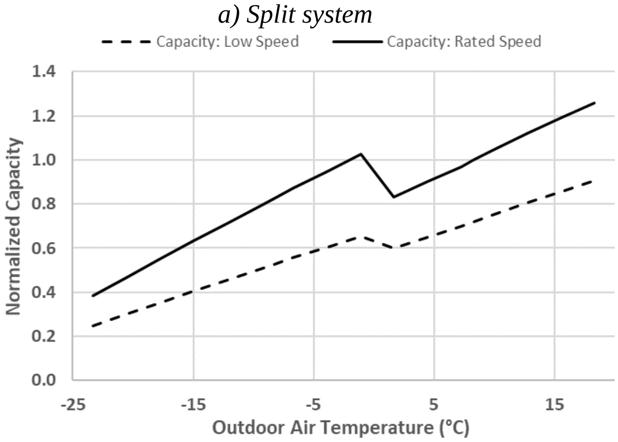
	Halifax	Montreal	Vancouver	Winnipeg
Heat Recovery Ventilator	Yes	No	No	No
Central Air Distribution	No	No	Yes	Yes
Heating Source and System	Electricity Baseboard Heaters	Electricity Baseboard Heaters	Natural Gas Forced Air Furnace	Natural Gas Forced Air Furnace
Heating Efficiency	100%	100%	78%	78%
Space Cooling System	1.5 ton split AC COP=3.3*	1.5 ton split AC COP=3.3*	1.5 ton central AC COP=2.5*	2.5 ton central AC COP=2.5*

*At AHRI rating conditions

The performance of variable capacity units is characterized by their rated capacity, as well as by the range over which they can modulate to meet reduced loads. Normalized heating capacity at minimum and rated speeds as a function of ambient temperature is presented in Figure 1 a) and b) for representative split and central VCHP systems, respectively. Heating capacity for the split unit was obtained from multiple polynomial regressions of experimental data across the full range of compressor frequencies (St-Onge, 2018), while manufacturer data was used for the central system. Both units considered can deliver approximately 40% of their rated capacity at their cut-off temperature. Although not explicitly shown here, the COP of VCHPs tends to increase as the compressor speed is reduced – resulting in improved part-load efficiencies.



a) Split system



b) Central system

Figure 1: Normalized VCHP heating capacity curves

Heat pump sizing and integration

The sizing methodology employed is based on the different approaches presented in NRCan's *Air-Source Heat Pump Sizing and Selection Guide*. Four sizing options are investigated, with different target capacities for the ASHP depending on the objectives to be reached in heating and cooling. Each option was simulated for all four cities (where applicable) to explore the impacts of heat pump selection on annual energy performance.

Option A: Emphasis on cooling

The ASHP unit is considered mainly as an alternative to the AC unit used in the base case, while the existing heating system is seen as the primary heating source for most of the heating season. The target capacity of the ASHP is based on the cooling load, with the *high-stage* cooling output of the ASHP matching a target cooling capacity range – defined as 80% to 125% of the design cooling load.

Option B: Emphasis on balanced heating and cooling

This sizing approach is similar to Option A, but the target capacity of the ASHP is based on the *low-stage* cooling output being within the target cooling capacity range. This criteria leads to the selection of a larger unit, such that the ASHP can meet a greater portion of the heating load throughout the year. The existing heating system is used as backup during colder periods.

Option C: Emphasis on heating

The main heating source for this option is the ASHP, while cooling performance is of secondary interest. The target heating capacity of the ASHP is the heating load of the *target zone* (i.e., building zones served by HP) at -8.3°C, so that the unit is sized to provide a major portion of the heating required. In this study, Option C systems are all electric given the more significant portion of heating covered by the heat pump. However, hybrid (furnace or boiler/HP) systems are still possible under this Option in the *Guide*. An electric backup heating system supplements heat pump operations as needed during colder periods.

Option D: ASHP as the sole heating source

Like in Option C, the ASHP is sized based on heating requirements. However, in Option D, the unit is to be used as the *sole* source of heating. The target heating capacity of the ASHP is therefore the design heating load (of the *target zone*) at the heating design temperature.

Systems sizing and integration

Beyond heat pump sizing, their integration in the building is also important. For the scenarios with ductless systems, the heat pump is assumed to be installed in the stairwell, serving only the two above-ground floors according to an assumed airflow distribution. Therefore, the heating and cooling design loads for Halifax and Montreal are calculated for this target zone only and exclude the basement. For the split unit integration, for all four sizing approaches, auxiliary heating is provided by electric baseboard heaters (same as in the base case scenarios). All ductless systems are modelled as single-split units (single indoor head) due to availability of the detailed test data required for the data-driven approach used in this study. While a multi-split unit (multiple indoor heads) is a more likely choice for larger capacities (i.e., >2 tons), these systems exhibit distinct performance characteristics that would require further modelling assumptions and introduce a greater degree of uncertainty into the analysis. A multi-split HP model based on additional testing will be the subject of future work.

Table 4: Summary of VCHP systems parameters for each sizing option

Scenario	Halifax	Montreal	Vancouver	Winnipeg
Target Loads	Htg: 13.3 kW (at -16°C) Htg: 10.8 kW (at -8.3°C) Clg: 5.2-8.1 kW	Htg: 14.3 kW (at -23°C) Htg: 8.4 kW (at -8.3°C) Clg: 6.1-9.5 kW	Htg: 11.7 kW (at -7°C) Clg: 4.6-7.3 kW	Htg: 17.4 kW (at -33°C) Htg: 8.5 kW (at -8.3°C) Clg: 6.2-9.6 kW
Option A	1.5 ton split VCHP COP = 4.2/4.1*	2 ton split VCHP COP = 3.8/3.5*	2 ton central VCHP - Hybrid COP = 3.9/3.7* BPT = 3.3°C	2 ton central VCHP - Hybrid COP = 3.9/3.7* BPT = -0.6°C
Option B	2 ton split VCHP COP = 3.8/3.5*	2.5 ton split VCHP COP = 3.1/3.9*	3 ton central VCHP - Hybrid COP = 4.1/4.1* BPT = -3.3°C	3 ton central VCHP - Hybrid COP = 4.1/4.1* BPT = -8.3°C
Option C	4 ton split VCHP COP = 4.0/3.8*	3.5 ton split VCHP COP = 2.7/3.7*	N/A	3 ton central VCHP COP = 4.1/4.1*
Option D	N/A	N/A	4 ton central VCHP COP = 3.8/3.9*	N/A

*At AHRI rating conditions (Cooling/Heating)

For the scenarios with centrally-ducted systems, the heat pump integration varies with the sizing option. In Options A and B, the heat pump is sized with an emphasis on cooling, so it is likely that homes will integrate the VCHP with their existing forced air furnace. This combined system is commonly known as a hybrid system, and represents a pathway to support greater heat pump adoption in markets with predominantly natural gas or other fossil fuel-based heating.

Hybrid systems operate using a switchover temperature, which defines when the heat pump or furnace operates. Above the switchover temperature, the heat pump is used as the *sole* heating source. Below the switchover temperature, the heat pump is turned off and the furnace covers the entire heating needs of the building. In this paper, switching is based on the balance point temperature (BPT), the temperature at which the HP rated capacity intersects the building heating load line.

When the VCHP is in use, auxiliary heating is provided by an electric duct heater, activated during defrost cycles to prevent excessive cooling of the space and as backup when the heat pump cannot meet the load or stops operating below its cut-off temperature. Since Options C and D target the heating loads, these cases assume that the natural gas furnace system is completely replaced by a VCHP (with auxiliary electric heating as described above).

Table 4 presents the target design loads, as well as the parameters for the selected VCHP by city and sizing option. Design loads have been calculated using a CSA F280-12 load analysis (CSA, 2018), with heating loads reported with a 30% oversizing factors as was typical past industry practice (CSA F280 M90, CSA 2009). The tabulated cooling loads correspond to the 80%-125% target cooling capacity range as recommended in the *Guide*. Option C was not simulated in Vancouver since the heating design temperature is higher than -8.3°C. Option D was not simulated in Halifax, Montreal nor Winnipeg, because no commercially available residential units could provide the required capacity at their low heating design temperatures (-16°C, -23°C and -33°C, respectively).

Results

To assess the energy savings potential of each sizing option, annual system simulations were performed in TRNSYS v.17 using the appropriate CWEC weather file and a 2.5-minute time step to more accurately represent system controls.

Annual energy performance in ductless systems

Table 5 summarizes energy performance for the ductless heat pump integrations in Halifax and Montreal. In general, all heat pump systems offer substantial reductions in heating energy use regardless of the sizing option, with greater energy savings in Halifax due to the warmer climate. A closer analysis reveals that total heating energy use reductions are limited somewhat by the method of heat pump integration. In both cities, the ductless heat pump serves only the first two floors of the home, with the basement heated solely using auxiliary electric baseboards (Elec. BB). Examining system performance for the first and second floors only (*target zone* served directly by the heat pump), it is evident that each heat pump system offers more substantial savings, with maximum heating and cooling energy use reductions reaching 42% in Halifax and 33% in Montreal. Cooling energy use is reduced considerably for all heat pump cases, primarily due to improved operating COPs and higher associated sensible heat factors (SHF, ratio sensible to total cooling capacity). As would be expected, each heat pump integration offers utility cost savings, primarily because the unit is displacing a less efficient auxiliary system (electric baseboards) using the same energy source.

It is important to note the impact that system sizing can have on energy performance. Results indicate that larger heat pump systems may increase heating and cooling energy use, with Option A providing the best energy performance in Halifax and Option B in Montreal. This trend is somewhat counterintuitive, and requires a closer examination of the operating performance for each heat pump system. Table 5 shows that larger heat pump systems have little impact on reducing the auxiliary energy use of the first and second floors, and can actually result in an increase in the use of the baseboards to compensate for a more significant cooling of the space during reverse-cycle defrost.

Larger heat pump systems (in this simulated case) appear to provide little energy savings benefit at colder conditions while also having a reduced ability to modulate to meet lower building loads during milder days, resulting in inefficient cycling. This is confirmed through an analysis of heat pump operations, which shows for Halifax that the 1.5 ton VCHP in Option A operates 90% more over the heating season (3,600 hrs vs. 1,900 hrs), while undergoing 80% less on/off cycles vs. the Option C 4 ton system.

Frequent cycling due to equipment oversizing can have a significant impact on system energy use. Figure 2 summarizes the average operating COP of each sizing option by outdoor temperature bin for Montreal. Readers may note that these values differ from those in Table 4, since the values in this figure are for temperatures other than AHRI rating conditions, and also include performance degradations due to cycling (AHRI COPs are steady state).

Frequent cycling associated with the larger heat pump in Option C leads to a significant degradation of operating COPs. This is particularly noticeable for temperatures -5°C to +10°C, with this temperature range comprising 44% and 53% of the heat pump operating time for Options C and A, respectively.

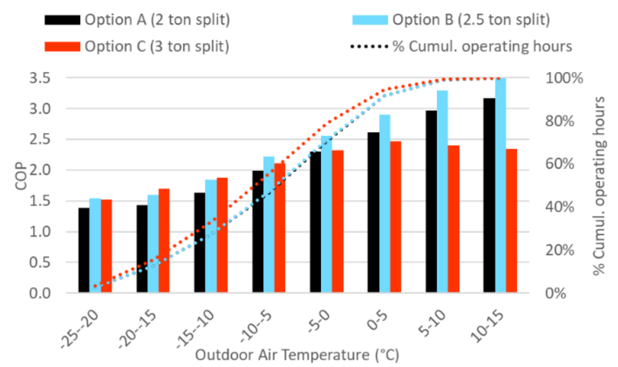


Figure 2: Average heating COP (excl. defrost) in Montreal

Table 5: Annual energy performance in Halifax and Montreal (split system)

	Halifax				Montreal			
End Use	**Base Case**	**Option A**	**Option B**	**Option C**	**Base Case**	**Option A**	**Option B**	**Option C**
Heating (kWh)	20,800	11,660	12,670	14,780	23,690	16,210	15,510	16,720
Heat pump	-	6,870	8,110	10,000	-	9,280	8,580	9,920
Aux: Elec. BB (1st & 2nd)	16,930	760	520	700	17,990	1,050	1,070	930
Other: Elec. BB Basement + HRV Elec. Duct Heater	3,870	4,030	4,040	4,080	5,690	5,870	5,860	5,870
Cooling (kWh)	550	340	410	510	1,080	770	930	1,020
Fans (kWh)	470	700	680	730	30	250	290	360
DHW (kWh)	4,580	4,580	4,580	4,580	4,630	4,630	4,630	4,630
Light/Equip (kWh)	9,520	9,520	9,520	9,520	9,520	9,520	9,520	9,520
Total (kWh)	35,930	26,800	27,860	30,130	38,950	31,380	30,880	32,250
Total Savings (kWh)	-	9,130	8,070	5,800	-	7,570	8,070	6,700
HVAC Savings (%)	-	42%	37%	27%	-	31%	33%	27%
Total Utility Cost	$5,610	$4,180	$4,350	$4,700	$3,130	$2,440	$2,390	$2,520
Utility Cost Savings	-	$1,430	$1,260	$910	-	$690	$740	$610
% heat load met by HP (1st & 2nd)	-	95%	97%	96%	-	94%	94%	95%

Annual energy performance in ducted systems

Table 6 summarizes the energy performance of each sizing option for the centrally-ducted systems in Winnipeg and Vancouver. Auxiliary energy use here refers to both electrical resistance heating during defrost, and the energy required to supplement VCHP operations during colder periods when its capacity is insufficient. Maximum heating energy savings are more significant than for the ductless cases, primarily because (i) the heat pump is now providing heating to all three levels of the home, and (ii) the heat pump displaces the use of a natural gas furnace with a lower efficiency (78% AFUE furnace vs. 100% Elec. BB efficiency). The largest savings are obtained in Vancouver, as the milder climate allows the heat pump to meet a larger percentage of total heating demand while also operating at a higher efficiency. Savings are lower for Winnipeg due to its colder climate: the design temperature being much below than the VCHP cut-off temperature, auxiliary heating is relied on to cover a larger portion of the heating load over the year. Significant cooling energy use reductions are also evident in all cases, driven by the improved operating COPs. Maximum energy savings for the ducted systems are obtained with Option B in Vancouver and Option C in Winnipeg. Options C and D are sized to meet a larger percentage of the building heating load, and also operate with a control strategy that prioritizes heat pump operation at ambient temperatures down to the heat pump cut-off temperature (-23°C). In general, Options A and B provide lower heating energy savings as these hybrid system integrations shift to the natural gas furnace below the BPT, reducing the number of hours the heat pump can operate.

Table 6: Annual energy performance in Vancouver and Winnipeg (central system)

	Vancouver				Winnipeg			
End Use	**Base Case**	**Option A**	**Option B**	**Option D**	**Base Case**	**Option A**	**Option B**	**Option C**
Heating (kWh)	30,950	15,140	5,410	5,890	37,680	29,770	25,900	15,510
Heat pump	-	2,880	4,960	5,630	-	2,180	3,320	8,260
Aux: Elec. Duct Heater	-	40	180	260	-	190	250	7,250
Furnace	30,950	12,220	270	-	37,680	27,400	22,330	-
Cooling (kWh)	420	200	210	250	970	520	500	490
Fans (kWh)	450	720	1,100	1,100	660	780	960	1,360
DHW (kWh)	5,310	5,320	5,320	5,330	6,680	6,690	6,690	6,690
Light/Equip (kWh)	9,520	9,520	9,520	9,520	9,520	9,520	9,520	9,520
Total (kWh)	46,650	30,900	21,560	22,080	55,510	47,280	43,570	33,580
Total Savings (kWh)	-	15,750	25,090	24,570	-	8,230	11,940	21,930
HVAC Savings (%)	-	50%	79%	77%	-	21%	30%	56%
Total Utility Costs	$2,030	$1,950	$1,990	$2,100	$1,940	$1,880	$1,890	$2,440
Utility Savings	-	$80	$40	-$70	-	$50	$50	-$500
% heat load met by HP	-	57%	98%	99%	-	24%	37%	72%

Focussing on Options A and B, several key points of interest can be noted. First, the energy savings with these hybrid systems are highly dependent on the fraction of total heating above the balance point temperature. In Vancouver, increasing the heat pump size from Option A to Option B shifts the balance point temperature from +3°C to -3°C. This apparently small shift reduces heating energy use by over 50%, primarily because the heat pump is able to increase the fraction of total heating it provides to the building (98% for Option B vs. 57% for Option A). These impacts are especially pronounced in Vancouver due to the milder climate, with the balance point for Option B approaching the local design temperature of -7°C. This justifies why, in Vancouver, Option B offers more energy savings than Option D. The heat pump in Option B in Vancouver covers almost all building heating loads, but, since the heat pump is smaller than in Option D (3 ton in Option B vs. 4 ton in Option D), it cycles 30% less.

Despite improved energy performance, some ducted heat pump systems result in an increase in annual utility costs, as the electrically-driven heat pump is now displacing less expensive natural gas heating. In Vancouver for example, electricity is upwards of 3.5 times more expensive per unit of energy vs. natural gas, meaning that the heat pump must operate with a seasonal COP greater than 3.5 to achieve *any* utility cost savings. New developments in hybrid heat pump/natural gas systems have examined the use of an economic switchover temperature, where switching between heat pump and furnace operations is dependent on energy prices instead of the balance point temperature used in the current analysis. This method can also be extended to include time of use structures typical in some regions, and can be an effective method of introducing heat pumps into more challenging Canadian markets. The use of the economic switchover is explored in a subsequent section. Alternatively, should all space and water heating be accomplished using electrically-driven systems (HP + elec. auxiliary for space heating, HP water heater or elec. resistance for DHW), additional utility cost savings may be possible by eliminating gas connection fees.

Readers may note the strong variation in fan energy use by city and sizing option, which primarily relates to differences in operating hours and airflows between the heat pump and base case furnace and AC. In general, heat pump systems tend to deliver a greater volume of air at a lower temperature vs. a conventional furnace system. Assuming a constant specific fan energy use (i.e., 0.3 W/CFM (Ueno, 2010)), this can have a significant impact on fan energy use, particularly when the heat pump is designed to cover a greater portion of the heating load. Using Winnipeg as an example, fan energy use is highest for Option C, as the heat pump is sized for a large portion of the building heating load. Fan energy use decreases for Option A and Option B, as the heat pump now covers a smaller portion of heating demand, with reduced airflows compared to the furnace.

Modelling Limitations

Some limitations exist in the modelling methodology employed in this study. First, for ductless systems, practical integrations are more likely to incorporate a multi-split system. With this type of integration, thermal energy from the heat pump system can be directly distributed to specific indoor spaces, rather than via an assumed airflow distribution as is done in the current model. This integration variant is also likely to change the loading on the heat pump, as heating/cooling will now be provided according to multiple thermostats distributed in the different indoor units, rather than tracking the temperature of only one space.

The current model also assumes single air nodes in each of the basement, first and second floors. This is sufficient in the present approach, as many heat pumps are controlled using a central thermostat that ideally represents the average temperature of a space. However, zonal approaches to control are likely to yield further energy savings, as reduced demand in some spaces may lessen the thermal loads on the heat pump. Building energy models with further refinement in thermal zoning are under development to capture this aspect.

Sensitivity Analysis

Oversizing a system can negatively impact overall efficiencies. With this in mind, it is important to recognize several factors that may contribute to oversizing.

Building Load Oversizing Factors. In this study, building loads were calculated using the CSA F280-12 procedure, along with an additional oversizing factor of 30% in heating. The oversizing implications resulting from the 30% safety factor can be significant, including reduced energy performance and increased capital and maintenance costs. The recent CSA F280-12 outlines the importance of right sizing systems, without oversizing factors.

Rated vs. Maximum Capacity. Typically, manufacturers provide performance data for a rated compressor speed. However, rated performance may not be equal to the maximum capacity of the unit, leading to unintended oversizing. An accurate estimate of the performance of variable capacity units is critical to maximize their energy savings potential, and drives a number of new standards including CSA EXP07 (CSA, 2020). In this study, the rated performance was used for all sizing selection, as what may be typically done by designers.

Two sensitivity analyses examine the above points:

SA1: Analysis of Oversizing Factor

In this case, the analysis is redone without the 30% heating load oversizing factor used in the original analysis. Removing the oversizing factor allows for a reduction in required heat pump size, with results for Montreal summarized in Table 7. Option C, for example, now requires a 3 ton heat pump (vs. the 3.5 ton originally specified). Interestingly, the impact on annual energy use is minimal. However, a closer examination of heat pump performance reveals that the new system greatly reduces heat pump cycling, which may potentially lead to longer system life, and improved thermal comfort during milder conditions. Associated reductions in capital costs are also a benefit to be considered.

Without the oversizing factor, it is also possible to find a market-available heat pump that meets the Option D requirements. However, simulation results show that this option may not be ideal in this particular case, as increased heat pump cycling appears to degrade energy performance.

SA2: Rated vs. Maximum Capacity

In this sensitivity analysis, performance at maximum (rather than rated) speed is used for system selection. The 30% oversizing factor from the main analysis is still applicable. Extensive testing of the ductless heat pump (St. Onge, 2018) used in this analysis reveals that the maximum heating capacity of the unit is approximately 1.6 times the rated value. This can have important implications for sizing as summarized in Table 7 for Montreal.

Sizing under SA2 results in a downsizing of the selected unit, even versus the SA1 analysis above. Option C can now be met using a 2.5 ton heat pump, allowing for a 1,300 kWh reduction in annual energy use while also minimizing system cycling and its associated maintenance and comfort impacts. Much like for SA1, it is also now possible to select a VCHP unit meeting Option D requirements. However, while a smaller heat pump can be used vs. SA1, the system still has reduced energy performance due to more frequent cycling.

Uncertainty regarding manufacturer-supplied data can potentially yield oversized systems that are more costly to both purchase and operate. This underscores the need for a clear, standardized approach to transfer performance data from equipment manufacturers to those using the data for simulation or sizing purposes. Many initiatives are underway including ASHRAE Standard 205 (ASHRAE, 2020), and provide a necessary link between detailed testing work and the application of this data in building simulation.

A Note on Economic Balance Point Controls

Heat pump integrations in central systems may benefit from an alternative switchover temperature, where the system switches between the heat pump and backup system to operate in the most economically profitable way. The transition point is then known as the *economic balance point*, and depends on utility rates (electricity and auxiliary fuel), heat pump COP and backup system (furnace in this case) efficiency. Additional simulations under this control strategy in Winnipeg and Vancouver resulted in greater energy use, as low natural gas rates (vs. electricity) meant that systems transitioned earlier to using a furnace. However, time of use rates (not examined here) could make heat pump use attractive during off-peak periods, increasing energy savings vs. furnaces while also (potentially) offering GHG reductions depending on grid carbon content.

Table 7: VCHP selection and simulation results for SA1 and SA2 for Montreal

	Option C	**Option C SA1**	**Option C SA2**	**Option D**	**Option D SA1**	**Option D SA2**
Target Heating Capacity (BTU/h	28610*	22010**	28610*	46180+	35530++	46180+
VCHP Sizing Selection	3.5 ton	3 ton	2.5 ton	N/A	5 ton	4 ton
Total Annual Energy Use (kWh)	32,250	32,230	30,880	N/A	35,010	32,590

*at -8.3°C, no oversizing factor; **at -8.3°C, with 30% oversizing factor

+at -23°C, no oversizing factor; ++at -23°C, with 30% oversizing factor

Conclusion

This paper presents a simulation-based assessment of the energy performance impacts of various air-source heat pump sizing approaches. Detailed models of single-family housing were first developed in four Canadian cities (Halifax, Montreal, Vancouver and Winnipeg) based on typical regional construction parameters. Using an improved VCHP model that better captures the impacts of key transients (cycling, defrost), four different heat pump sizing methods were then examined, ranging from cooling-driven selections to those based on covering the entire heating loads of the building. Results demonstrate the strong energy savings potential of heat pumps, and the performance pitfalls of oversizing. For ductless heat pump cases (Halifax, Montreal), larger heat pump sizes showed slightly reduced energy performance, driven by reduced operating COPs caused by more frequent on/off cycling. For ducted heat pump systems (Vancouver, Winnipeg), results show that energy savings increased as the heat pump was sized for a greater portion of the heating load, primarily because the ASHP is displacing the use of a less efficient natural gas furnace. A deeper analysis of the results also revealed the sensitivity of hybrid furnace/heat pump systems to the selection of the switchover temperature used for system control.

The current study represents an initial analysis regarding the energy performance impacts of heat pump sizing. Future work will explore peak demand implications and the impact of thermal zoning and other modelling assumptions.

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