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Techno-Economic Assessment of Dual-Source Heat Pump Systems: Borehole Size Reduction and Life-Cycle Cost Analysis Across Three Cities in Canada

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Abstract— Dual-source heat pumps (DSHPs) mitigate high upfront costs of ground-source heat pump (GSHPs) systems by dynamically switching between air and ground sources. This study evaluates DSHP performance and economic feasibility across three Canadian cities (Edmonton, Toronto, and Montreal) through semi-analytical dynamic simulations of DSHP system and life-cycle cost analysis. Lowering the outdoor air temperature set points (0°C, -5°C, -10°C) —above which the heat pump operates in air-source mode and below which it switches to ground-source mode during heating mode—reduces borehole lengths by 4.5–42%, with Toronto achieving the highest savings (42% borehole reduction, 24% capital cost reduction, and 14% net present value (NPV) of costs reduction at -10°C) due to milder climate.

Keywords: Dual-source heat pump, Ground-source heat pump, Borehole size reduction, Life-cycle cost analysis

I. Introduction

Ground-source heat pump (GSHP) systems leverage stable subsurface temperatures for efficient heating and cooling, offering significant emission reductions in cold climates when electricity grids are sufficiently decarbonized [1]. For instance, in heating mode, GSHPs with a coefficient of performance (COP) of 4 outperform natural gas furnaces at electricity carbon intensities below 760 t/GWh [1]. Despite their environmental benefits, high upfront costs—driven by borehole drilling, loop installation, and grouting—limit their widespread adoption [2].

Hybrid ground-source heat pump (HGSHP) systems address these economic barriers by integrating auxiliary heat/sink sources and systems, to reduce borehole length requirements and lifecycle costs [3]. Dual-source heat pumps (DSHPs), a subset of HGSHPs, dynamically switch between air and ground sources, achieving 15–55% reductions in borehole lengths compared to conventional GSHPs in temperate climates [4]. Studies in Northern Italy (Bologna) demonstrate additional benefits, including mitigated ground temperature imbalances and up to 50% lower environmental impacts when electricity generation relies heavily on renewable sources [4,5]. However, existing research is focused on mild-to-moderate climates, leaving critical gaps in understanding DSHP viability in regions with extremely cold climates such as Canada, where air temperature in the winter drops below −20°C. Furthermore, earlier work [4,5] utilized a static, rule-of-thumb approach for borehole sizing—dividing the building's peak heating load by a fixed heat extraction rate and ignoring the ground temperature variation that impact borehole size. In addition, prior research has commonly employed the Duct Heat Storage (DST) model in TRNSYS [4,5] for simulating ground heat exchangers (GHEs), relying on precomputed g-functions and fixed borehole layouts.

To address the abovementioned shortcomings of the assessment of DSHPs cost, the GHE model used in this study, proposed by Laferrière et al. [6], captures short-term transient dynamics within the borehole with a corrected g-function method, thereby supporting arbitrary configurations and variable time steps. In addition, this study refines the design method used in the past studies of DSHP by establishing an optimal entering liquid temperature (ELT) range for the heat pump (based on ASHRAE guidelines [7]). Dynamic simulations over a 20-year period are performed, with iterative adjustments to borehole length to ensure the ELT remains within the optimal range while minimizing borehole size. With such design and modelling refinements in assessment of DSHPs, this study evaluates the technical feasibility, potential of borehole design length reduction, and lifecycle costs of DSHPs in three Canadian cities—Edmonton, Toronto, and Montreal—that experience very cold climates. By analyzing performance of DSHP systems under severe outdoor air thermal constraints the trade-offs between upfront cost savings and operational efficiency are quantified, thereby advancing DSHP deployment for decarbonizing cold-climate heating systems.

II. Methodology

A dual-source heat pump (DSHP) system integrates air and ground heat exchange to provide a more efficient heating and cooling solution than air-source heat pumps while requiring lower capital investment than ground-source heat pump (GSHP) systems (Fig. 1). The ground-source component employs a ground heat exchanger (GHE), typically consisting of subsurface boreholes containing U-tube pipes filled with a fluid (commonly a water-antifreeze mixture), with grout filling the space between the pipes and surrounding ground. The GHE facilitates heat exchange between the heat pump and the ground, using it as a heat sink in cooling mode and a heat source in heating mode. The thermal interaction between the system and the ground is characterized by the ground thermal load, which represents the amount of heat extracted from or rejected to the ground over time, impacting subsurface temperature. Because borehole length is designed based on the fluid temperature entering the heat pump unit and exiting the GHE (Point 13 in cooling mode or Point 14 in heating mode as shown in Fig. 1)—referred to as the entering liquid temperature (ELT)—which is directly affected by ground temperature, excessive ground temperature rise or drop necessitates a longer borehole length to maintain efficient system performance. An outdoor air temperature set point can be implemented to automatically switch between air- and ground-source modes. This strategy reduces the thermal load on the ground, mitigates excessive heat extraction in cold areas such as Canada, and minimizes the risk of long-term ground temperature drop. Consequently, the required borehole length for the GHE is reduced.

A semi-analytical dynamic simulation model of a DSHP system was developed in OpenModelica to assess the techno-economic performance of DSHP systems across the three Canadian cities with different climates. This model allows for the analysis of how key system parameters—such as GHE running fluid temperature, heat pump capacity, input power, and coefficient of performance (COP)—change over time, reflecting the transient nature of the DSHP operation. This capability to capture time-dependent variations is what defines the model as "dynamic." The methodology couples technical performance analysis with a life-cycle cost assessment (LCCA) to evaluate the impact of air/ground switching temperature set points on both borehole sizing and economic viability.

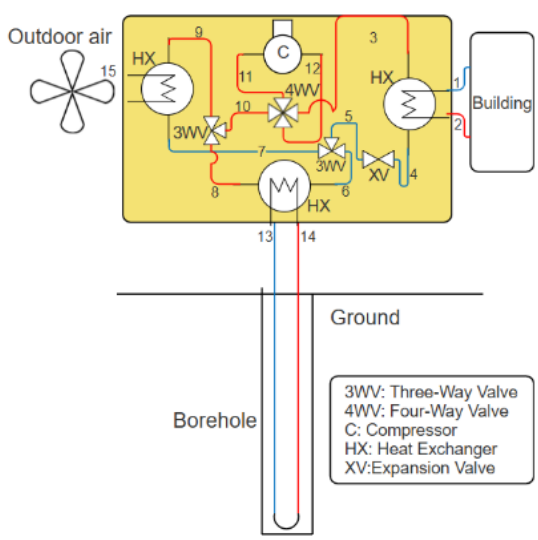


Figure 1. Schematic of a dual-source heat pump system [4].

A. Heat Pump Model

The dual-source heat pump in this study is a three-speed inverter-driven system that adjusts its operating frequency (30, 70, or 110 Hz) to efficiently meet the heating and cooling demand of the building. As illustrated in Fig. 1, the system consists of three heat exchangers: one connected to a ground heat exchanger (GHE), another to outdoor air, and a third to the water loop of the building. Additional components include a compressor, an expansion valve, two three-way reversible valves, and a four-way reversible valve [4]. The valves regulate refrigerant flow, ensuring the heat pump operates exclusively in either air- or ground-source mode at any given time—directing heat exchange to either the outdoor air or GHE, but never both simultaneously.

The air-source and ground-source modes of the heat pump are modeled separately, with each mode utilizing performance curves derived from experimental results reported by Grossi et al. [4]. These curves relate heating/cooling capacity and COP in both modes to the entering liquid temperature (ELT) (Point 13 in cooling mode or Point 14 in heating mode as shown in Fig. 1) and entering air temperature (EAT) (Point 15) at the three inverter frequencies. The ELT is obtained from the GHE model (See Section II. B.) and EAT is obtained from the weather data (See Section II. C.) at each time step of simulation, which is set here as 300s.

Using the heating/cooling capacity and COP in each mode, the power consumption of the heat pump and the heat rejection/extraction rate in ground-source mode are determined based on fundamental thermodynamic principles (definition of COP and the first law of thermodynamics). The model calculates the load-side inlet temperature to the heat pump (T_{in}) (Point 1 in heating and Point 2 in cooling mode) by maintaining a constant load-side water outlet temperature (T_{out}) (45°C for heating (Point 2) and 7°C for cooling (Point 1)) and incorporating the water mass flow rate ($\dot{m}_w$) and specific heat capacity ($C_{p,w}$), and hourly building load data ($\dot{Q}_b$) in each time step:

$$T_{in} = T_{out} - \frac{\dot{Q}_b}{\dot{m}_w C_{p,w}} \tag{1}$$

To account for the degradation caused by on-off cycling, a part-load fraction (PLF) is applied. The PLF is obtained iteratively following Henderson and Rengarajan's approach [6] (using a 60-second time constant and a maximum cycling rate of 2.5 as recommended by Henderson et al. [7] for typical conditions), with a regression fit as in Biglarian et al. [8]. The adjusted COP and power consumption at each time step i ($COP_{adj,i}$ and $Power_{adj,i}$) are calculated as:

$$COP_{adj,i} = PLF_i \times COP_i \tag{2}$$

$$Power_{adj,i} = PLF_i \times Power_i \tag{3}$$

B. Borehole Modeling and Sizing

To model temperature variations in the GHE circulating fluid and the surrounding ground due to heat delivery or extraction, analytical models for heat transfer both inside and outside the borehole are integrated using the transient borehole wall temperature as a key parameter. This integration is essential because the temperature at the borehole wall governs the interaction between the ground heat exchanger and the surrounding ground. The borehole wall temperature, determined by the external ground model, enables the calculation of fluid temperatures at the GHE inlet and outlet via the internal borehole model [6]. In this study, the semi-analytical GHE model proposed by Laferrière et al. [6] is utilized, which combines a thermal resistance-capacitance (RC) model for short-term transient dynamics inside the borehole and a corrected g-function method synthesizing cylindrical heat source (CHS), infinite line-source (ILS), and finite line-source (FLS) models to address long-term ground interactions outside the borehole. This hybrid approach enables seamless simulation of borehole thermal behavior across timescales spanning minutes to decades [6]. Unlike prior studies using Duct Heat Storage (DST) model implemented in TRNSYS software [4, 5], which relies on precomputed g-functions and fixed cylindrical borehole layouts, the proposed framework supports arbitrary configurations and variable time steps. While TRNSYS DST remains effective for standardized long-term simulations, Laferrière et al.'s model enhances adaptability and accuracy for dynamic hybrid systems [6].

Borehole sizing is performed by iteratively adjusting the borehole length to ensure that the entering liquid temperature (ELT) remains within an optimal range over 20 years of operation. According to ASHRAE guidelines [7], during heating mode the ELT should not fall more than 5 – 8° C below the undisturbed ground temperature, while in cooling mode it should not exceed 11 – 17° C above the ground temperature. The process starts with an initial length estimate, followed by a 20 – year simulation, and continues adjusting the length until the ELT reaches one or both boundaries at least once—without exceeding them. The boundaries are defined here as 8°C below and 17°C above the undisturbed ground temperature according to ASHRAE GHE design guidelines [7].

C. *Control Strategy*

The control logic determines the operation mode of the heat pump based on an outdoor temperature threshold during heating mode. When the outdoor temperature is above the threshold, the system operates in air-source mode, following the refrigerant flow path: Points 4, 5, 7, 9, 10, 11, 12, 3 (Fig. 1, heating mode). When the temperature drops below the threshold, the system switches to ground-source mode, with the refrigerant flow path: Points 4, 5, 6, 8, 10, 11, 12, 3 (Fig. 1, heating mode). Weather data in this study is obtained from the EnergyPlus [11].

In cooling mode, only ground-source mode is active to restore the extracted heat during the heating mode and balance the thermal load on the ground. For example, in Edmonton, the borehole wall temperature at the end of the heating season and beginning of the cooling season is observed to be below -1°C, while the undisturbed ground temperature in Edmonton is 4.44°C. The system utilizes reversible three-way and four-way valves, which allow the refrigerant flow to reverse for cooling mode.

D. *Model Integration*

The mentioned heat pump model, borehole model, and control strategy are developed and integrated in OpenModelica. To model the dual-source heat pump, two separate components for air-source and ground-source modes are implemented and coded based on the performance curves obtained from Grossi et al. [4]. The borefield module from the Buildings library (Buildings.Fluid.Geothermal.Borefields) utilizes the model by Laferrière et al. [6]. The control strategy uses outdoor air temperatures and hourly building load data to switch between modes and set/calculate load-side water temperatures (Points 1 and 2 in Fig. 1). Fig. 2 shows the integrated DSHP system, which comprises three subsystems: ground-source (including the heat pump, borefield model, circulating pump, and control valves), air-source (featuring the heat pump component with mass flow sources for incoming outdoor air and load-side water), and control (logical components).

E. *Life-Cycle Cost Analysis*

The cost analysis accounts for both upfront capital costs of equipment (either the DSHP or GSHP unit and its installation, as well as the vertical ground heat exchanger, including drilling, loop installation, and grouting) and operating costs, which are primarily driven by electricity consumption over 20 years. Salvage value and decommissioning costs are assumed to be zero. Electricity expenses are estimated using location-specific rate structures and then adjusted for inflation (2% per annum) and discounted using an interest rate of 6% per annum to determine the net present value (NPV) of the system. The NPV for each case is calculated as follows:

$$\mathrm{NPV} = C_0 + \sum_{t=1}^{20} \frac{OC_t \cdot (1+i)^t}{(1+r)^t} \tag{3}$$

where C_0 is the capital cost, OC_t represents the operating cost in year t, i is the inflation rate, and r is the annual interest rate.

III. CASE STUDY DESCRIPTION

This section outlines the details and assumptions for the case studies, which include building load profiles, weather data, electricity rate structures, ground and ground heat exchanger properties, and financial parameters.

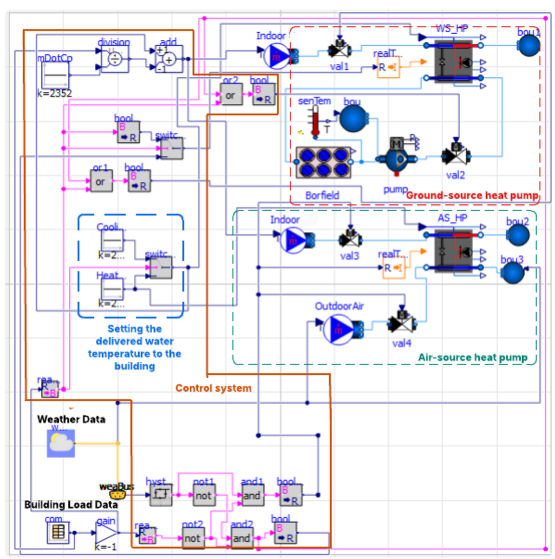


Figure 2. Layout of the dual-source heat pump system developed in OpenModelica.

Hourly heating and cooling load profiles for a building in Edmonton (Climate Zone 7), Toronto (Zone 5), and Montreal (Zone 6) were obtained from the UrbanOpt OpenStudio Prototype Loads repository [12]. To match the capacity range of the DSHP system under study, the building data were uniformly scaled to represent small residential buildings, preserving the temporal characteristics and relative load variations. Fig. 3 presents the monthly heating and cooling energy consumption of the buildings in Edmonton, Toronto, and Montreal. A positive building energy consumption value indicates energy delivered to the building during heating mode, while a negative value represents energy extracted from the building during cooling mode. Overall, the building in Toronto has the highest annual heating and cooling energy consumption at 17.98 MWh, followed by Edmonton at 15.84 MWh and Montreal at 13.42 MWh. During the heating season, the highest building energy consumption alternates between Edmonton and Toronto, whereas the building in Montreal consistently exhibits the lowest consumption. In contrast, throughout the cooling season, the building in Toronto generally experiences the greatest consumption—except in May, when the building in Edmonton surpasses it—while Montreal remains the lowest. Notably, Edmonton and Montreal exhibit a similar split between heating (approximately 69%) and cooling (31%) energy consumption, whereas Toronto shows a relatively larger share of cooling energy consumption (42% cooling vs. 58% heating). These variations are critical for analyzing the corresponding patterns in borehole length reduction (see discussions of Fig. 5).

The thermal properties of the ground as well as the ground heat exchanger specifications are listed in Table 1. The undisturbed ground temperature for Edmonton, Toronto, and Montreal is 4.44°C, 8.89°C, and 7.77°C, respectively [16]. All cases assume a single vertical borehole configuration.

The equipment and installation costs are listed in Table 2. To calculate operation costs, electricity rate structures were selected based on regional standards: the Rate of Last Resort (RoLR) for Edmonton [13], the Time-of-Use (TOU) plan for Toronto [14], and the Rate D structure for Montreal [15]. These rate structures consider only energy costs and do not include demand charges for residential buildings.

IV. RESULTS AND DISCUSSION

The borehole sizing and simulation for each location were conducted using three outdoor air temperature set points (0°C, -5°C, and -10°C). Above these thresholds, the heat pump operates in air-source mode, while below them, it switches to ground-source mode during heating operations. These cases are compared to a conventional ground-source heat pump (GSHP) system, which exclusively relies on the ground to meet the thermal load of the building.

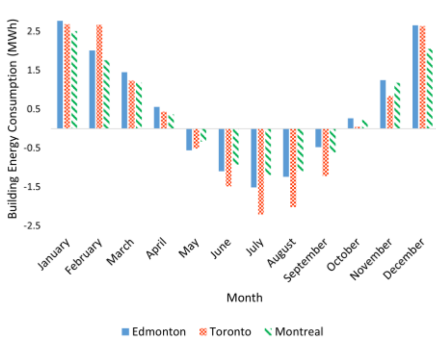


Figure 3. Monthly energy demand for the buildings in Edmonton, Toronto, and Montreal.

TABLE 1. GROUND THERMAL PROPERTIES AND GROUND HEAT EXCHANGER SPECIFICATIONS.

Parameter	Value
Borehole Diameter	200 mm
U-tube pipe outer radius	16 mm
U-tube pipe inner radius	13mm
Spacing between U-tube legs	5.2 cm
Tube thermal conductivity	0.5 W/mK
Ground thermal conductivity	1.25 W/mK
Ground specific heat capacity	1550 J/kgK
Ground density	1950 kg/m^3
Grout thermal conductivity	2.6 W/mK
Grout density	1600 kg/m^3

TABLE 2. CAPITAL COSTS (ALL CONVERTED TO CAD IN 2025).

Parameter	Value
Borehole installation cost (including drilling, loop installation, and grouting)	\$59/m [17]
Dual-source heat pump with installation costs	\$10,600 [4]
Water-source heat pump with installation costs (for GSHP-only configuration)	\$10,150 [4]

In Fig. 4, the entering liquid temperature (ELT) of a DSHP system (with an outdoor temperature set point of -10°C) and a GSHP system in Edmonton are compared, both using a 220 m borehole (designed for the GSHP). The comparison covers the heating season from September 18 of the first year to May 22 of the second year. This period is chosen as it effectively highlights the difference between the ELTs of the GSHP and DSHP, which becomes more pronounced during the heating season when the DSHP alternates between air- and ground-source operation. Over this period, the DSHP operated in ground-source mode 42% of the time and in air-source mode 58% of the time. This high proportion of air-source operation reduces the ground thermal load, resulting in a smaller decrease in ground temperature and, consequently, a less pronounced ELT drop compared to the GSHP system. This effect suggests the potential to reduce the required borehole length.

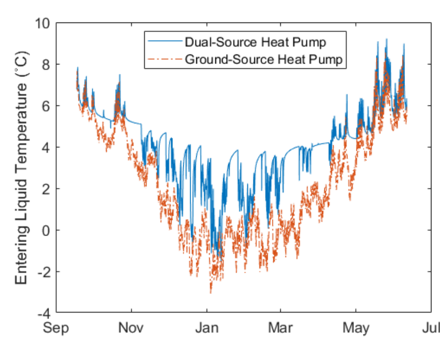
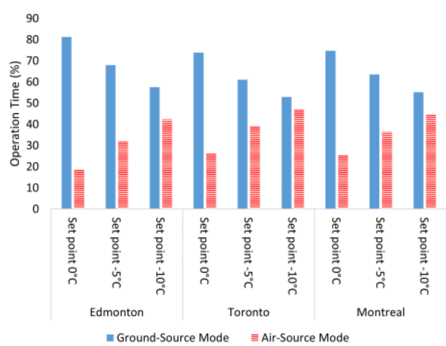


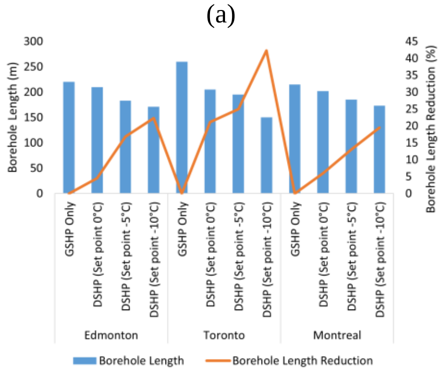
Figure 4. Comparison of DSHP and GSHP Entering Liquid Temperature (ELT) Trends Over the Heating Season.

Fig. 5 (a) illustrates the percentage of air-source and ground-source mode operation time for each location and each set point. Fig. 5 (b) shows the required borehole lengths for each location and scenario as well as the percentage reduction in borehole length relative to the GSHP-only system. As expected, based on the climate of the three locations, Toronto exhibits the highest percentage of air-source mode operation time for each temperature set point, followed by Montreal, with Edmonton having the lowest. Results show that lowering the temperature set points (from 0°C to -5°C and -10°C) extends the air-source mode operation time, thereby reducing the design borehole length in all cases. Edmonton achieved a borehole design length reduction of 4.5–22%, while Toronto and Montreal experienced reductions of 21–42% and 6.0–19%, respectively. Toronto exhibits the greatest reduction in borehole design length due to two factors: First, Toronto has a higher proportion of building cooling energy consumption (as discussed in Section III), which results in greater heat injection into the ground during cooling mode. This compensates for the heat extracted during heating mode, leading to a smaller decline in ground temperature during the heating season. Second, Toronto has the highest percentage of air-source mode operation time due to its warmer climate, which reduces the overall thermal load on the ground.

Edmonton and Montreal have a similar distribution of building heating and cooling energy needs (as discussed in Section III) Although Montreal has a slightly higher percentage of air-source mode operation time, this difference is not sufficient to outweigh the similarities in energy demand distribution. As a



(a)



(b)

Figure 5. (a) Percentage of air-source and ground-source mode operation time for each location. (b) Required borehole lengths for each location and scenario as well as the percentage reduction in borehole length relative to the GSHP-only system.

result, both locations exhibit comparable reductions in borehole size.

Notably, Toronto has the highest borehole length in the GSHP-only configuration compared to the other locations, primarily because its annual building energy consumption is greater than that of the other cities, as discussed in Section 3.

Fig. 6 presents the average heating and cooling COPs of the DSHP during a typical year for the three locations. While lowering the temperature set points reduces the borehole length, this benefit comes at the cost of a lower heating mode COP. This decline results from the increased temperature difference between the heat source and sink in air-source mode compared to ground-source mode. As expected, the GSHP system achieves a higher heating mode COP than the DSHP cases, while the average cooling COP remains
relatively unchanged across all cases, as cooling is exclusively provided by the ground-source mode.

Fig. 7 (a) shows the net present value (NPV) of costs for each scenario, including the capital cost and the NPV of electricity costs over 20 years of operation for the year 2025. It also highlights the capital cost savings and total savings (i.e., overall cost reduction). Fig. 7 (b) illustrates the cumulative 20-year energy consumption across all cities and scenarios, along with the corresponding changes in electricity costs.

Lowering the temperature set point reduces capital costs by decreasing borehole requirements. For instance, in Edmonton, the DSHP system with a -10°C set point achieves a capital cost savings of 11% compared to the GSHP system. However, this reduction comes at the expense of increased long-term electricity consumption and costs due to greater reliance on air-source operation in colder conditions (e.g., Edmonton: 85.9 MWh vs. 82.1 MWh over 20 years, with an electricity cost NPV of $7,465 vs. $6,628 (CAD in 2025)). Despite this increase in operational expenses, the capital cost savings outweigh the higher electricity costs in all cases, leading to a lower overall NPV of costs.

Toronto achieves the highest cost savings, with a 14% reduction in NPV of costs at a -10°C set point, primarily due to a significant decrease in capital costs ($19,450 vs. $25,490 for GSHP (CAD in 2025)). In contrast, Edmonton's colder climate limits potential savings, with a maximum NPV cost reduction of only 5.4%. Montreal exhibits savings comparable to Edmonton, with a 5.6% NPV reduction at -10°C, primarily due to similar borehole length reductions. Notably, the lower electricity rates

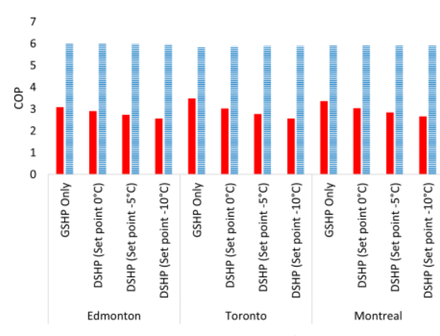
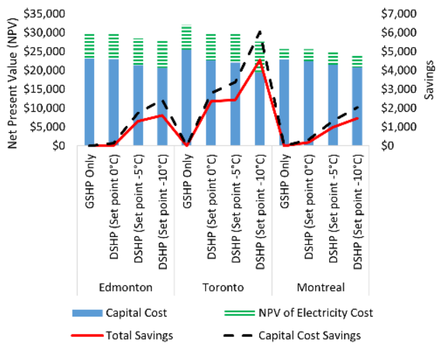
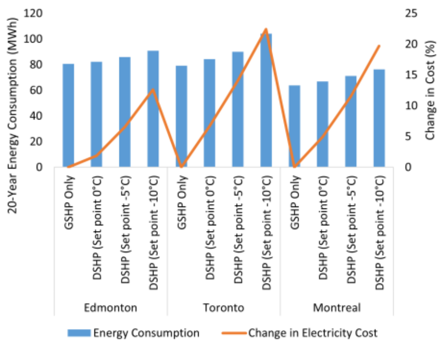


Figure 6. Average heating and cooling COPs a typical year of operation.



(a)



(b)

Figure 7. (a) Net present value and savings for each scenario. (b) 20-year energy consumption and percent change in electricity cost for each scenario.

under Rate D in Montreal help offset the higher percentage increase in electricity expenses relative to Edmonton, as shown in Fig. 7(b).

These findings underscore the trade-off between upfront capital cost savings and long-term operational expenses, highlighting the importance of climate-specific set point optimization to enhance the viability of dual-source heat pump systems.

V. CONCLUSION

This study demonstrates that dual-source heat pumps (DSHPs) offer a viable solution to reduce both upfront and overall costs of ground-source systems in cold climates by reducing the required borehole length, these potential savings are tightly coupled to regional climatic, operational, and financial factors. In this case study, Toronto's milder climate yields the most significant reductions, with a 42% decrease in borehole length, 24% reduction in capital cost, and a 14% reduction in net present value (NPV) of costs at the -10°C set point. In contrast, Edmonton and Montreal achieve comparable maximum borehole length reductions (approximately 20%) and similar reductions in NPV of costs (approximately 5%), despite climatic differences. While Montreal experiences slightly warmer temperatures than Edmonton, the similar distribution of heating and cooling energy demand between the two cities leads to comparable outcomes. These findings emphasize the importance of climate-specific set point optimization to enhance the viability of dual-source heat pump systems.

These savings come with critical trade-offs: lower temperature set points reduce borehole length requirements but degrade heating coefficients of performance (COP) by up to 26% compared to GSHP-only operation and increase long-term energy costs due to heightened reliance on less-efficient air-source operation. The NPV of all cases that are studied, however, shows that such long-term heightened operational costs are compensated by the lower capital costs. The most important benefit of the lower capital cost of the GSHP system is perhaps its role in increased adoption of GSHPs, which could be the subject of further study.

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REFERENCES

[1] J. Hanova and H. Dowlatabadi, "Strategic GHG reduction via GSHP technology," Environ. Res. Lett., vol. 2, no. 4, p. 044001, Oct. 2007.

[2] S. Alqaed, J. Mustafa, K. P. Hallinan, and R. Elhashmi, "Hybrid CHP/geothermal borehole system for multi-family buildings in heating-dominated climates," Sustainability, vol. 12, no. 18, p. 7772, Sep. 2020.

[3] K. Allaerts, M. Coomans, and R. Salenbien, "Hybrid GSHP system with active air source regeneration," Energy Convers. Manage., vol. 90, pp. 230–237, Jan. 2015.

[4] I. Grossi, M. Dongellini, A. Piazzi, and G. L. Morini, "Dynamic modelling and energy performance of an innovative dual-source heat pump system," Appl. Therm. Eng., vol. 142, pp. 745–759, Sep. 2018.

[5] S. Marinelli, F. Lolli, M. A. Butturi, B. Rimini, and R. Gamberini, "Environmental performance of a dual-source heat pump system," Energy Build., vol. 223, p. 110180, Sep. 2020.

[6] A. Laferrière, M. Cimmino, D. Picard, and L. Helsen, "A semi-analytical model for simulating vertical geothermal bore fields," Geothermics, vol. 86, p. 101788, Jul. 2020.

[7] S. P. Kavanaugh, K. D. Rafferty, and ASHRAE, Geothermal Heating and Cooling: Design of GSHP Systems, Atlanta, GA: ASHRAE, 2014.

[8] H. I. Henderson and K. Rengarajan, "Model to predict the latent capacity of air conditioners and heat pumps at part-load conditions," ASHRAE Trans., vol. 102, no. 1, pp. 266–274, 1996.

[9] H. Henderson, Y. J. Huang, and D. Parker, "Residential equipment part-load curves for DOE-2," Lawrence Berkeley Natl. Lab., CA, 1999.

[10] H. Biglarian, M. Abbaspour, and M. H. Saidi, "Evaluation of a transient borehole heat exchanger model in GSHP simulation," Energy, vol. 147, pp. 81–93, Mar. 2018.

[11] EnergyPlus, "Weather Data | EnergyPlus," Energyplus.net, 2019. [Online]. Available: https://energyplus.net/weather.

[12] urbanopt, "GitHub - urbanopt/openstudio-prototype-loads," GitHub, 2020. [Online]. Available: https://github.com/urbanopt/openstudio-prototype-loads.

[13] "Regulated Residential Electricity Rate & Fees (RRO)," Epcor.com, 2024. [Online]. Available: https://www.epcor.com/ca/en/ab/edmonton/account/rates/home/regulated-residential.html.

[14] "Hydro One," Hydroone.com, 2019. [Online]. Available: https://www.hydroone.com/rates-and-billing/rates-and-charges/electricity-pricing-and-costs.

[15] "Rate D," Hydro-Québec, [Online]. Available: https://www.hydroquebec.com/residential/customer-space/rates/rate-d.html.

[16] Geothermal Heat Pump Design Manual: Application Guide AG 31-008, McQuay Int., 2002. [Online]. Available: https://www.mcquay.com.

[17] Urban Geoexchange Alberta, Quote from Mr. Don Manns, Wombat Industries, Lethbridge, AB, Canada, Feb. 2025.