Application of air-source heat pump (ASHP) technology for residential buildings in Canada

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Abstract. The air-source heat pump (ASHP) is a relatively new, highly efficient technology which has been proven to be a feasible alternative in mild temperature climates. However, an ASHP’s application tends to be limited by outdoor temperature in cold climate zones. This study was intended to explore the feasibility of ASHPs in conjunction with traditional furnaces to serve as an innovative energy-efficient method for heating homes in Canada. The goal was to quantify the cost and emissions savings of an ASHP hybrid heating system as compared with a furnace-only system for a residence in three Canadian cities. A prototypical residential building with a hybrid heating system was generated for heating load calculations. The theoretical analysis included the determination of the outdoor-temperature-dependent heat loss rate from the residence and heat supply rate of ASHPs. The building model has proved to be useful for further analyses, while the feasibility of the hybrid system has been determined to be highly region-dependent.

1. Introduction
Residential heating accounts for 17% of Canada’s Secondary Energy Use [1]. As such, there is a drive for more energy-efficient heating systems and heating systems that utilize sustainable energy. Air source heat pump (ASHP) technology has proved to be a very common heating system that is already being utilized in many places around the globe. Some studies have already shown the capability of ASHP to be beneficial in mild climate homes, such as New England [2] and Halifax [3]. However, the capacity of a heat pump operating in heating mode is dependent on the outdoor temperature and humidity, which tend to significantly limit the heating capacity of a heat pump. There have been notable issues that arise when outdoor temperatures reach extremely low temperatures [4].

In most Canadian homes, natural gas furnaces are used to provide heating, as that is currently the most reliable and inexpensive source of energy. Although natural gas furnaces have become extremely efficient, they still possess greenhouse gas (GHG) emission issues. Thus, an alternative heating method for the residential sector is desired. It is hypothesized that an ASHP will be able to meet the heating requirement for a fraction of the heating season, and when the outdoor conditions become more severe, the heat pump can be shut off, and the furnace will be turned on to fulfill the heat load for the rest of the season. While this makes the mechanical system of a residence more complex and start-up costs are higher, there is a long-term benefit expected, especially in the realm of reducing GHG emissions.

The goal was to evaluate the thermal requirement of a typical Canadian residence characterized by a model building, for three major cities in the country and to compare required energy with the heating supply performance of a group of commercially available heat pumps. Additionally, the seasonal operating cost and emissions performance of a hybrid ASHP-furnace heating system were assessed, which were contrasted to ones of a traditional furnace-only heating system.
2. Methodology

2.1 Heating Load Analysis
The governing piece of literature surrounding the energy performance of buildings in Canada is the National Energy Code for Buildings (NECB 2017), which documents that the analysis procedures are followed with the 2017 ASHRAE Fundamentals Handbook. These documents specify that transmission, infiltration, and ventilation make up the main components of heat loss from a residential building and clearly illustrate the equations, charts, and tables that pertain to each component.

2.2 Building Model
The model residential building was designed using a collection of parameters necessary for heat loss and economic analysis for the conditioned floor area, number of bedrooms and infiltration flowrates for the infiltration and ventilation heat loss calculations. The values for the U-factors of the envelope, infiltration coefficients (0.2 L/s·m² for opaque assemblies and 0.5 L/s·m² for fenestration and doors), and the fenestration-and-door-to-wall-area ratio (32%-40% depending on the region in consideration) were taken from the tables and charts outlines in the prescriptive path of compliance in the NECB. The remaining parameters of the residence were determined by referring to the Canadian Single-Detached and Double/Row Housing Database (CSDDRD), generated by Swan et. Al. [5], which has proved useful to other studies based on Canadian residential homes [6]. Statistical analysis (sample size = 11,857 homes) yielded the average values shown in Table 1, representative of a standard Canadian single-family detached home that is either one-, two-, or three- storey tall, including a basement.

### Table 1. Average quantities of building parameters taken from statistical analysis of the CSDDRD.

| Component                                   | Mean  | Std. Dev. | 15\textsuperscript{th} Per. | 85\textsuperscript{th} Per. |
|-----------------------------------|-------|-----------|-----------------------------|-----------------------------|
| Conditioned Floor Area (m\textsuperscript{2}) | 127.8 | 48.3      | 79.4                        | 175.7                       |
| Gross Wall Area (m\textsuperscript{2})    | 138.1 | 49.0      | 89.5                        | 187.4                       |
| Fenestration and Door Area-Vancouver/Toronto (m\textsuperscript{2}) | 55.4  | 19.6      | 35.8                        | 75.0                        |
| Fenestration and Door Area-Edmonton (m\textsuperscript{2}) | 44.3  | 15.7      | 28.6                        | 60.0                        |
| Ceiling Area (m\textsuperscript{2})       | 89.3  | 39.1      | 50.2                        | 128.4                       |
| Basement Wall Area (m\textsuperscript{2})  | 92.4  | 22.0      | 70.4                        | 114.4                       |
| Basement Floor Area (m\textsuperscript{2}) | 91.7  | 28.1      | 63.6                        | 119.8                       |
| Number of Occupants                    | 3     | 1         | 2                           | 4                           |

2.3 Region Selection
Table 2 shows the values required for heat loss and economic analysis for three major Canadian cities, obtained from ASHRAE weather documentation and other related resources. These cities were chosen because they represent populous regions with distinctly different climate conditions.

### Table 2. Canadian cities used for analysis.

| Location               | Vancouver, BC | Toronto, ON | Edmonton, AB |
|------------------------|----------------|-------------|--------------|
| Zone                   | Zone 4         | Zone 5      | Zone 7A      |
| Heating Outdoor Design | -6.1 °C        | -16.4 °C    | -28.9 °C     |
| Temperature            |                |             |              |
| Above-Grade Walls U-Factor | 0.315     | 0.278       | 0.21         |
| Above-Grade Roofs U-Factor | 0.227    | 0.183       | 0.162        |
| Below-Grade Walls U-Factor | 0.568     | 0.379       | 0.284        |
| Below-Grade Floors U-Factor | 0.757    | 0.757       | 0.757        |
| Fenestration and Doors U-Factor | 2.4      | 2.2         | 2.2          |
Natural Gas Utility Rate [7][8][9] $2.49 \pm 1.05 \text{ per GJ}$ $4.49 \pm 2.0 \text{ per GJ}$ $2.05 \pm 0.65 \text{ per GJ}$
Electricity Utility Rate [10] 10.6 ± 0.6₵ per kWh $9.5 \pm 2.0$ ₵ per kWh $3.47 \pm 2.3$ ₵ per kWh
Electricity Emission Factor [11] $11 \pm 2$ gCO$_2$/kWh $70 \pm 35$ gCO$_2$/kWh $938 \pm 40$ gCO$_2$/kWh
Natural Gas Emission Factor [11] $1926 \pm 75$ gCO$_2$/m$^3$ $1888 \pm 73$ gCO$_2$/m$^3$ $1928 \pm 75$ gCO$_2$/m$^3$

2.4 Housing Model Validation
In order to verify the results predicted by the housing model, a numerical simulation was conducted using EnergyPlus. A model house was constructed using the above-mentioned parameters in the standard procedures for prototypical house development outlined in ASHRAE Standard 90.2-2018. The residence was a 2-storey, square home with a basement and a flat ceiling. The fenestration was represented by two rectangular units (with varying U-factors depending on the region) on each side of the house. EnergyPlus weather files for each of the locations were used in the simulation of the residence in each climate zone.

In addition to the numerical results for each city, a case study was conducted in Edmonton. The project is an upcoming net-zero ready townhome unit to be constructed by a local home builder, which will feature technologies that exceed the minimum requirements of the National Energy Code such as high-insulating, low-leakage envelope and a high-velocity ventilation system. This case helps provide a sense of potential in utilizing ASHP for residential heating in the future.

2.5 HVAC system Characteristics
As part of the study to determine the feasibility of applying a hybrid heating system in the residential homes of Canadian regions, a series of cold climate commercially available ASHPs and furnaces were selected. Tables 3 and 4 show a summary of the performance data of three heat pumps and three furnaces.

| Heat Pump A | Heat Pump B | Heat Pump C |
|-------------|-------------|-------------|
| Rated Heating Capacity @ 8°C | 12 kW | 7 kW | 16 kW |
| Operating Temperature Range | -35°C – | -20°C – | -13°C – |
| Temperature Range | 15°C | 18°C | 30°C |

| Furnace A | Furnace B | Furnace C |
|-----------|-----------|-----------|
| Furnace Type | Condensing | Condensing | Non-condensing |
| Efficiency | 97% | 92% | 80% |

2.6 Economic and Emissions Analysis of Heating Systems
As outlined in 2017 ASHRAE Fundamentals, the seasonal costs and GHG emissions associated with heating the residence by the hybrid heating system were determined. The most feasible heat pump, as determined by thermal balance analysis, was evaluated for the temperatures within its operating range. Outside of the operating temperatures, the two metrics associated with supplementing the residence with a natural gas furnace were calculated. The sum of these results represents the total seasonal cost and emissions of heating the home with the hybrid heating system. The alternative was a furnace-only heating system, in which the furnace was used as the only source of heating throughout the entire year. The utility costs and emission factors used in this analysis were included for each city in Table 2, and uncertainty analysis was included due to the variability of utility costs and electricity generation emissions over the last four years.
3. Results and Discussion

3.1 Thermal Balance

Figures 1-3 show the rate of energy loss from the prototypical residence; as a range within one standard deviation as found from the statistical analysis of the CSDDRD, for the winter temperature range of each of the three locations, and maximum heating rate that each of the three heat pumps can provide. The intersection points between the ‘mean’ residence heat loss curve and the heat pump operation curves represent the thermal balance point; the temperature below which the heat pump is physically unable to supply heat to the interior space quickly enough to overcome the rate of energy loss from the residence. This means that supplemental heat is required below this temperature from furnace heating. The closer the thermal balance point is to the heating design temperature of the specific region, the greater the potential for utilizing an ASHP for residential heating in this region. It is evident that the energy requirement of the residence varies drastically throughout the different climate zones of Canada.

The city of Vancouver shows great potential for the utilization of ASHP technology in residential heating (Figure 1) due to its mild winter temperatures, which are fully encompassed by the proposed commercial heat pump models; proving that local conditions pose no threat of mid-winter shut-off. In addition, the thermal balance point of heat pumps A and C, are relatively low or non-existent, meaning that very little supplemental heating will be necessary.

Figure 2 shows the results for Toronto, Ontario, where it represents the moderate climate in the central region of Canada. The performance of a commercially available ASHP, even the most high-capacity model heat pump, becomes limited for significant portions of the heating season, showing a need for supplementary heating devices in these regions.

![Figure 1. Energy loss and heat supply rate results for Vancouver, BC](image1.png)

A similar case exists in Edmonton, Alberta where winter tends to be noticeably harsh. It is obvious from Figure 3 that a standard Edmonton home based on the housing model would struggle to achieve enough output from the heat pumps proposed. However, if future homes continue to be built to stricter requirements; similar to the upcoming local project, heat pump heating systems can be expected to become significantly more viable.

![Figure 2. Energy loss and heat supply rate results for Toronto, ON.](image2.png)
3.2 Economic Feasibility

Figure 4 shows the economic and CO₂ emissions results for Edmonton with varying furnace models, which indicates that a higher efficiency condensing furnace has lower overall emissions and annual operating costs. Thus, furnace A was selected for this hybrid heating system. Figure 5 shows the seasonal cost of operating the hybrid heating system using a combination of Heat Pump C and natural gas furnace A in the model residence over a single winter period in each city. In general, the price of natural gas is lower than that of electricity, so a longer operation period for the heat pump results in higher costs overall. This is especially true in Vancouver, where the heat pump can operate all winter, which also means the emissions are virtually non-existent due to the popularity of hydroelectric systems [12]. Thus, the ASHP, alone, is a fully viable and environmentally friendly, yet expensive alternative as an independent heating source. In Toronto, although the hybrid system is still costly to operate, it shows a reduction in CO₂ emissions; making the hybrid system applicable. Finally, Edmonton presents unfavorable results. The emissions associated with the hybrid heating system outweigh those of the traditional system due to the reliance on coal-fired power plants [12]. Moreover, the cost savings of the hybrid system are still non-existent; despite being relatively cheaper overall. The results indicate that, presently, Edmonton shows the lowest feasibility for application of the hybrid heating system by every metric. This system will have greater potential if future socio-economic and political factors force Alberta’s coal-fired power plants to be phased out and replaced with renewable energy sources [13].

4. Conclusion

Renewable electricity-driven-ASHP technology can potentially serve as a sustainable solution to supply heating to homes for our society’s decarbonization purpose. A techno-economic study was conducted to provide a preliminary assessment of the feasibility of utilizing an ASHP-furnace hybrid heating system in Canada. From heat loss, economic, and emissions analysis of a prototypical residence, it was found that Vancouver has the highest potential for applicability of this system due to its mild outdoor temperatures and renewable electricity generation systems. To a lesser extent, the same trend was found...
for Toronto, Ontario. On the contrary, the city of Edmonton showed the lowest potential for application due to its harsh winter season and high GHG emissions from non-renewable electricity generation. In addition, the building model proposed in this project can be used to predict the geographically-dependent energy loss of other types of homes, as well as the energy performance of Canadian residential buildings incorporated with advanced energy-saving technologies in the future.

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