Recharging ground heat exchangers with industrial waste heat using mobile thermal energy storage tanks

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Abstract

This study examines intermittent "recharging" of ground heat exchangers (GHE) using industrial waste heat (IWH) to raise ground temperatures in heating dominated systems. The IWH is stored in a reservoir mounted on a truck. This mobile thermal energy storage (M-TES) system is then transported to a site where GHE recharging is required. A GHE with two independent circuits is used. One circuit is linked to a ground-source heat pump (GSHP) and the other is used for recharging, thus allowing both circuits to be used independently.

TRNSYS simulations of a typical residential heating system in a cold climate are performed. A special four-pipe GHE model with two independent circuits developed in an earlier study is used here. The purpose of the simulations is to examine the impact of different recharging frequencies and durations with the objective to minimize GHE length and reduce energy consumption.

Results show that regular heat injection in the ground during the heating season can reduce the required GHE length by up to 46 %. Furthermore, it is shown that ground recharging has the potential to improve GSHP performance.

Introduction

Ground-source heat pumps (GSHP) collect/reject energy from the ground via a heat transfer fluid circulating in a ground heat exchanger (GHE). This is a very efficient process with coefficients of performance (COP) of 3 to 5 in both heating and cooling. The resulting energy savings are however insufficient to compensate for the extra cost associated with the GHE, especially in the residential sector. Consequently, reducing the length of the GHE, without sacrificing energy savings, would enable widespread utilisation of GSHP.

In order to understand how recharging could impact the GHE length, it is important to review how GHE are sized. GHE can be sized either using multi-year simulations (Ahmadfard et al., 2016) using various software tools or the ASHRAE sizing equation (Philippe et al, 2010). Both methods give similar results if applied properly (Ahmadfard and Bernier, 2019). In the first case, a GHE model is used to predict ground heat transfer for a given annual ground load at specified time steps (typically one hour). The GHE length is adjusted until simulations show that the return temperature from the borehole (i.e. the inlet temperature to the heat pump) matches the desired design temperature in the worst conditions. In heating applications, this threshold temperature is typically 0 ℃ for the inlet temperature to the heat pump.

The ASHRAE sizing equation (ASHRAE, 2011) requires the determination of three thermal pulses representing the peak hourly ground load, q_h, the monthly average ground load, q_m, and the annual average ground load, q_y. With these three values, the GHE length, L, can be determined according to:

$$L = \frac{q_h R_h + q_m R_m + q_y R_y + q_h R_b}{\frac{T_i + T_o}{2} - (T_g + T_p)} \qquad (1)$$

where R_h, R_m, and R_y are effective ground thermal resistances based on thermal pulses of 6 hours, 1 month and 10 years. R_b is the borehole thermal resistance. R_h, R_m, and R_y only depend on ground thermal properties and the durations of the pulses, while R_b depends on the borehole characteristics (number of pipes and grout properties). For all practical purposes, these four thermal resistances are independent of L. T_i and T_o are the inlet and outlet temperatures and T_g is the undisturbed ground temperature. The temperature penalty, T_p, which only applies to fields of multiple boreholes accounts for the thermal interference from other boreholes. It is assumed to be zero as only single borehole systems are studied.

The technique proposed here aims at reducing the three ground loads so as to reduce L.

In heating applications, there has been several studies that examined ways to "recharge" boreholes by injecting heat into boreholes. Kjellson et al. (2010) studied the use of solar collectors with a residential single borehole system. They concluded that winter recharging could be beneficial, but that summer heat injection has no significant effect for winter operation of the GSHP. Brischoux (2016) studied the injection of heat derived from photovoltaic-thermal solar panels into one or multiple boreholes. The heat storage in the ground is not conclusive with a single borehole, but in the case of a field of boreholes, the solar coupling increases the seasonal performance factor of the ground heat storage as well as the temperatures returning from the borehole fields.

The major disadvantage of hybrid solar-GSHP systems is that the availability of solar heat rarely coincides with the need for thermal recharge. The heat input depends on the solar resource, which is mostly present in summer and in the middle of the day, whereas the need for heat is usually in winter, in the morning and evening. Solar heat injection into boreholes can be enhanced by using latent heat storage. Eslami-Nejad and Bernier (2012) simulated ground freezing during heat extraction by a GSHP heating system. Solar heat could then be injected in the borehole during the day to thaw the ground. A 18 % reduction of the borehole length was observed with this method. Bastani et al. (2023) studied a similar system, considering borehole fields in a water-saturated ground. With a consequent amount of solar energy injected into the ground, a 45 % diminution of the borehole length or alternatively a 91 % diminution of the borehole field area is reached.

In areas with a high density of GHE such as in Stockholm (Fasci, et al. 2021) there are concerns that thermal interference will grow with time (i.e. T_p will increase) which will adversely affect the system performance. Ground recharging appears as a solution to maintain the performance of these systems.

In this study, industrial waste heat (IWH) is used as the heat source to recharge the GHE. IWH has been considered in many projects as a resource that is underutilized and presents a high potential to be exploited.

Marcotte et al. (2021) evaluated the potential of using thermal waste in the province of Québec to meet the thermal needs of buildings. They estimated the yearly IWH in Québec at 56.7 TWh, while the heating needs of residential buildings are around 56 TWh. This study was conducted as part of a financial assistance program offered by the government of Québec (2023) for the valorization of waste heat. This aid is calculated to refund 125$ per ton of CO_2 and 8$ per GJ of energy saved during the 20 first years of projects, proving the political will to foster the use of thermal waste such as IWH.

Miró et al. (2016) provided an overview of the multiple thermal energy storage (TES) options suitable to IWH recovery. For off-site use, mobile thermal energy storage (M-TES) using trucks to convey the energy should be chosen when the distance between the source and the delivery point is limited, and when the heat demand is small. M-TES use show considerably lower energy consumption and carbon emissions than conventional systems using fossil fuel. It is however difficult to determine the real costs of the M-TES solutions because of weak information in technical aspects, mainly due to the lack of maturity of the technologies.

Another review carried out by Du et al. (2021) gives more details on M-TES based on phase change materials (PCM), which offer high thermal storage density. A lot of parameters influence the charge and discharge efficiency, including the exchange type with the heat source (direct or indirect contact), the temperature of phase change or the heat transfer medium flow. These technical considerations are not integrated in the present study.

A case study to integrate IWH using M-TES in the district energy network (DEN) of Surrey, in Canada, was led by Shedadeh et. al. (2021). IWH supplied by M-TES appears to be the cheapest solution among other renewable energy sources considered to replace gas boilers in the DEN. IWH can also be stored into borehole thermal energy storage (Guo, 2022). Heat is kept in the ground at a temperature around 50°C and used as the hot source of an absorption heat pump powered by high temperature waste heat. This double use of IWH ensures a stability in the heat availability and the recovery of low-quality heat. The system covers 85 % of the heating needs in the considered DEN.

A linear predictive model controlling heat injection in a borehole was developed by Laferrière and Cimmino (2019) to anticipate peak heating demand and reduce the use of auxiliary heat in GSHP systems. The strategic use of heat allows optimum sizing of the borehole.

In this study, M-TES charged with IWH offers available heat to a site where GHE recharging is required. As shown in Figure 1, a four-pipe GHE with two independent circuits is used to enable simultaneous recharging of the ground and heat pump operation. The objective of the simulations is to identify the influence of injection duration and frequency on GHE length and GSHP energy consumption, with the aim of reducing them.

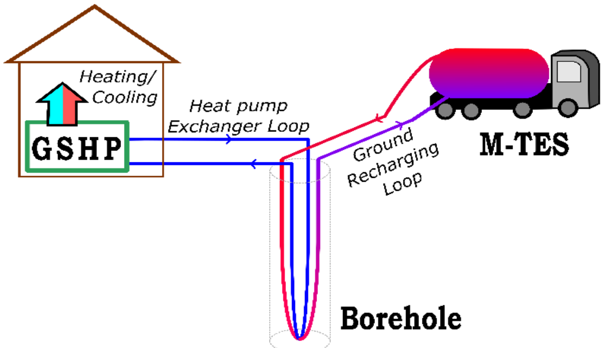

Figure 1: Schematic description of the system under investigation

This article does not intend to develop an effective strategy for achieving financial and energy improvements for the building studied, nor to optimize all the parameters of ground recharge. Rather, it aims to study this process in a simple case, in order to identify opportunities and developments that can be studied in the future.

System under study

The system under study is simulated in TRNSYS. This system is largely inspired by the TRNSYS model developed by Sabbagh et al. (2021). The four main components of the system will now be briefly described.

Building

The residential building is composed of three floors, including a basement. Each story has a 139 m^2 area. It is modelled in TRNSYS using Type 56. It is designed to comply with the National Energy Code of Canada for Buildings (NCEB, 2022). The heat gains from occupants and equipment are those provided by Swinton et al. (2002). The peak heating and cooling loads are 13.1 kW and 6.3 kW, respectively. Simulations are preformed using the latest typical meteorological year for Montréal (CWEC2020) for Montreal-Trudeau (Environment Canada, 2022).

The building is heated and cooled with a water-to-air heat pump activated by a central thermostat. The cooling set point is 24°C. Three-stage heating is provided. The heat pump is activated in the first stage when the interior temperature is below 21°C and remains active even when auxiliary heat is started. The first stage of auxiliary heat (the second heating stage), providing a 15 kW heating power, is activated when the interior temperature falls below 20°C. Finally, the second stage of auxiliary heat (the third heating stage), is activated when the interior temperature is below 19°C, adding another 15 kW heating power. This second stage is never needed in the cases studied here.

Ground-Source Heat Pump

The water-to-air heat pump is modelled using Type 919 in TRNSYS. The rated heating capacity (at 10°C) of the GSHP is set at 9.67 kW. This capacity is selected to meet the criteria set by standard C448 (ANSI/CSA/IGSHPA, 2021), where:

1. The heat pump should be sized to cover at least 65 % of the design heat load for a borehole return temperature of 0°C.
2. Auxiliary heating should provide less than 5 % of the house heating energy over a year.

The other caracteristics of the GSHP are listed in Table 1.

Table 1 : Characteristics of the heat pump.

Parameter	Value
Rated heating capacity	9.67 kW
Rated heating power	2.06 kW
Rated cooling capacity	11.6 kW
Rated cooling power	2.00 kW
Auxiliary power : stage 1	15.0 kW
Auxiliary power : stage 2	15.0 kW
Air flowrate	495 L/s
Liquid flowrate	1663 kg/h

The variation of the heating capacity and COP as a function of the entering fluid temperature over the range -1°C to 32°C is given in Figure 2. The performance data used is the TESS default values for Type 919 which are based on the performance of a commercially-available heat pump. It is shown that the heating COP varies from around 4 to 6 while the heating capacity varies between 7 kW and 13 kW.

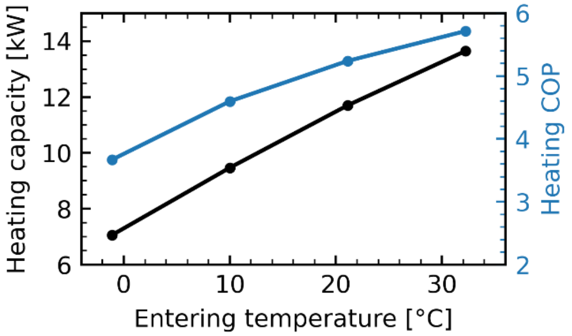

Figure 2 : Heating Capacity and COP of the heat pump

Double U-tube borehole

One key aspect of the present study is the use of a double U-tube borehole with two independent circuits to decouple the recharging and heat pump circuits. This model was developed by Godefroy (2014) and is part of a suite of TRNSYS types that simulates single boreholes and borefields (Bernier et. al., 2024). Type 203 of this suite (equivalent to Type 243 in Godefroy's thesis) is based on the model presented by Eslami-nejad and Bernier (2011). As shown in Figure 3, the four pipes interact with each other and exchange heat with the ground through the borehole wall (T_b). In this approach, grout thermal capacitance is neglected.

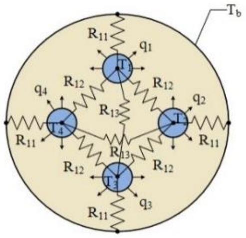

Figure 3 : Schematic representation of the borehole and thermal resistances between pipes (Eslami-Nejad, 2011)

The resulting temperature distribution within each pipe is given by:

$$\begin{aligned} T_1(z) - T_b &= R_{11}q_1 + R_{12}q_2 + R_{13}q_3 + R_{12}q_4 \\ T_2(z) - T_b &= R_{12}q_1 + R_{11}q_2 + R_{12}q_3 + R_{13}q_4 \\ T_3(z) - T_b &= R_{13}q_1 + R_{12}q_2 + R_{11}q_3 + R_{12}q_4 \\ T_4(z) - T_b &= R_{12}q_1 + R_{13}q_2 + R_{12}q_3 + R_{11}q_4 \end{aligned} \quad (2)$$

Godefroy (2014) explains how to determine the various thermal resistances (R_{11}, R_{12}, R_{13}). The value of T_b is obtained using the Finite Line Source analytical solution to ground heat transfer (Eskilson, 1987) and load aggregation is performed using Liu's technique (Liu, 2005) as detailed by Godefroy (2014). The model predicts the outlet fluid temperature from both circuits (outlet of pipes 3 and 4) for given values of the inlet temperatures (inlet of pipes 1 and 2). The model was successfully verified by Godefroy (2014) by comparing the results with a thermal resistance capacitance (TRC) model which uses a different approach than the one used in Type 203. The TRC model was later experimentally validated by Godefroy et. al. (2014) and Marcotte and Bernier (2019).

It is important to define the various energy flows into and out of the borehole. As shown in Figure 4, the injected heat rate Q_{Inj} is defined as the total energy rate leaving the recharging branch of the borehole. This energy is transferred both to the heat pump branch and to the ground. The ground load Q_{Ground} is defined as the net energy rate from the ground to the borehole wall, taking into account the injected energy. It can be negative in case of injection or when the heat pump works in cooling. Q_{GHE} is the heat carried by the ground heat exchanger loop to the heat pump:

$$Q_{Ground} = Q_{GHE} - Q_{Inj} \tag{3}$$

When no heat is injected into the ground, the double U-tube borehole acts as a regular single U-Tube borehole with $Q_{Ground} = Q_{GHE}$. The extracted heat transferred to the heat pump can be expressed as follows when the heat pump is in heating mode:

$$Q_{GHE} = Q_{Heat}\left(1 - \frac{1}{COP}\right) \tag{4}$$

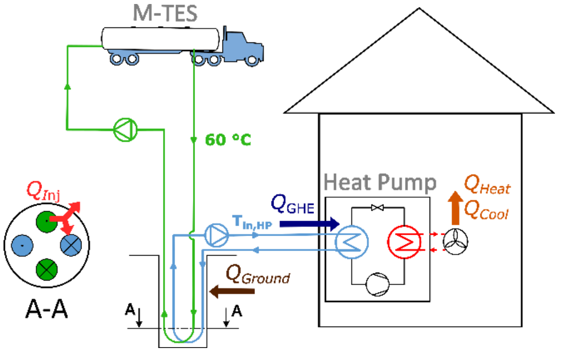

Figure 4 : Detailed representation of the system

It is important to note that when there is injection, the return temperature from the borehole will increase, thus increasing the COP and heating capacity (see Figure 2). In turn, this increases the amount of heat to be exchanged in the borehole.

The required borehole length is determined based on a minimum return borehole fluid temperature (i.e. heat pump inlet temperature, $T_{in,HP}$) of 0 °C. For the reference case (without recharging), the borehole length was determined to be 190 m for the conditions listed in Table 2. Finally, in this study, energy consumption from both circulating pumps is not considered.

Table 2 : Characteristics of the GHE.

Parameter	Value
Borehole length (reference case)	190 m
Buried depth	3 m
Ground thermal conductivity	2.22 W/m-K
Ground thermal capacitance	2000 kJ/m^3-K
Undisturbed ground temperature	10 °C
Grout thermal conductivity	1.67 W/m-K

Mobile Thermal Energy Storage

The truck carrying the IWH to the borehole is simulated in TRNSYS with Type 1537, which models a horizontal fluid storage tank without an internal heat exchanger. The tank volume is set at 10 m^3, corresponding to a medium size tank truck. Heat losses to the environment are assumed to be negligible. The temperature stratification inside the tank is represented by five isothermal nodes occupying the same volume. Heat transfer between nodes is determined with both thermal conduction and fluid displacement (due to convection or flows in and out of the tank). Figure 5 shows the stratification and the thermal evolution inside the tank, when water flows from the tank into the borehole for the ground recharge. Due to stratification, the water on top of the tank, which is injected in the ground, is warmer than the lower layers.

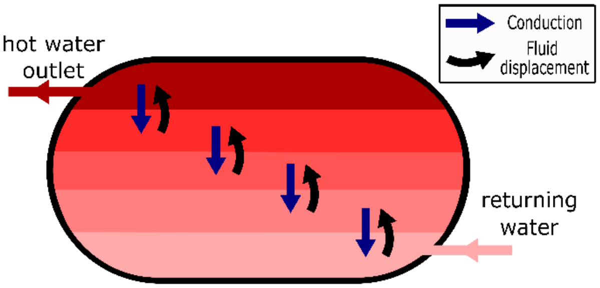

Figure 5 : Schematic representation of the tank during ground recharge

Before each heat injection in the borehole, the tank is reloaded with hot water from IWH, and reaches a uniform temperature of 60°C. This article focuses on the ground injection phase, hence the process of loading the M-TES is not examined in detail.

Reference case (without recharge)

The first studied case is the reference case without recharge. Thus, the borehole acts as a regular single U-tube borehole. As noted earlier, the required length is 190 m.

Monthly and yearly performance

The simulations are performed in TRNSYS over a three-year period with a 15-minute time step. As the weather and occupation data represent only one year, the same data is repeated over the three years.

Figure 6 represents the evolution of $T_{in,HP}$ during the three simulated years. The minimum entering temperature (0°C) occurs in January, at the peak of the heating period. This peak condition is used to determine that 190 m of borehole is needed to meet the heating load. It can be considered that the entering fluid temperature reaches a steady-periodic state at year 3, and in the following only the system performance in year 3 will be studied.

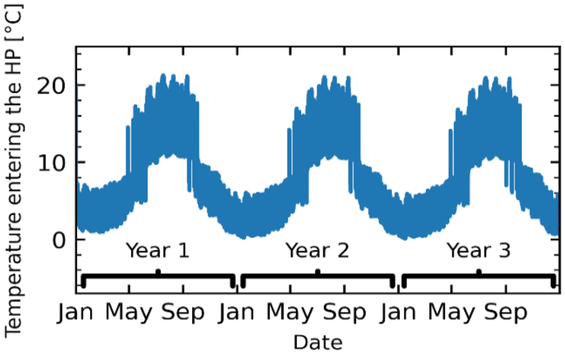

Figure 6 : Inlet temperature to the heat pump

The annual energy performance indicators of the system are presented in Table 3. The total heat pump energy consumption is the electrical power required by the heat pump for the compressor, the circulating fan and the auxiliary heater. The ground load, Q_{Ground}, has a positive value indicating that more energy is extracted from the ground than is rejected.

Table 3 : Annual energy performances of the reference case.

Parameter	Value
Auxiliary heat	1.01 MWh
Heating needs	24.3 MWh
Cooling needs	3.6 MWh
Ground load	11.0 MWh
Total HP consumption	8.74 MWh

The monthly energy consumption is presented in Figure 7. Cooling is used in the building from May to September, and in this period the heating is low compared to the needs of the other months. In winter, the heat extracted from the ground does not grow proportionally to the heating load provided by the heat pump, because when the needs increase, a bigger part is fulfilled by the auxiliary that does not take heat from the ground.

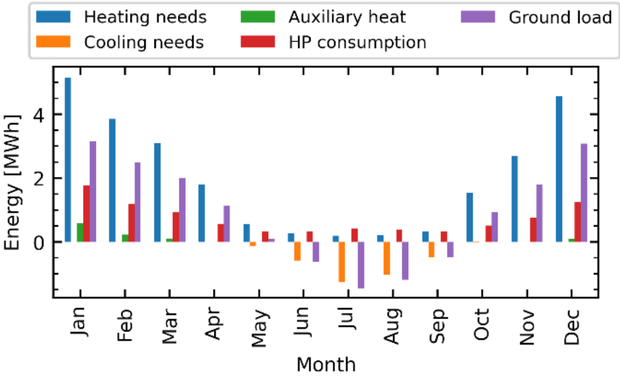

Figure 7 : Monthly energy performances of the GSHP

Injection

The injection of hot water in the borehole follows a regular pattern. There is no injection from May to September, when the building uses mainly cooling and the heat pump rejects heat to the ground. The injection is always performed at the same hour of the day, set at 8 pm. The flowrate of injection is 20 000 kg/h. Several frequencies and durations of injection are considered to determine their impact on the performance of the system. The tested delays between two injections are 1, 2, 4, 7 and 14 days, and the tested durations of injection are 30 minutes, 1 hour, 2 hours and 4 hours. During an injection, water flows continuously from the M-TES tank in the recharge circuit and returns to the tank. The heat injected over a year in the borehole depends on both injection duration and frequency.

Figure 8 presents the heat pump energy consumption (including the auxiliary heating) coupled to a 190 m deep borehole for different recharge frequencies and durations. The dotted line represents the reference consumption of the system without any recharge. In the case where a recharge is performed every day for a duration of 4 hours, the energy consumption is reduced by 14 % compared to the reference system. This reduction can be explained by a higher heating COP of the heat pump, caused by the increased returning fluid temperatures from the borehole. Additionally, the higher working temperatures also increase the heating capacity of the heat pump. There are then lower needs for auxiliary heating, thereby further decreasing the energy consumption of the system.

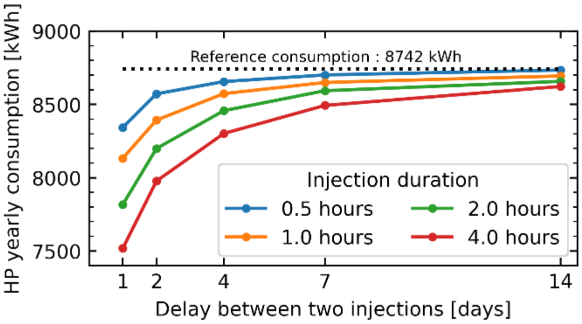

Figure 8 : Energy consumption of the heat pump system with heat injection in the ground

The efficiency of the injection can be defined by the ratio between the energy savings and the energy transferred to the ground from the IWH:

$$\eta = \frac{E_{HP} - E_{HP,ref}}{E_{Inj}} \qquad (5)$$

where E_{HP} and $E_{HP,ref}$ are the GSHP yearly energy consumption in the recharge and reference case scenarios, and E_{Inj} is the thermal energy injected into the ground. It is calculated as the difference between the energy rates leaving and entering the tank, integrated over a year.

The injection efficiencies for different scenarios are shown on Figure 9. As can be seen, most strategies have injection efficiencies between 4.3 % and 5 %. Thus, the energy savings represent a relatively small part of the thermal energy injected into the ground.

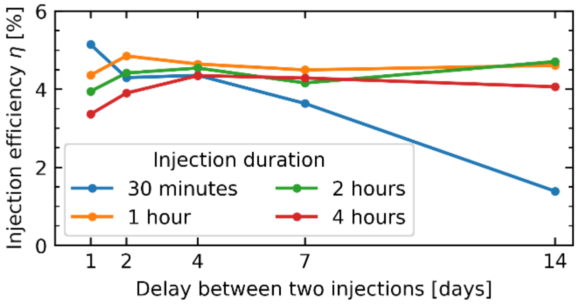

Figure 9 : Injection efficiency of the different scenarios

As mentioned earlier in conjunction with Equation 1, the borehole length required depends directly on the thermal load on the ground, considering multiple time scales. The recharging of the ground contributes to balancing the ground load, and a reduction of the necessary borehole length can be expected.

For each injection scenario, the depth of the borehole is recalculated so that the minimum inlet temperature to the heat pump is 0°C. These new lengths are presented for each injection frequency and duration in Figure 10.

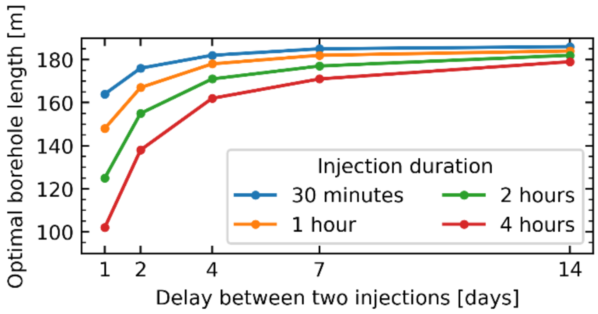

Figure 10 : Optimized borehole length with heat injection in the ground

The optimal borehole length decreases when the duration and the frequency of the recharge increase, i.e. when the amount of heat injected into the ground increases. For an injection of 4 hours performed every day, the borehole length drops to 102 m. This represents a reduction of 46 % in comparison to the borehole length of the reference case.

Detailed analysis for one day

Figure 11 presents the evolution of the heat extracted by the heat pump in the GHE and the heat pump COP between January 3, 7:00 AM and January 4, 8:00 AM. The three curves show the reference case and the scenarios of an injection every 2 days for two hours, with and without reduction of the borehole length. Heat is injected into the ground between 8 AM and 10 AM.

The extracted heat during the injection is calculated as the energy extracted by the GHE circuit to the GSHP. Thus, it includes the heat taken from the ground and the heat directly exchanged between the two pipes. The drops in ground load witnessed during the simulation indicate that the HP stopped functioning (i.e. the HP is cycling).

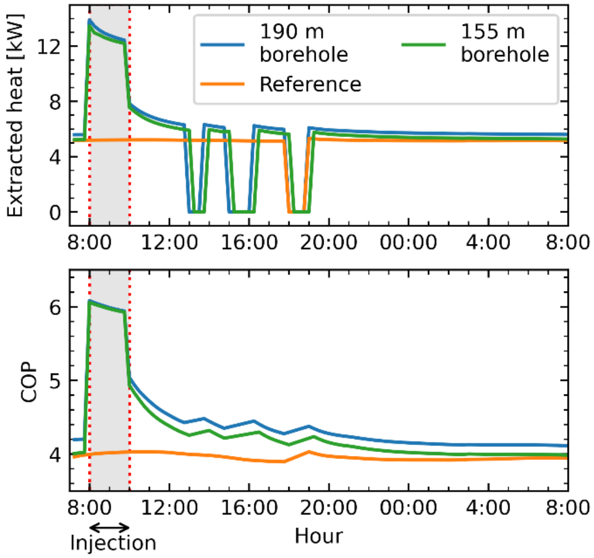

Figure 11 : Ground load and COP during one day following a 2-hours heat injection

Right after the ground recharge, the fluid enters the GSHP at a higher temperature, and the performance is boosted in comparison with the reference without any injection. This implies a higher heat extraction from the ground as indicated earlier with reference to equation 4.

This impact of the injection on the following performance of the GSHP is lasting in the case of a 190 m borehole. We can see that even 24 hours later, the COP is still higher than in the reference case. When the borehole length is optimized to 155 m (to meet the minimum returning temperature criterion), the COP and the ground load approach the reference values after one day.

Ground load

The required length of the GHE associated to the GSHP can be approximated with the help of the ASHRAE sizing presented earlier (equation 1).

In this study, the values of the effective thermal resistances are $R_b = 0.142$ m.K/W, $R_h = 0.093$ m.K/W, $R_m = 0.160$ m.K/W, $R_y = 0.172$ m.K/W. These values are calculated using the sizing calculation spreadsheet developed by Philippe et al (2010). They are assumed to remain constant when heat is injected and when the borehole length is modified, because they mainly depend on the ground properties which are assumed to remain constant.

The three typical ground loads have similar weights in the determination of the borehole length; all three have a significant impact on the reduction of the GHE length.

Figure 12 presents the values of q_h, q_m and q_y evaluated for an injection every 2 days and for the different injection durations, using the optimized borehole length of 155 m shown on Figure 10. Positive ground loads mean that heat is extracted from the ground by the GSHP. The value of q_h is calculated as the ground load occurring when the temperature of the fluid returning from the borehole is minimum. This is not necessarily the peak hourly load, which occurs after a recharge of the ground in injection scenarios. Indeed, the ground load increases significantly just after injections, as the COP increases and more energy is extracted from the ground (see equation 4). However, the sizing equation is based on a T_o of 0 °C and the ground load q_h must correspond to this temperature. The maximum monthly load, q_m, occurs in January for every scenario.

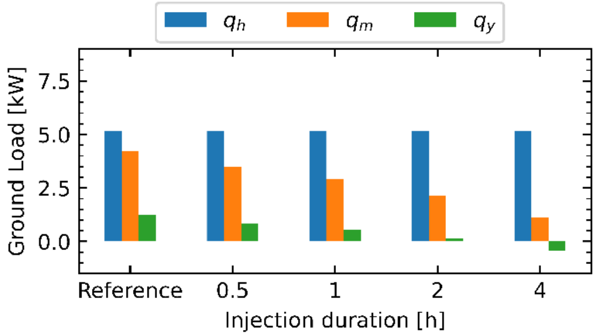

Figure 12 : Maximum hourly, monthly and annual ground loads for an injection every 2 days

The scenario of 2 hour injection every two days appears to be optimal because the annual ground load, q_y, approaches 0, meaning that the annual amount of heat injected is equal to the amount of heat extracted. If more heat is injected into the ground, when the injection duration is 4 hours (for example), q_y becomes negative. A reversed imbalance could then affect the cooling performance during the summer.

The three variables q_h, q_m and q_y provide insights into the ground behavior and its ability to deliver heat to the GHE. The decrease in the values of the monthly and yearly loads are responsible for the decrease in the required borehole length. The typical annual and monthly ground loads, q_y and q_m, decrease as expected when the injected heat is increased. This is not the case for the maximum hourly ground load q_h, which is constant for all scenarios. As can be seen in equation 4, q_h only depends on the capacity and the COP of the GSHP that are both determined with the temperature entering the heat pump $T_{in,HP}$, here set to 0°C. Thus, the hourly load cannot be modified, and the injection only influences variables q_m and q_y. Furthermore, the total energy injected by the recharge during the year almost goes totally in the ground. The decrease of q_y can be determined this way and is bounded if the quantity of IWH to inject over the season is limited. Finally, the parameter q_m could be modified by changing the frequency of the recharges to inject more energy during the cold months.

This preliminary analysis shows that the process studied here can be improved by introducing more complex injection strategies. Using IWH to inject into the ground is here profitable, because it allows to plan the injections to optimize the benefits.

Discussion

The process studied here achieves the expected result, namely a reduction in the necessary GHE length for the GSHP. The tested heat injections lead to a reduction of the heat exchanger size by up to 46 % of its initial size. This can be compared to the solar heat injection in boreholes, which was discussed in several studies. The solar assisted systems, when combined to latent heat storage, lead to a similar reduction of the GHE length.

However, the process studied here is an inefficient use of the available heat. The borehole length reduction is linear with the injected heat, with around 2 % of length reduction for each MWh of injection. Thus, 25 MWh of heat is required to divide the borehole length by two, which is more than the actual heating needs of the house.

This low efficiency could be partly explained by the rather low quality of the heat, that could hardly be used directly in heating applications. More significantly, it is linked to the fact that the heat pump capacity in this study is always kept the same, whereas the available heat increases with the heat injection. The heat pump happens to be oversized for the injection scenarios, which leads to an excessive use of the injected heat. As the nominal capacity is more easily reached with the injection process allowing higher returning temperatures to the heat pump, this nominal capacity can be reduced to fit the real needs of the house. The hourly ground load, q_h, would then be decreased, facilitating the heat exchanger length reduction.

Even if this process has shown potential to reduce the length of boreholes in GSHP systems, it should still be analyzed more precisely to define its possible applications. More injection parameters such as flowrate or tank size should be optimized as well. A smarter injection strategy could be developed, taking into account the weather data and constraints, for instance a limited quantity of available heat or schedule restrictions. Eventually the costs and feasibility of the use of IWH should be analyzed. The financial aspect has purposedly not been addressed in this study, since it is meant to be a preliminary analysis to assess if the ground recharge process presents a general potential in improving GSHP system performances. The cost balance of such projects depends on many factors, that were not examined here to keep a simple view over the process.

Conclusion

This study presents a process designed to use available industrial waste heat to recharge a double U-tube borehole ground heat exchanger and reduce borehole length and energy consumption of a ground-source heat pump system. The study focuses here on a typical house in Montréal modeled in TRNSYS.

Simple heat injection strategies are tested with different frequencies and duration, to understand the potential of this method. The evolution of the heat pump energy consumption and of the necessary borehole length are observed and indicate the benefits of these injections.

This method leads to a small reduction of the heat pump energy consumption, up to 10 % when compared to the no-recharge reference case. However, the benefits are much greater with the necessary borehole length, that can be almost divided by two.

This initial analysis of the proposed process is encouraging and should be followed by further studies to develop a feasible methodology of recharging GHE with available waste heat.

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References

Ahmadfard, M. and M. Bernier. (2019). A review of vertical ground heat exchanger sizing tools including an inter-model comparison, *Renewable and Sustainable Energy Reviews 110*, 247-265.

Ahmadfard, M., M. Bernier, and M. Kummert. (2016). Evaluation of the design length of vertical geothermal boreholes using annual simulations combined with GenOpt. *Proceedings from the eSim 2016 Building Performance Simulation Conference*, Hamilton (Canada), 3-6 May 2016.

ANSI/CSA/IGSHPA (2021). *Design and installation of ground source heat pump systems for commercial and residential buildings (C448 Series-16).*

ASHRAE (2011). Geothermal Energy, Ground-Source Heat Pumps, Ground-coupled heat pumps, Vertical design (34.14-34.16), In *ASHRAE Handbook - HVAC Applications.* I-P Editions.

Bastani, A., A. Nguyen, P. Eslami-Nejad, and M. Badache. (2023) Numerical investigation of using a field of shallow boreholes with latent heat storage and solar injection in cold climates. *Geothermics*, *112*, 102729

Bernier, M. and collaborators. (2024). PolyGHE – TRNSYS suite to simulate borefield. Software (dll) available at *http://www.profs.polymtl.ca/michel.bernier/Open_geo.html.*

Brischoux, P. (2016). Stockage thermique saisonnier par puits géothermiques pour bâtiments résidentiels équipés de panneaux photovoltaïques-thermiques. *M.A.Sc thesis,* École Polytechnique de Montréal, Montréal (Canada).

Laferrière, A. and M. Cimmino. (2019). Linear model predictive control for the reduction of auxiliary electric heating in residential self-assisted ground-source heat pump systems. *Science and Technology for the Built Environment*, *25(8)*, 1095-1110.

Du, K., J. Calautit, P. Eames, and Y. Wu (2021). A state-of-the-art review of the application of phase change materials (PCM) in Mobilized-Thermal Energy Storage (M-TES) for recovering low-temperature industrial waste heat (IWH) for distributed heat supply. *Renewable Energy, 168*, 1040-1057.

Environment Canada, (2022). Engineering Climate Datasets: *https://climate.weather.gc.ca/prods_servs/engineering_e.html*

Eskilson, P. (1987). Thermal Analysis of Heat Extraction Boreholes. *Ph.D. thesis*, University of Lund, Lund, (Sweden).

Eslami-nejad, P. and M. Bernier. (2011). Heat transfer in double U-tube boreholes with two independent circuits, *ASME Journal of Heat Transfer 103(8).*

Eslami-Nejad, P. and M. Bernier. (2011). Coupling of geothermal heat pumps with thermal solar collectors using double U-tube boreholes with two independent circuits. *Applied Thermal Engineering 31(14-15)*, 3066-3077.

Eslami-Nejad, P. and M. Bernier. (2012). Simulations of a new double U-tube borehole configuration with solar heat injection and ground freezing. *Proceedings from eSim 2012, the 7th Conference of IBPSA-Canada*. Halifax (Canada), 1-4 May 2012.

Fascì, M.L, A. Lazzarotto, J. Acuna, and J. Claesson. (2021). Simulation of thermal influence between independent geothermal boreholes in densely populated areas, *Applied Thermal Engineering 196*, 117241.

Godefroy, V. (2014). Élaboration et validation d'une suite évolutive de modèles d'échangeurs géothermiques verticaux. *M.A.Sc thesis,* École Polytechnique de Montréal, Montréal (Canada).

Godefroy, V., C. Lecomte, M. Bernier, M. Douglas and M. Armstrong. (2016). Experimental validation of a thermal resistance and capacity model for geothermal boreholes. *Proceedings from ASHRAE winter conference*, Orlando (USA), 23-27 January 2016.

Government of Québec. (2023). Programme Valorisation des rejets thermiques – cadre normatif. *Available at https://cdn-contenu.quebec.ca/cdn-contenu/environnement/rejets-thermiques/cadre-normatif-valorisation-rejets*-thermiques-02-2024.pdf

Guo F., X. Zhu, P. Li, X. Yang. (2022). Low-grade industrial waste heat utilization in urban district heating: Simulation-based performance assessment of a seasonal thermal energy storage system. *Energy 239(E)*, 122345.

Kjellsson, E., G. Hellstrom, G., and B. Perers. (2010). Optimization of systems with the combination of ground-source heat pump and solar collectors in dwellings. *Energy 35(6)*, 2667-2673.

Liu, X. (2005). Development and Experimental Validation of Simulation of Hydronic Snow Melting Systems for Bridges. *Ph.D. thesis*, Oklahoma State University, Stillwater (USA).

Marcotte, B. and M. Bernier. (2019). Experimental validation of a TRC model for a double U-tube borehole with two independent circuits, *Applied Thermal Engineering 162*,114229.

Miró, L., J. Gasia and L. F. Cabeza. (2016). Thermal energy storage (TES) for industrial waste heat (IWH) recovery: A review, *Applied Energy 179*, 284-301

National Research Council of Canada, (2022). *National Energy Code of Canada for Buildings: 2020. Canadian Comission On Building And Fire Codes.*

Philippe, M., M. Bernier and D. Marchio. (2010). Sizing Calculation Spreadsheet: Vertical Geothermal Borefields, *ASHRAE Journal*, *52(7)*, 20-28.

Marcotte, B. and 8 authors (2021). Évaluation du potentiel de valorisation des rejets thermiques au Québec. *Available at : transitionenergetique.gouv.qc.ca/fileadmin/medias/pdf/publications/Evaluation-potentiel-valorisation-rejets-thermiques-Quebec-2021.pdf*

Sabbagh, G. and M. Bernier. (2022). Climate change effects on the energy performance of a residential ground-source heat pump system. *Proceedings from International Ground Source Heat Pump Association annual Conference.* Las Vegas (USA), 06-08 december 2022.

Shehadeh, M., E. Kwok, J. Owen, and M. Bahrami. (2021). Integrating Mobile Thermal Energy Storage (M-TES) in the City of Surrey's District Energy Network: A Techno-Economic Analysis, *Applied Sciences, 11(3)*, 1279.

Swinton, M., H. Moussa and R. Marchand. (2001). Commissioning twin houses for assessing the performance of energy conserving technologies. *Proceedings from Performance of Exterior Envelopes of Whole Buildings VIII: Integration of Building Envelopes*, Clearwater Beach (USA), 2-7 December 2001.