Assessment of Hybrid Ground-Source Heat Pumps to Mitigate Soil Thermal Imbalance and Reduce Ground Heat Exchanger Drilling Costs in Cold Climates

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ABSTRACT

In severe cold climates, building heating loads are several times higher than the cooling loads, which causes an imbalance in the heat taken from and returned to the ground by ground-source heat pumps (GSHPs), known as soil thermal imbalance. Additionally, the high cost of installing the vertical ground heat exchangers (GHEs) needed for GSHPs limits their applicability in severe cold climates.

Hybrid ground-source heat pumps (HGSHPs) are GSHPs that use an auxiliary heat source, such as natural gas heating, to supplement part of the building heating load. This decreases the amount of heat extracted from the ground during the heating season, making is closer to the amount of heat put back into the ground during the cooling season, thus decreasing the soil thermal imbalance.

A numerical investigation is conducted to assess the performance of a HGSHP with auxiliary natural gas heating using the TRNSYS-18 software package. The performance is compared with a standalone GSHP system in the city of Saskatoon (ASHRAE – Zone 7), classified as a severe cold climate. The simulation is conducted for 20 years to assess the long-term impact of the thermal imbalance caused by the HGSHP operation on the ground temperature.

The results indicate that for HGSHP systems, the annual average ground temperature decrease was 0.4°C to 1.5°C for GHE lengths of 600 m to 2000 m. For a standalone GSHP with a 2000 m GHE length the ground temperature experienced a 3.3°C decrease. HGSHPs cost 20-60% lower than standalone GSHPs due to the reduction in drilling costs. While HGSHPs are not able to reduce emissions as much as standalone GSHPs, they are able to reduce emissions by 28-38% compared to pure natural gas heating system. The results of this study indicate that HGSHPs can be used to find an optimal balance between cost, emissions and maintaining balanced soil temperatures.

Keywords: Soil thermal imbalance, Ground-source heat pumps, Hybrid heating, Cold-climate heat pumps

INTRODUCTION

Ground-source heat pumps (GSHPs) operate by harnessing heat from the ground, which is an excellent heat source during winter due to it having a higher mean temperature than the ambient air (Staffell et al. 2012). GSHPs transfer heat to indoor spaces using a ground heat exchanger (GHE) and vapour compression mechanism, as depicted in Figure 1 (Emmi et al., 2015). A ground heat exchanger fluid (GHEF), which is at a temperature lower than the ground, flows through the GHE, and extracts heat from the surrounding ground. The extracted heat is supplied at a higher temperature to indoor spaces via a compressor and condenser (Çengel, 2004; Nag, 2002).

GSHPs are cleaner electric alternatives to fossil fuel-based heating systems. If the electricity that powers them is generated from renewable sources, they have the potential to mitigate 12.5% of the global greenhouse gas emissions generated by building heating systems (IEA, 2022b, 2022a). GSHPs have efficiencies of over 200% compared to the typical efficiencies of 85-90% for fossil fuel-based heating systems (Staffell et al., 2012). However, their adoption in cold climates is limited by the high capital costs required to install a GSHP and the problem of soil thermal imbalance (You et al., 2016). As a result of imbalance in the building heating load to the cooling load, the heat extracted from the ground is several times larger than the heat replenished back into the ground, and over a period of several years, the ground temperature is reduced, making extraction of heat from the ground difficult, and expensive as the COP

of the system decrease. The studies carried out in the literature to address the problem of soil thermal imbalance are discussed below.

One possible solution to reduce soil thermal imbalance when operating GSHPs is to change the borehole design parameters, which is an easy but costly solution (Spitler et al., 2020). Increasing the GHE length will increase the volume of soil available for heat transfer, and the rate of decrease of the soil temperature will be slower. Furthermore, proper grouting will improve the heat transfer in the GHE (Bae et al., 2018) which also slows the drop in ground temperatures. However, borehole design alterations are expensive. The highest cost of GSHPs is the borehole drilling and grouting costs. Increasing the GHE length more than necessary would add to the already high installation costs.

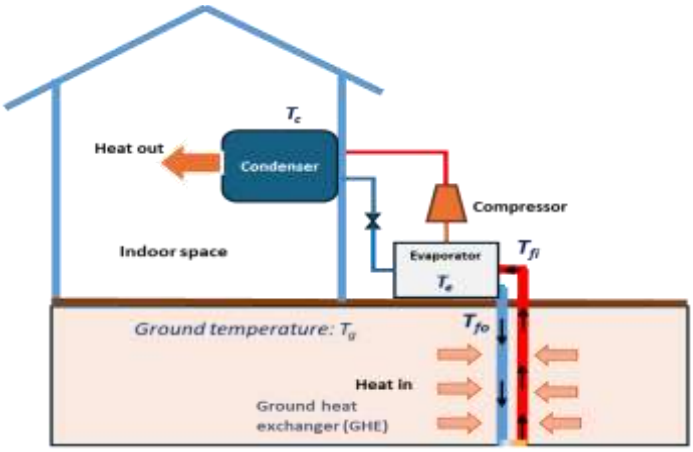

Figure 1: Schematic representing the operation of a GSHP in typical winter operating conditions. Heat is extracted from the ground and supplied to indoor spaces.

Supplemental heating is an alternative approach to mitigate soil thermal imbalance. Supplemental heat sources can aid GSHP operation or pump heat back into the ground during the non-heating season, decreasing the net amount of heat extracted from the ground. Some examples of supplemental heating solutions include solar assistance, air compensation units (ACU) and auxiliary heating.

Solar Assistance: Solar energy is used to replenish the soil temperature and decrease the heat extracted from the soil (Si et al., 2014; Emmi et al., 2015). During winter operations, heat from the ground is supplemented by the heat collected from the sun, thereby increasing system efficiency. In summer, the heat from the sun can be used to replenish the ground temperature. Si et al. (2014) investigated solar assistance to mitigate soil thermal imbalance and found that the drop in soil temperature with solar assistance was 0.8°C compared to 3.1°C without solar aid over ten years of operation. Furthermore, the coefficient of performance (COP) of the solar coupled GSHP dropped by only 0.17 compared to 0.43 for a standard GSHP. However, including solar assistance increases the initial investment needed to set up the GSHPs.

An ACU extracts heat from the ambient air and injects it into the ground during the summer to match the excess heat extracted during the winter. Fundamentally, the ACU works like an air-source heat pump (ASHP), transferring heat from hot summer air into the ground. (You et al., 2014) combined an air-source thermosyphon unit and an ASHP as an ACU to replenish ground heat in summer. The proposed system can save up to 15% on operational costs and maintain a more stable soil temperature compared to standard GSHPs over long periods. An economic comparison between ACU and solar assistance reported that an ACU had a shorter payback period, and solar systems had higher initial investments, leading to more extended payback periods (Wu et al., 2013; You et al., 2015).

Auxiliary heating utilizes a natural gas furnace to meet a portion of the peak heating load. This hybrid GSHP system mitigates the thermal stress on the ground and reduces the severity of thermal imbalance (Xu et al., 2021). The peak load fraction measures the ratio of the peak heating demand supplied by the GSHP system to the building's peak demand load. Similarly, the energy fraction, defined as the ratio of the thermal energy provided by the GSHP to the total thermal energy demand of the building, plays a crucial role in optimizing the system's performance. Research indicates that increasing the energy fraction leads to lower annual operational costs but increases the initial investment (Alavy et al., 2013; Nguyen et al., 2014). Therefore, finding the optimal load fraction is essential to minimize costs while maximizing energy savings.

Incorporating solar assistance and ACUs to pump heat back into the ground has yielded a notable reduction in thermal imbalance. However, it is essential to consider that these additional systems can significantly increase the operational costs and initial investment of GSHPs (You et al., 2014). Furthermore, groundwater flow can pose challenges when injecting heat into the ground, as the flowing groundwater can carry away the replenished heat, reducing its effectiveness.

Considering these factors, the feasibility of implementing a hybrid GSHP system, combining a GSHP with a natural gas furnace, is a practical approach for cold climatic conditions. For Saskatoon natural gas is approximately five times cheaper and at present has half the emissions intensity of electricity, making it an attractive heating solution. Several studies have examined the optimal load fraction between the GSHP and natural gas furnaces in hybrid systems, aiming to mitigate costs and achieve significant energy savings. However, a limited number of studies investigate the long-term impact of the hybrid operation with different GHE lengths apart from the design GHE length on the soil temperature over a prolonged period (20 years).

The present paper investigates a HGSHP operating to supply the heating and cooling needs of a small office building in Saskatoon with different GHE lengths, and the effects on the soil temperature. The energy consumption, emissions and temperature drop of the soil, over 20 years are compared with the results of a standalone GSHP. A feasibility study is performed to determine if HGSHPs are capable alternatives to standalone GSHPs for reducing thermal imbalance while maintaining low costs and emissions.

2.0 METHODOLOGY

The simulation methodology consists of two main parts: (i) the TRNSYS building and ground heat exchanger simulation package and (ii) the thermodynamic model of the GSHP. Both modelling procedures are explained in the following subsections.

2.1 TRNSYS building and GHE simulation package

The building used for the present study is a Department of Energy, USA benchmarked model (Torcellini et al., 2008). The area of the building is 510 $m^{2,}$ and the characteristics of the building envelope are presented in Table 1. More detailed building simulation inputs are presented in (Gollamudi et al., 2024). The peak heating demand of the building is 67 kW, while the peak cooling demand is 32 kW. The annual heating energy consumption of the building is 70.2 MWh, and the cooling energy consumption is 12.4 MWh. The maximum deviation in the year-on-year change in annual heating energy demand over a 20-year period is 0.5%. It must be noted that the effect of climate change is not considered in the present study. Given the increase in average global temperatures it is expected that the annual heating consumption of the building would decrease.

The main component used in the TRNSYS-18 simulation package is a Type-548, which simulates the heat transfer with the ground. The main inputs required for the Type-548 are the GHEF outlet temperature, mass flow rate of the GHEF, average ground storage temperature at the start of the simulation and the GHE length. Values of all the critical design parameters are presented in Table 2.

Table 1: Building envelope

Component	U-value (W/(m²·K))
Wall	0.204
Roof	0.252
Floor	0.279
Window	2.89

The soil thermal conductivity is set at 1.5 W/(m·K), and the thermal diffusivity is set at 1e-6 m^2/s, the typical value in Saskatoon (Sjoberg; Rod E., 1963). It must be noted that the soil properties will vary depending on the location, so this must be considered when assessing different locations. The configuration of the GHE consists of 10 boreholes, each spaced 6 m from each other. The average ground storage temperature is 1.5°C higher than the average air temperature (Sarbu & Sebarchievici, 2016).

The design GHE length depends on the building's heating load, cooling load, soil thermal properties, and borehole configuration. Appropriate sizing of the GHE is crucial for the operation of a GSHP. Under sizing the GHE would lead to poor performance of the GSHP and severely deteriorating ground soil temperatures as the amount of

ground available for heat exchange is lower. Oversizing a GHE would be very costly, rendering the installation of GSHP economically infeasible. In the present study, the GHE sizing tool from Sarbu & Sebarchievici (2016) is used to size the GHE. The hourly heating and cooling loads are input into the worksheet to estimate the design GHE length.

Table 2: Inputs for GHE design length and TRNSYS Type-548 module

Parameter	Values
Soil thermal conductivity	1.5 W/(m·K)
Soil thermal diffusivity	1e-6 m^2/s
Undisturbed soil temperature	4°C
Pipe size	120 mm
Borehole separation	6 m
Number of boreholes	10 m

The design constraint for estimating the GHE length is that the monthly average fluid inlet temperature does not drop below -4°C over 20 years (Sarbu & Sebarchievici, 2016). Based on the inputs discussed above, the estimated design length required for the building is 2000 m (200 m x 10 boreholes). The monthly average fluid inlet temperature is presented in Figure 2. This temperature profile was obtained using the combination of the TRNSYS Type-548 module and the thermodynamic model presented in the next subsection.

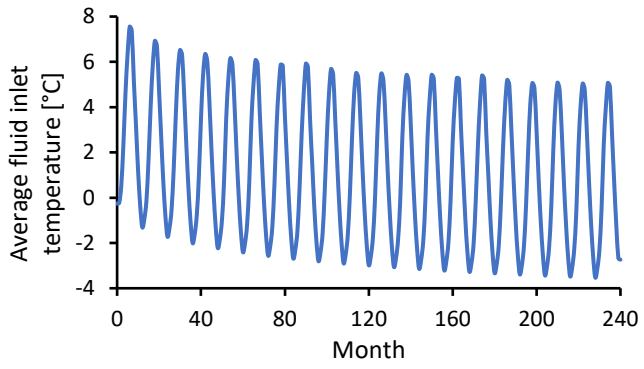

Figure 2: Average GHEF inlet temperature for a GHE length of 2000 m in Saskatoon.

2.2 GSHP thermodynamic model

The GSHP thermodynamic model employs mass and energy balance equations to solve each component of the GSHP and arrive at an estimate of the GSHP's COP. The associated mass and energy balance equations are presented in Table 3. The inputs of the GSHP thermodynamic model include the GHEF entering temperature (T_{fi}) and mass flow rates, and the building heating/cooling load. The main output from the thermodynamic model is the GSHP COP.

Table 3: Governing equations for the GSHP thermodynamic model

Component	Governing equations	Equation no.
Condenser	$\dot{q}_{con} = \dot{m}_r(h_{con_in} - h_{con_out})$	(1)
	$\dot{q}_{eva} = \dot{m}_r(h_{eva_out} - h_{eva_in})$	(2)
Evaporator	$\dot{q}_{eva} = (\dot{m}c_p)_{GHFE}(T_{fi} - T_{fo})$	(3)
	$\dot{q}_{max} = \dot{m_{air}}c_{air}(T_{fi} - T_{eva})$	(4)
	$\dot{q}_{eva} = \varepsilon\dot{q}_{max}$	(5)
Compressor	$\dot{W}_{comp} = \frac{\dot{m}_r(h_{con_in} - h_{eva_out})}{\eta_{isentopic}}$	(6)
	$\eta_{isentopic} = f(P_{eva}, P_{con})$	(7)
Expansion valve	$h_{exp_in} = h_{exp_out}$	(8)

The TRNSYS building module estimates the building heating and cooling loads using real weather data, and the Type-548 module estimates the GHEF inlet temperature of the GSHP. The temperature of the GHEF after the refrigerant extracts heat is the input to the Type-548 module, as shown in Figure 3. Figure 3 also illustrates how different modules are linked to each other in the modelling process.

During the cooling season, the condenser of the GSHP in the indoor space acts as an evaporator and extracts heat from the space. The evaporator acts as the condenser and rejects heat to the GHEF. The condensation temperature set during heating is 50°C, and during

cooling, it is set at 42.5°C, while the evaporator temperature during a cooling cycle is set at 8.3°C. The heating and cooling COPs (COP_h and COP_c) of the heat pump are calculated as shown in Equations (9) and (10).

$$COP_h = \frac{Q_{con}}{W_{compressor}+W_{pump}} \quad (9)$$

$$COP_c = \frac{Q_{eva}}{W_{compressor}+W_{pump}} \quad (10)$$

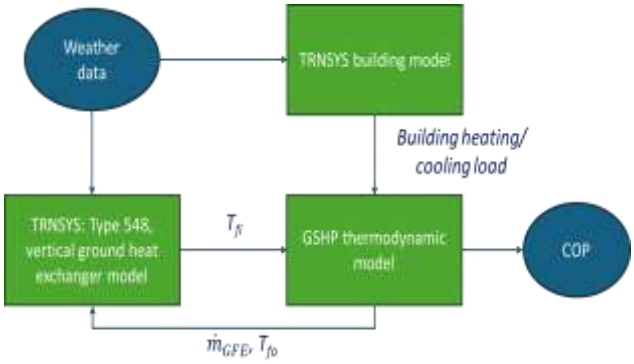

Figure 3: Integration of building simulation, ground heat exchanger model and the GSHP thermodynamic model.

The work done by the pump is calculated using Equation (11). A constant potential head (p) of 15 m is assumed to account for the ground loop losses. The pump's efficiency is 90%, and g is the acceleration due to gravity.

$$W_{pump} = \frac{\dot{m}_{GHFE} \cdot g \cdot (\Delta p + \Delta p_{losses})}{\eta_{pump}} \quad (11)$$

3.0 RESULTS AND DISCUSSION

The performance of the standalone GSHP operating to supply heat to the defined office building is presented, followed by a comparison with HGSHP with varying GHE lengths.

Figure 4 represents the ground soil temperature drops over 20 years for a GHE length of 2000 m. The average temperature of the ground dropped by 3.3°C. However, the minimum temperature of the ground during the 20 years dropped to -0.37°C from 4°C at the start of GSHP operation. The drop in temperature, as mentioned previously, is due to the significant disparity between the annual heating demand and the cooling demand in Saskatoon. It can be observed that the average yearly heating COP drops by 5% from 2.47 to 2.35. Although the drop in COP is only around 5%, the allowable temperature drop of the ground is not recommended to be more than 2.0°C over 20-30 years (Desideri et al., 2011)

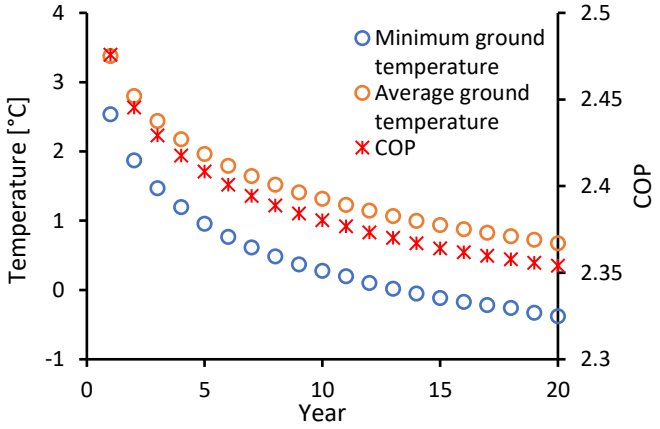

Figure 4: Average and minimum ground soil temperature and COP variation over 20 years for a standalone GSHP with 2000 m design GHE length.

To combat the large drop in ground soil temperature, a HGSHP with natural gas auxiliary, which can help reduce the cost of drilling by reducing the size of the GHE and controlling the loss of ground temperature over 20 years is presented.

3.1 Performance of a HGSHP

The GSHP system is sized to meet the peak cooling load of the building, which is 35 kW. The GSHP is used for heating up to 35 kW, and the NG heating system meets the heating loads above 35 kW. Additionally, if the temperature of the GHEF entering the GSHP is lower than 0°C, the entire building load is supplied by the GSHP system. It must be noted that the results presented in this section are highly influenced by the hybrid heating logic used. In the present study, the HGSHP is sized to meet the peak cooling demand, as the study aims to assess if HGSHP can be an alternative to standalone GSHP. Future studies will consider different hybrid heating logics to attain maximum emission reduction while having minimum costs and thermal imbalance.

Figure 5 illustrates that the auxiliary heating fraction (α) defined in Equation (12) decreases as the length of the GHE increases. Smaller GHE lengths have less ground volume available for heat transfer, and the temperature of the entering GHEF drops below 0°C more frequently than an HGSHP system with a large GHE length. As a result, the dependence on natural gas auxiliary heating

increases and the amount of heat extracted from the ground decreases. The 20-year average ground temperature drop (ΔT_{20}) increases with an increase in GHE length because larger GHE lengths allow the extraction of more heat from the ground, which is also reflected in the auxiliary heating fraction.

$$\alpha = \frac{Heating\ energy\ supplied\ by\ auxiliary\ source}{Total\ annual\ heating\ energy\ demand} \quad (12)$$

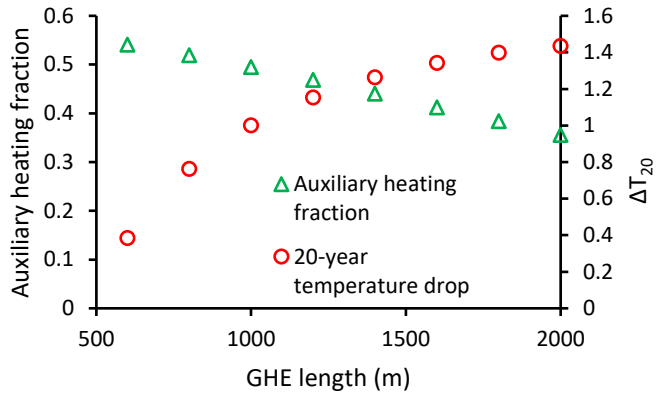

Figure 5: Variation of auxiliary heating fraction and (ΔT_{20}) GHE lengths varying from 600 m to 2000 m.

3.2 Comparison of HGSHP with standalone GSHP

In the present section, emissions, and economics from HGSHPs are compared with standalone GSHP with design GHE length and a natural gas heating system. The emissions intensity projections from the electricity grid are considered to estimate the lifecycle operation emissions. The projections are taken from SaskPower estimates for the province of Saskatchewan (SaskPower, 2021). The emission intensity is estimated to reach 230 g/kWh of CO_{2e} by 2045 from current levels of 540 g/kWh. It must be noted that the actual emissions from manufacturing, transporting, and disassembling the GSHP after the life cycle are not considered.

Figure 6 displays the GHG emissions of the HGSHP varying with GHE length, as well as that of the stand-alone GSHP and a pure NG system. When the GHE length is lower, the emissions are higher because the NG system must supply a significant portion of the heating load. Compared to conventional natural gas systems, HGSHP can achieve significant emissions reductions. The HGSHP system, with 600 m and 2000 m GHE lengths, has 28% and 38% lower emissions than a NG heating system.

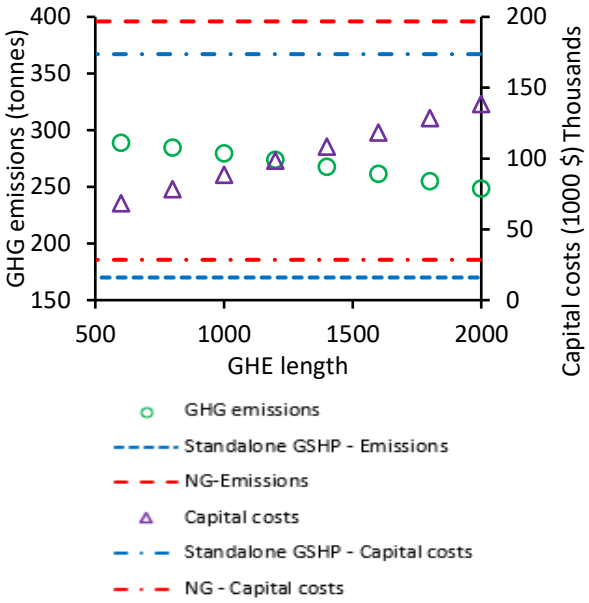

Figure 6: Comparison of GHG emissions over a 20-year period and capital costs between HGSHP, standalone GSHP and pure natural gas (NG) system.

As the electric grid is projected to get cleaner, using electric auxiliary instead of natural gas will also lead to more emissions reduction potential for HGSHP systems. One of the biggest advantages of using the auxiliary heating system is reducing the GHE's length, thereby reducing capital costs, as shown in Figure 6, while maintaining an acceptable soil temperature drop and achieving a reduction in emissions. A standalone GSHP costs 5.6 times more than a pure NG heating system, for this building in Saskatoon. A HGSHP with a 600 m long GHE costs 2.3 times more than a pure NG heating system. The HGSHP with a 600 m long GHE costs only 40% of cost incurred to install a standalone GSHP.

Since natural gas is approximately five times cheaper than electricity in Saskatoon, the energy savings obtained by using higher GHE lengths do not offset the high capital costs. This indicates that HGSHP can be used as a trade-off between cost and emissions reduction potential in severe cold climates like Saskatoon. However, the downside of the HGSHP system with natural gas auxiliary is that they cannot be 100% net-zero emission devices. Net-zero emissions could be achieved if an electric auxiliary is used instead of an NG auxiliary.

CONCLUSIONS

Hybrid ground source heat pumps supplying heat to a small office building are assessed for their ability to maintain acceptable levels of soil thermal imbalance and reduce installation costs in severe cold climates. Furthermore, the emissions reduction potential and installation cost of HGSHP are compared with standalone GSHP. The main conclusions of the study are as follows:

1. The standalone GSHP with a GHE length sized to meet the entire building's heating and cooling loads had a ΔT_{20} of 3.3°C, while the acceptable value is 2°C. This indicates that the GHE length must be further increased to account for the severe disparity in heating and cooling loads.
2. HGSHP with auxiliary natural gas heating and varying GHE lengths from 600 m to 2000 m could maintain ΔT_{20} < 2°C while the auxiliary heating fraction increases as the GHE length decreases.
3. The emissions reduction potential of HGSHP is lower than that of standalone GSHP because of the use of auxiliary heating. Compared to NG heating, HGSHP could reduce emissions from 28% - 38% compared to natural gas heating.
4. HGSHPs cost around 40-80% of standalone GSHPs as the GHE length varies from 600 m to 2000 m while still achieving significant emission reduction.

The results of the work show the potential of HGSHP to achieve a compromise between capital costs and emission reduction in extreme cold climates where standalone GSHP might be prohibitively expensive to install.

FUTURE WORK

The feasibility of the HGSHP system in mitigating emissions and costs is investigated in the present work. Future work will include investigating the influence of soil properties on life cycle cost, emissions, and thermal imbalance. Furthermore, as noted previously, the results presented in this paper are influenced by the hybrid heating logic. Future studies will consider developing a methodology to compare different hybrid heating logics and to attain maximum emission reduction while having minimum costs and thermal imbalance.

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NOMENCLATURE

c	Specific heat	(kJ/(kg·K))
COP	Coefficient of performance	(-)
GHE	Ground heat exchanger	(W)
GHEF	Ground heat exchanger fluid	
h	Specific enthalpy	(kJ/kg)
HGSHP	Hybrid ground-source heat pump	
$\dot{m}$	Mass flow rate	(kg/s)
NG	Natural gas	
p	Potential heat	(m)
$\dot{q}$	Heating load	(kW)
$\dot{W}$	Power consumption	(kW)
T	Temperature	(°C)
Subscripts		
con	Condenser	
eva	Evaporator	
exp	Expansion valve	
fi	GHEF fluid inlet to heat pump	
fo	GHEF fluid outlet heat pump	
r	Refrigerant	
Greek Symbols		
α	Auxiliary heating fraction	(-)

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