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A technical and economic evaluation of a ground source heat pump with thermal and battery energy storage systems for residential dwellings in Quebec

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ABSTRACT

Ground source heat pump (GSHP) systems have been identified as promising solutions to help buildings achieve future carbon neutral targets. However, two main barriers decelerate the wide adoption of this technology in every location. One barrier is the high initial cost, which is sometimes justified by high local energy prices. The other potential barrier that always imposes a major bottleneck on a transition to electrification by using GSHP systems is the impact on the electrical grid at peak demand times. In this study, a solution has been proposed to address both issues by integrating thermal and battery energy storage systems into a conventional GSHP system. Numerical simulations are performed to evaluate the technical and economic feasibility of the proposed configuration. In addition, a comparative analysis is performed with other commonly recognized GSHP configurations with and without thermal energy storage. Results show that the new configuration requires a 22% shorter borehole by using the thermal energy storage, and reduces the annual peak electricity demand by almost 500kW cumulatively by using the battery energy storage. These benefits contribute to improving the net present value of the new configuration by 23% compared to the conventional GSHP configuration.

INTRODUCTION

The transition toward a sustainable society will be accelerated with greener and more energy-efficient technologies that emit lower amounts of greenhouse gas emissions (Shi et al. 2021). The heating and cooling energy use of buildings account for 22% of the total electricity produced (Schwartz et al. 2017). In this regard, ground-sourced heat pump systems (GSHP) offer an attractive solution in terms of energy efficiency and sustainability. But one of the major issues for their development is their high initial cost, which has resulted in a payback period of more than 14 years (Nguyen et al. 2016;Lu et al. 2017;Eslami Nejad et al. 2017). Because of this, in cold climate countries such as Canada, their most expensive components (boreholes and heat pumps) are usually designed undersized and topped up with a less efficient auxiliary heating system. The undersized system jeopardizes the superior energy efficiency of the GSHP systems. The addition of a less efficient auxiliary heating system, such as electric resistance heating in Quebec, Canada, not only increases the cost of the electricity bill for the user but also puts more pressure on the grid during peak hours. Therefore, several solutions have been proposed to further improve the efficiency of hybrid GSHP systems and address their high peak electricity demands.

To diminish the pressure on the grid, one possibility is the integration of thermal, electricity storage, or both systems into the GSHP system. By using thermal energy storage (TES), the excess heat produced during off-peak periods by the heat pump is stored in the storage medium and used during peak hours to meet the building's energy demand. Eslami Nejad et al. (2017) proposed a self-assisted GSHP system that is linked to a double U-tube borehole with two

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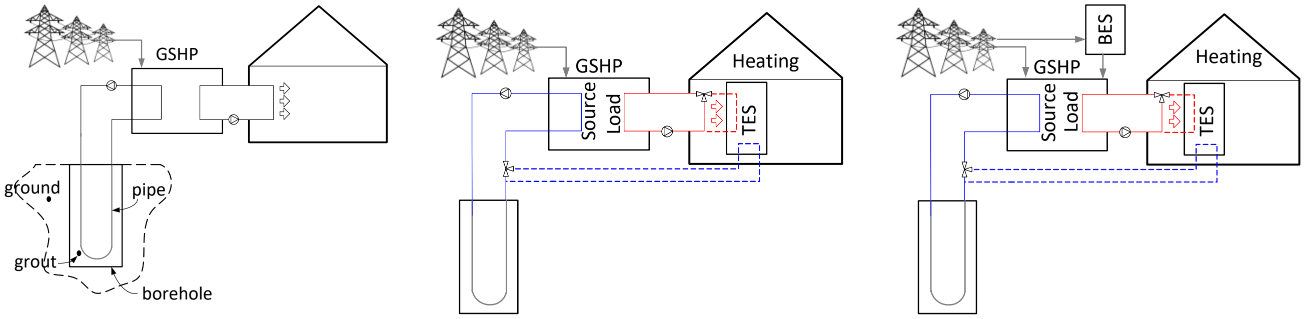
independent circuits. In this system, the ground plays the role of TES so that the excess heat produced by the heat pump during off-peak hours is injected into the ground through one of the U-tubes inside the borehole. The proposed self-assisted system can decrease the peak power demand by 47%. However, the proposed system increases the total power consumption by 4.1%. Shi et al. (2021) combined an underground hybrid water and phase-change-material (PCM) storage system with a GSHP system and showed that the electricity consumption during peak hours is reduced by 40%. However, they reported a 4.5% increase in total electricity consumption. In general, coupling the TES system with the GSHP system reduces the systems' peak power consumption significantly, as high as much as 50%, although the total power consumption increases by up to 8% (Shi et al. 2021;Hirmiz et al. 2019;Eslami Nejad et al. 2017). Lv et al. (2016) performed a thermal and economic analysis of a GSHP system integrated with a TES system for a typical building in Tianjin through a TRNSYS simulation. It was shown that coupling the TES system with the GSHP system could save 35.2% and 18.3% of the operation costs during the heating and cooling seasons, respectively.

Few studies have been conducted on building electricity storage using batteries to reduce or eliminate the electricity consumption of GSHP systems during peak hours. Kamazani et al. (2022) recently performed a techno-economic analysis of a combined GSHP, PCM, and photovoltaic thermal collector (PVT) system. Using multi-objective optimization, they concluded that the combined system can achieve both economic and energy efficiency targets. The results demonstrated that the annual necessary energy use of the GSHP system can be reduced by 6.5% using integrated PVT and batteries.

In this study, to address the peak electricity demand and the initial cost issues of GSHP systems, a TES system is integrated with a GSHP system; furthermore, a relatively small battery energy storage (BES) system is used to reduce the peak electricity demand during time periods identified by the local utility (Hydro-Québec). It is to take economic advantage of the existing rebate program offered by Hydro-Québec for reducing electricity consumption during peak hours. All this is conceptualized through a new GSHP configuration in which TES and BES are both integrated with a GSHP system. Comprehensive thermal and economic analyses are performed to investigate the merits of the proposed system in comparison with other cases.

2. Systems descriptions and case studies



(a) (b) (c)

Figure 1. Schematic presentation of the system configurations used for (a) Case 1, (b) Case 2, and (c) Case 3

In this section, a new GSHP configuration integrated with thermal and battery storage systems along with two other conventional GSHP configurations and a reference case with baseboard electric heating is described in detail.

2.1 Case R

This case refers to a conventional system used for the heating and cooling of residential dwellings in the province of Quebec, Canada. In Case R, an air conditioning system and an electric resistance baseboard system are used to provide the cooling and heating loads of a building, respectively. This case is used as a reference case, and its results are compared against other cases considered in this project.

2.2 Case 1

The subject of this case is a simple GSHP system, in which the heat pump is connected to a single U-tube vertical borehole. The heat pump capacity and the borehole size are such that 100% of the building's heating and cooling loads are fulfilled, and, therefore, there is no need for auxiliary heating/cooling in this case (Figure 1a).

2.2 Case 2

This case concerns a self-assisted GSHP system linked to a single U-tube borehole (Figure 1b). For this case, during the heating season, a TES tank (water and phase change material) is charged during off-peak hours using the extra heat produced by the heat pump. During peak hours, the stored energy is used to increase the GSHP's entering fluid temperature (EFT). The storage temperature is 25°C, and the tank is charged when the temperature is below 25°C. The control strategy is optimized to avoid unnecessary heat pump power consumption for charging the storage tank. The tank is used when the EFT falls below -6°C to prevent the HP from turning off. The heat pump capacity is the same as in Case 1, and the borehole is sized to ensure that the EFT does not reach the cutoff temperature (-6°C).

2.3 Case 3

Case 3 refers to the proposed new configuration where both TES and BES systems are used to store thermal energy and electricity respectively, during off-peak hours (Figure 1c). The BES system is used to supply heat pump power during high peak electricity consumption events announced in advance by Hydro-Québec (Quebec's public utility). The conditions for charging and discharging the TES tank are the same as in Case 2. For charging the BES system, the power consumption of the GSHP should be less than the GSHP's peak power consumption (in this case, 4.90 kW). During cooling seasons, Case 1, Case 2, and Case 3 operate identically (Figure 1a). In Case 3, the heat pump capacity and the borehole size are both the same as that in Case 2. Similar to cases 1 and 2, the heat pump in Case 3 never stops due to going beyond the cutoff temperature.

3. Methodology

3.1 Single U-tube borehole

The numerical model used for the single U-tube borehole is based on the work of Pasquier et al. (2012) with slight modifications to account for axial heat conduction inside the borehole. This model is a 3-D transient model that uses the thermal resistance and capacitance approach to simulate heat transfer inside the borehole and the ground. In this model, the thermal capacities of the grout and fluid are also taken into account. For the ground model, the transient heat conduction equations are discretized by using the finite volume method. The resulted system of linear equations is solved by using the Gauss-Seidel method

3.2. Thermal and battery energy storage

For the thermal storage tank containing phase change material (PCM) and water, a stratified model is used similar to the one used by Hirmiz et al. (2018). The PCM is considered to be encapsulated in 2 cm thick horizontal rectangular slabs. In this model, the heat transfer inside the tank is assumed to be one-dimensional and the PCM is considered to melt consistently in one direction. The parameters used for the simulation of the borehole and TES are all given in Table 1.

The BES system is modeled relatively simply without considering any efficiency or performance degradation. It is assumed that it takes one hour to charge the BES system (5kWh capacity) from 0% to 100%. Also, the battery size is selected to provide the entire required power of the heat pump during one hour.

Hourly simulations over a thirty-year period are performed for cases 1, 2, and 3; however, it is assumed that the results of Case R do not change over time, and therefore, in Case R, the hourly simulation results for the first year are applied to each year.

3.3 Building load

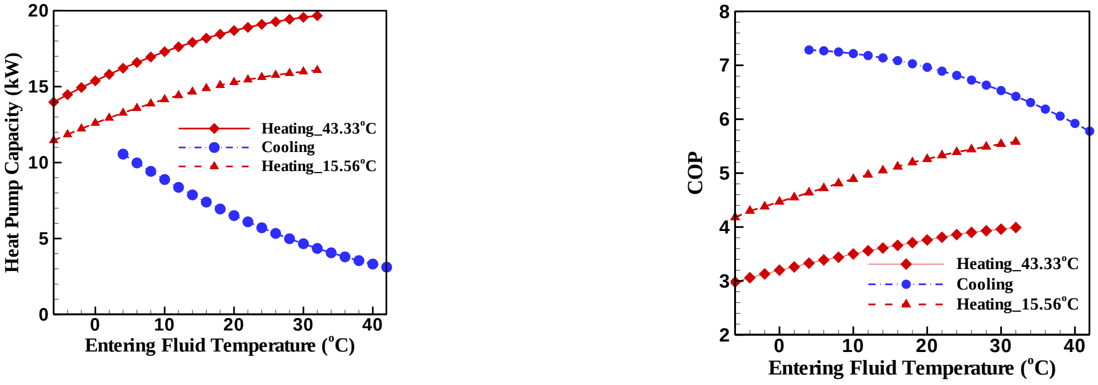
All the cases are used to provide heating and cooling loads of a 210 m² building . The building is a typical 1980's single-family detached home without ventilation located in Montréal, Canada (Kegel et al. 2012). An hourly load profile of this building is simulated using TRNSYS v.17 (Klein et al. 2010). The building's peak heating and cooling loads are 14.18 kW and 4.21 kW, respectively; furthermore, the building's annual space heating and cooling demands are 29,023 kWh and 1,510 kWh, respectively. Montréal's building load profile and ambient air temperature can be found in Eslami Nejad et al. (2017).

Table 1. Parameters used for case simulation

	Parameters	Value	Unit	Parameters	Value	Unit
Borehole	Diameter	15	cm	Shank	3.6	cm
Grout	Material	Sand+Bentonite+Water		Thermal capacity	983	J/(kg.K)
	Density	1984	kg/m³	Thermal conductivity	1.4	W/(m.K)
Pipe	Material	HDPE		Conductivity	0.48	W/(m.K)
	Wall thickness	0.4	cm	Density	1350	kg/m³
	Outer diameter	4.2	cm	Thermal capacity	900	J/(kg.K)
Ground	Thermal conductivity	2	W/(m.K)	Undisturbed temp.	10	°C
	Thermal diffusivity	0.075	m²/day	Initial temp.	10	°C
Working fluid	Type	Water-Ethylene Glycol (38%)		Flow rate	0.44	kg/s
	Density	1045	kg/m³	Specific heat	3720	J/(kg.K)
	Viscosity	1.254×10^{-2}	Pa.s	Thermal conductivity	0.4	W/(m.K)
TES tank	Type	Water+PCM (Calcium Chloride Hexahydrate)		Latent heat capacity	195	kJ/kg
	Melting temperature	25	°C	Sensible heat capacity	2.2	kJ/(kg.K)
	Volume	0.355	m³	Surface heat loss coefficient	0.9	W/(m².K)
	PCM Density	1530	kg/m³			

3.4 Heat Pump

For cases 1, 2, and 3, the same heat pump is used to provide the building's heating and cooling loads. The heat pump's COP and nominal heating capacity as a function of the EFT are demonstrated in figures 2a and 2b, respectively. The air conditioning system in Case R uses the same cooling COP and capacity curves as those shown in figures 2a and 2b to satisfy the building cooling load; however, the EFT is equivalent to the ambient air temperature in Case R. It is important to mention that to simulate the charging of the TES system and the heating of the building, the data from the 15.56°C and 43.33°C curves are used, respectively.



(a) (b)

Figure 2. (a) Heat pump capacity and (b) COP curves

3.3 Cost analysis

The initial costs of the systems are presented in tables 2 and 3 for Case R and cases 1-3 respectively. GSHP costs include the heat pump, borehole installation, and piping costs. The data presented by Hakkaki-Fard et al. (2015) are used with a price increase factor to account for inflation during these years. The initial cost of the TES is calculated based on material costs listed in Hirschey et al., 2018. The BES initial cost is considered 600$/kWh based on the average price of the existing battery manufacturer for houses.

Table 2. Total construction costs for Case R

	Mode	Type	Nominal Capacity (kW)	Cost (CAD)	Total Cost (CAD)
Case R	Cooling	Air conditioning system	5.42	1,390	3,030
	Heating	Baseboard	17	1,640	

Table 3. Total construction costs for cases 1, 2 and 3

	Heat pump Nominal Capacity at 20°C EFT (kW)	GSHP cost (CAD)	TES with PCM costs (CAD)	BES costs (CAD)	Total costs (CAD)
Case 1	19.36	22,120	0	0	22,120
Case 2	19.36	18,120	1,500	0	19,620
Case 3	19.36	18,120	1,500	3,000	22,620

The operating cost includes electricity consumption costs. Quebec's electricity rates for residential dwellings, which are 6.319¢/kWh for the first 40 kWh/day and 9.749¢/kWh for the remaining energy consumed, are used. Also, the rebate program in Quebec for the reduction of electricity use in residential homes during peak demand times is accounted for in the cash flow calculation for Case 3. In the rebate program, for a maximum of 100 hours during winter, if customers reduce their power consumption during the peak demand times by more than 2 kW, they enjoy a rebate of 51.967¢/kW on their electricity bill. Furthermore, it is assumed that the systems in cases 1, 2, and 3 are being financed through a bank loan in exchange for a cash down payment, future payments of the remaining principal amount, and the annual interest. The annual payment (loan repayment) is calculated based on the equations presented by Nguyen et al. (2022) as follows:

$$M_y = IC \times (1-d) \times \frac{f}{1-(1+f)^{-s}} \tag{1}$$

where, *IC*, *d*, *f*, *s,* and *y* are initial cost, rate of cash down payment, fixed loan term, loan term and year number, respectively. The other economic parameters include C_y, *NPC*, and *NPV*, which are cash flow at year *y*, net present cost, and net present value, respectively, and are calculated as follows:

$$C_y = M_y + (O_y - R_y) \times (1+i)^y \tag{2}$$

$$NPC = IC \times d + \sum_{y=1}^{30} \frac{C_y}{(1+r)^y} \tag{3}$$

$$NPV = NPC_{Case\,R} - NPC_{Case\,j} \quad where\ j = 1, 2 or\ 3 \tag{4}$$

In the above equations, O_y and Ry are the operating costs and the rebate at year number y, respectively; in addition, i and r are the inflation and discount rates, respectively. The amounts of the discount rate, inflation rate, fixed loan term, and rate of cash down payment are 7%, 3.4%, 3%, and 20%, respectively. Also, the amount of the loan term (*s*) is assumed to be 5 years.

RESULTS AND DISCUSSION

This section consists of two parts. In the first part, the results of the thermal performance evaluation of all the cases are presented using the total energy use (EU_{total}), the peak electric power consumption (peak demand), the overall system coefficient of performance (COP), and other related parameters such as the thermal energy added to the fluid entering the heat pump from the TES system (Q_{st}) as well as the heat loss from the TES system (Q_{loss}). In the second part, the results of the economic evaluation of all the cases are quantified using the net present value (NPV) and the discounted payback.

As shown in Table 4, the reference case consumes the highest amount of electricity, three times more than Case 1 on an annual basis. As mentioned before, the issue of Case 1 might be the costs associated with the borehole installation. Results showed that the required borehole length can be reduced significantly if a TES tank (water+PCM) is integrated into Case 1. The borehole length is calculated so that the GSHP system never reaches the cutoff temperature (-6°C) while operating during peak hours.

As shown in Table 4, the borehole length is reduced by 22% in Case 2 compared to Case 1 (from 182 m in Case 1 to 142 m in Case 2) by integrating a 355-liter tank. Case 2 consumes 4% more electricity than Case 1 due to the heat loss from the TES tank and the fact that the GSHP system with a shorter borehole works at lower temperatures in the heating mode. In Case 2, 527 kWh is stored annually in the TES system to increase the EFT to above -6°C when required. The average annual heat loss from the TES system is also reported, at 77 kWh. The peak electric power consumption is nearly the same in cases 1, 2, and 3 (4.82 kW in Case 1 and 4.9 kW in cases 2 and 3) and it is significantly reduced (more than 60%) compared to Case R. The system installed in Case 3 is the same as the one installed in Case 2 except for a relatively small BES system (5 kWh), which is added to take advantage of Quebec's rebate program for reducing the electricity consumption at peak times. The BES system is used to supply the electricity to the GSHP system during 100 events (100 hours) announced in advance by Hydro-Québec. As presented in Table 4, using the BES system does not have any effect on the system's energy performance, and, therefore, the results for Case 3 are the same as those reported for Case 2.

Table 4. Results of 30-year simulations (annual average values)

	Borehole Length (m)	Thermal Storage Tank Volume (m^3)	Battery Capacity (kWh)	EU_{total} (kWh)	Peak Demand (kW)	COP	Q_{ST} (kWh)	Q_{loss} (kWh)
Case R	NA	0	0	29233	14.18	1.04	NA	NA
Case 1	182	0	0	9299	4.82	3.28	NA	NA
Case 2	142	0.355	0	9725	4.90	3.14	527	77
Case 3	142	0.355	5	9725	4.90	3.14	527	77

In the second part, the results of the economic analysis are discussed. As mentioned in the cost analysis section, for cases 1, 2, and 3, 20% of the construction costs are paid upfront (initial costs) and the rest is paid in equal yearly payments over 5 years (loan term equals 5 years). As shown in Table 5, Case R has the highest net present cost (NPC), which is $46,227. It is worth mentioning that 93% of the NPC of Case R is its electricity costs ($43,197). The net present value (NPV) of the other cases is calculated based on Case R (Equation 4). As shown in Table 5, Case 3 has the highest NPV ($18,733). Quebec's rebate program for the reduction of consumption at peak times contributes to this case's NPV increase of $4,493 over 30 years. It is worth mentioning that Case 2 can reduce the peak of Case R significantly; however, it cannot reduce the peak power demand of Case 1 since it has a shorter borehole. In order to use the rebate, peak reduction is calculated and compared against similar systems, Case 1, 2, and 3. Although the electricity consumption of Case R is 300% greater than that of cases 3 and 2, its electricity cost is 383% greater. This is due to Hydro-Québec's different electricity rates for under and over 40kWh daily consumption. Cases 1, 2, and 3 rarely consume more than 40kWh of electricity per day. Among cases 1, 2, and 3, Case 1 has the lowest NPV due to the higher borehole construction costs. However, this case has the lowest electricity cost, which is four times less than the electricity cost of the reference case (Case R) but only 4% less than the electricity costs of cases 2 and 3. Using Case 3 instead of Case 1 improves the NPV by 23% over 30 years.

Table 5. Results of the economic analysis

	Initial Costs (CAD)	Loan Repayment (CAD)	Electricity Costs (CAD)	Rebates (CAD)	NPC (CAD)	NPV (CAD)	Discounted Payback (Years)
Case R	3,030	0	43,197	0	46,227	0	-----
Case 1	4,424	15,843	10,786	0	31,053	15,174	12.1
Case 2	3,924	14,053	11,262	0	29,238	16,989	10.4
Case 3	4,524	16,201	11,262	4,493	27,494	18,733	10.9

For Case 1, the discounted payback is calculated slightly over 12 years based on the costs of the reference case; however, it is calculated at 10.4 and 10.9 years for Case 2 and Case 3 respectively. Although the increase in the NPV is noticeable if Case 3 is used, the discounted payback might not encourage the building owners to invest in the technology. It is worth mentioning that the loan term (5 years) has a significant impact on the discounted payback of cases 1, 2, and 3. For instance, the loan term of 20 years with an upfront payment of 20% of the system costs, potentially drops the discounted payback of both cases 2 and 3 below 2 years which will be very attractive for building owners. This means that if the borehole installations are at least considered as part of the building infrastructure, the long-term loan can be used to significantly reduce the technology's discounted payback. In terms of the discounted payback, Case 2 shows a slightly earlier return of investment compared to Case 3; however, Case 3 presents the highest NPV among all cases considered in this study.

CONCLUSION

In this paper, a new GSHP configuration integrated with both thermal and battery energy storage systems is investigated to quantify its economic and thermal performance. This configuration is compared against conventional GSHP configurations and the commonly used electric resistance baseboard and air conditioning system in Quebec, Canada. It is shown that using the rebate program for reducing electricity consumption at specific peak times, the new configuration integrated with TES and BES systems presents the highest NPV over a 30-year operation period. Furthermore, the annual electricity consumption and the peak power consumption of all the GSHP cases (cases 1-3) are significantly reduced, by more than 60%. Due to the different electricity rates for different daily electricity consumption levels, the electricity price can be reduced by as much as 75% compared to the base case with electric resistance baseboard heaters.

Future works on this topic would include accounting for depreciation costs of system components such as the heat pump, the battery, the air conditioning system, and the baseboard electric heater. Furthermore, the model of the battery can be improved to account for the performance and capacity degradation over years. Parametric analysis of the effect of electricity costs, borehole installation costs, and battery costs on the NPV of the cases would also be beneficial for making the right choices.

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NOMENCLATURE

C_y = Cash flow
d = Rate of cash down payment
f = Fixed loan term
i = Inflation rate
IC = Initial cost
M_y = Loan repayment
NPC = Net present cost
NPV = Net present value
O_y = Operating cost
r = Discount rate
R_y = Rebate cost
s = *Loan term*

Acronyms

BES = Battery energy storage
EFT = Entering fluid temperature
GSHP = Ground source heat pump
PCM = Phase change material
TES = Thermal energy storage

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