IGSHPA Research Track
Las Vegas, December 6-8, 2022

Economic Optimization and Parametric Analysis of Large Hybrid Ground Source Heat Pump Systems: A Case Study

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ABSTRACT

Hybrid ground source heat pump systems offer a solution to reduce initial costs and make systems more economically viable. Their design is however complex and their financial profitability difficult to establish. The design of hybrid system is usually determined by following rough rules and is neither mathematically rigorous nor optimized. In this paper, a methodology recently introduced by the same authors for economic optimization of hybrid ground source heat pump systems is used to carry out a parametric analysis and assess the impact of uncertainty on the optimal design solution. The results show that all the parameters have signifcnant impact on the optimization, and the ground heat exchanger construction costs and ground source heat pump COP had the most impact on the net present value. Howver trends are difficult to observe because if the non-linear nature of the problem, and thus there is a need for more robust optimization of hybrid GSHP systems under uncertainty.

INTRODUCTION

Ground source heat pump (GSHP) systems are considered as a solution for efficient heating and cooling in buildings (Qi et al. 2004). In order to reduce project costs, they are often integrated with auxiliary heating/cooling systems to cover peak demands of buildings (Soni et al. 2016). However, demonstrating the financial viability of these so-called hybrid GSHP systems is a challenge due to the varying technical and economic conditions at each site and in each city.

There exist many studies on economic analysis of hybrid GSHPs, from simple techno-economical analysis (Seo et al. 2018, Yousefi et al. 2018) to more complex financial optimization approaches (Retkowski et al. 2014, Henault et al. 2016, Nguyen et al. 2016, Ikeda et al. 2017, Kayaci et al. 2018, Beckers et al. 2018, Aditya et al. 2020, Dusseault and Pasquier. 2021). Finding the optimal design of a hybrid GSHP system that minimizes the expected long-term cost while providing significant energy savings remains a complicated and computationally tedious task. In general, the difficulty of optimizing GSHP systems can be mainly associated with three tasks. First, it calls for the repetitive construction of the transfer functions of the borefield. Second, it involves constrained nonlinear programming for multi-year hourly simulations. Third, it requires finding the global optimal solution of a multidimensional multimodal cost function. Recently, Nguyen et al. (2022) developed a new simulation-based method that efficiently performs these three tasks for

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DOI: https://doi.org/10.22488/okstate.22.000027

rapid economic optimization of large hybrid geothermal heat pump systems. The objective of this article is to use this new algorithm to carry out a parametric analysis and assess the impact of uncertainty on the proposed optimal design.

METHODOLOGY

For large commercial buildings, hybrid GSHP systems can be a reliable alternative to conventional boiler and chiller systems. For a simple illustration, Fig. 1 shows a two-pipe system with terminal air handling (AH) units, but can be extended to four-pipe systems or water loop heat pump systems for simultaneous multi-zone cooling and heating. In such system, the GSHP serves as the primary system while the gas boilers and air-cooled chillers are used as back-up auxiliary systems during peak hours, hence the term "hybrid".

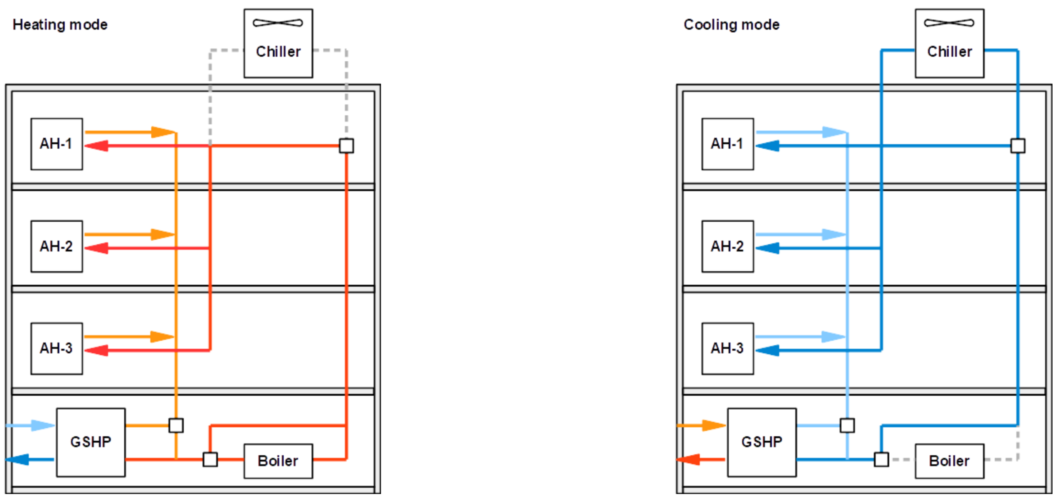

Figure 1. A hybrid ground source heat pump in a two-pipe system with terminal air handling (AH) units. Left: Heating mode. Right: Cooling mode.

On the source side of the GSHPs, we consider conventional vertical grouted ground heat exchangers (GHE) sized to maintain fluid temperature within design temperature limits so that the GSHPs can operate continuously as the system's first stage, even during peak periods. In off-peak periods, the auxiliary systems are bypassed with appropriate controls and valves, thereby maximizing system energy efficiency. We assume that the GSHPs are equipped with variable frequency drives to minimize cycling and maximize efficiency during part load periods.

Based on these assumptions, the energy saving provided by a given hybrid GSHP design is evaluated by means of dynamic hourly energy simulations. In this study, the methodology outlined in Nguyen et al. (2022) is used as a base for all simulation, optimization and parametric analysis. The general methodology aims to numerically model the hybrid GSHP system to assess its long-term cost and identify, through optimization algorithms, the design parameters that maximize its economic performance. The procedure in determining the optimal design outlined in Nguyen et al. (2022) is as follows:

1. Construct the objective function described in terms of the net present value (NPV) as a function of three design parameters: 1) the borefield geometry, 2) the minimum fluid temperature limit, and 3) the maximum fluid temperature limit;
2. Optimize the objective function to provide the design that maximize the NPV.

Objective function

Naturally, the design of hybrid GSHP systems is a complex task involving many technical and financial parameters. For example, increasing the capacity of the heat pump leads to more energy savings, but also requires more drilling and therefore higher construction costs. Hence, the design's Net Present Value, expressed as the difference between the Net Present Cost of the reference boiler/chiller system and the hybrid GSHP system, is adopted as the sole indicator of the objective function. The NPV over a 20-year period expressed as in terms of three design parameter:

$$NPV = fun_{obj}(F, T_{min}, T_{max})$$

where F is the distance between the boreholes in a circular layout, T_{min} is the minimum fluid temperature limit and T_{max} is the maximum fluid temperature limit. The first parameter F is used generate the position vectors of the boreholes by means of Delaunay triangulation (Fig. 2), and ultimately, to generate the g-function of the borefield (Nguyen 2021).

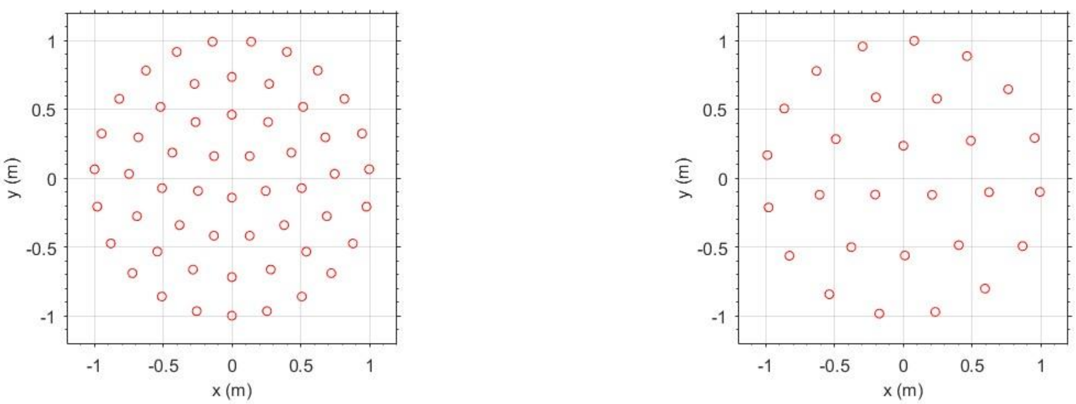

Figure 2. A borefield layout in a unit circle generated by Delaunay triangulation. Left: F = 0.25. Right: F = 0.35.

The second and third parameter are used to control the GSHP capacity. Simply put, increasing design temperature limits (i.e. lowering T_min and increasing T_max allows the GSHP system to operate at higher capacity, but at the cost of a lower COP (Nguyen, 2021). Ultimately, the three design parameters are used for standard calculation of the heat pump source inlet fluid temperature, which allows for the evaluation of the energy cost. The energy cost of the hybrid GSHP system is estimated based on local electricity and gas tariffs from 2018 (Table 1). Electricity tariffs include a tiered tariff for monthly consumption and a tariff for maximum power demand monthly, while gas tariffs include only a staggered tariff for monthly consumption. Note that in this study, natural gas prices are comparable with electricity prices. We remind the reader that these prices are specific to the GSHP market in Canada and that the relevant costs should be used for studies in other regions of the world.

Here we consider Hybrid GSHP systems as capital assets. To take into account their depreciation and their eventual replacement, the depreciation costs are calculated on an annual basis according to the linear method without salvage value. The lifetime of a GHE and GSHP is assumed to be 75 years and 25 years, while the lifetime of a gas boiler and chiller is assumed to be 20 years and 15 years, respectively. In sum, the NPV over a 20-year period considers the cost of boreholes, GSHPs, boilers and chillers, their depreciation cost, the operation cost and the debt repayment.

Table 1. Energy tariffs.

Source	Criteria	Rates	Unit
Electricity	≤ 210 MWh/mo.	4.99	¢/kWh
	≥ 210 MWh/mo.	3.70	¢/kWh
	any kW	14.46	$/kW
	CO2 emissions	1.3	gCO2e/kWh
Gas	≤ 341 MWh/yr.	4.71	¢/kWh
	≤ 1,023 MWh/yr.	4.45	¢/kWh
	≤ 3,413 MWh/yr.	4.02	¢/kWh
	CO2 emissions	214	gCO2e/kWh

A positive NPV indicates that the proposed hybrid GSHP project will be profitable relative to the reference system, while a negative NPV will result in a net loss. In this methodology, we assume similar maintenance and design costs for the hybrid and reference systems, so that neither of them affects the NPV. Finally, a representative energy model of a large office building in Montreal, Canada is used as a base for all analysis. The corresponding load profile is shown in Fig. 3. The peak heating load and cooling load are 836 kW, 696 kW respectively, while the total annual energy demand for heating and cooling are 915 MWh and 385 MWh, respectively. For more details, one could refer to Nguyen et al. (2022) for a thorough description of the ground thermal parameters, heat pump COP curves, economic parameters, as well as costs.

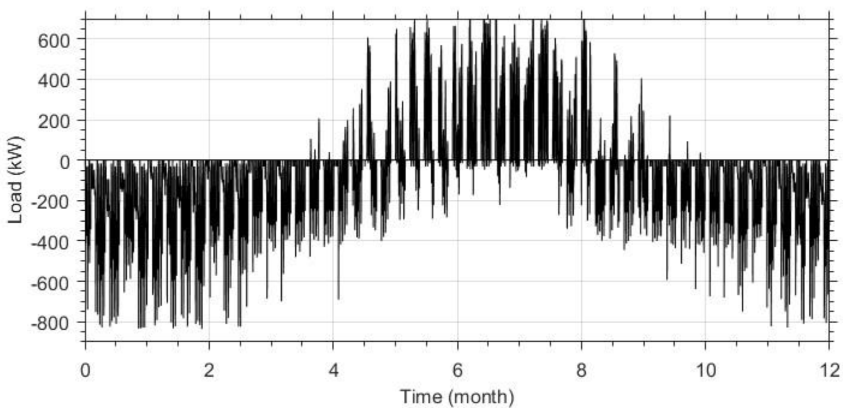

Figure 3. A hybrid ground source heat pump in a two-pipe system with terminal air handling (AH) units Left: Heating mode. Right: Cooling mode.

Parametric analysis

In this article, a parametric study was performed to evaluate the effect of uncertainty on the optimal solution found by the algorithm. We focus on four parameters to generate a set of eight alternative cases, where the value of each parameter is set to 80% or 120% of the base value. The four parameters are: 1) the building load, 2) the construction cost of the GHE, 3) the ground thermal conductivity and 4) the heat pump COP. Building load uncertainty could be related to weather conditions, building occupancy and/or retrofitting, while COP uncertainty could be related to load fluid temperature, part load and/or control strategy.

The parametric analys is divided into two parts. In the first part, the base optimal design is used with new parameters to evaluate the effect of each parameter on the economic performance of the base design. This will be quantified using the NPV value of each case. In other words, it is shown how the uncertainty of some design parameters affects the economic performance of the project if the design is not adapted accordingly. In the other part, it is shown that for each case a specific optimal design exists that could increase both the NPV and the energy performance of the project.

Table 2. Parametric analysis

Heading Number One	Q_b	Cost	K_s	COP
Base	1.0	1.0	1.0	1.0
Case 1	0.8	1.0	1.0	1.0
Case 2	1.2	1.0	1.0	1.0
Case 3	1.0	0.8	1.0	1.0
Case 4	1.0	1.2	1.0	1.0
Case 5	1.0	1.0	0.8	1.0
Case 6	1.0	1.0	1.2	1.0
Case 7	1.0	1.0	1.0	0.8
Case 8	1.0	1.0	1.0	1.2

RESULTS AND DISCUSSION

First, the base case optimal design obtained with the optimization is the following: 29 boreholes with [Tmin,T_max] = [-3.30,32.00]). Table 3 then presents the heat pump heating and cooling load coverages and the NPV of different cases including the base case if the optimal base design is kept for all other cases. To calculate the results listed in Table 3, all cases use base optimal design. As shown in Tabel 3, the base case covers 35% and 52% of the building heating and cooling peak demands respectively however it can cover more than 80% of the total heating and cooling demands of the building with the overall COP of 3.8. In this case, the optimal NPV is $1.45e+05. It is obvious that if the building load is lower by 20% (Case 1) with the same base design, both building heating and cooling load coverages will increase. However, it is interesting to mention that the NPV drops significantly by 61%. To put it very simply, this is due to spending the same GHE construction costs for less energy savings. It is also shown that the COP improves slightly (from 3.8 to 3.94) due to the lower design temperature limit. On the other hand, a 20% building load increase results in less building heating and cooling load coverages and a 15% increase in the NPV. As shown for cases 3 and 4, the change in the construction cost does not change the building load coverage as 29 boreholes are always used. However, a ±20% change in the GHE construction cost would cause a∓46% change in the NPV.

Table 3. Performance and NPV of base optimal design.

Heading Number One	COP	HEAT(%peak/%tot)	COOL(%peak/%tot)	Base Optim Design NPV ($)
Base	3.80	35.4/82.8	52.4/80.2	1.45e+05
Case 1	3.94	49.0/92.1	66.4/91.2	5.69e+04
Case 2	3.75	27.6/73.1	43.0/70.5	1.67e+05
Case 3	3.80	35.4/82.8	52.4/80.2	2.11e+05
Case 4	3.80	35.4/82.8	52.4/80.2	7.87e+04
Case 5	3.78	28.9/74.9	44.3/72.1	8.73e+04
Case 6	3.86	41.8/88.2	59.5/86.4	1.75e+05
Case 7	3.19	43.3/89.1	52.1/79.9	7.15e+04
Case 8	4.37	31.4/78.4	52.5/80.3	1.27e+05

If the ground thermal conductivity is 20% lower in reality than the value used for the design, the heat pump works with lower COP and covers less building load which means consuming more energy, and therefore the NPV decreases (here by 40%). On the contrary, a 20% higher K_s improves the performance of the heat pump and covers more building load which means reducing the energy consumption of the system and therefore contributes to a 21% higher NPV. Table 3 shows that K_s and the building load heating and cooling coverages are directly correlated. This means that the increase in the K_s would increase the building load coverages and vice versa. However, the change in the COP did not present any obvious trend for both the load coverages and the NPV. Both lower and higher COPs (Cases 7 and 8) result in lower NPV of 51% and 12% respectively. This is explained by the higher total energy consumption of the system in both cases. In Case 7, the increase in the total building heating load coverage is not enough to compensate for the energy consumption increase associated with lower COP. It is worth mentioning that if the COP is higher by 20%, the ground load is also higher and the building heating load coverage drops because the GSHP capacity modulates to avoid reaching the cutoff, and therefore the auxiliary heat is used more. Building cooling load coverage does not vary significantly by the ±20% change in the COP. It is very important to realize that higher COP does not necessarily result in higher NPV if the optimal base design is used. In other words, to benefit economically from an improved COP the design has to be optimized accordingly for higher COP values. Interestingly, note that the mean NPV is lower then base case NPV ($1.22e+05 vs $1.45e+05).

Case-specific optimal design:

Table 4 presents the optimum number of GHEs and the design temperature limit (T_{min} and T_{max}) of each case while Table 5 summarizes the results interms of performance and NPV of each case-specific optimal design. Note that the NPV column is always higher than the one in Table 3. This means that if the uncertainty of parameters is accounted for carefully before the design phase, a specific design would exist that maximizes the NPV of the project. For instance in in Case 1, where the building load is lower by 20% compared to the base case, the optimized solution includes a higher design temperature limit (i.e. higher T_{min}= -0.52°C and lower T_{max}=31.95°C) with 38% more GHEs compared to the base optimal design (40 in Case 1 instead of 29 in the base case). This allows the heat pump to operate at higher COP.

Table 4. Optimal design parameters

Heading Number One	N borehole	T_{min}	T_{max}
Base	29	-3.30	32.00
Case 1	40	-0.52	31.94
Case 2	34	-3.78	32.00
Case 3	50	-1.03	31.81
Case 4	26	-3.23	32.00
Case 5	33	-3.60	32.00
Case 6	45	-0.73	31.98
Case 7	25	-1.95	32.00
Case 8	49	-2.74	32.00

Among the cases, a 20% decrease in the heat pump COP (Case 7) and a 20% increase in the GHE construction cost (Case 4) result in using fewer GHEs for their specific optimal designs. For instance, in Case 7, the optimization algorithm reduces the number of boreholes and therefore the construction costs to compensate for the increase in the operation costs caused by the lower COP. However, in Case 4, the optimization algorithm decreases the number of boreholes to directly compensate for the increase in the construction costs of the boreholes. On the other hand, lower GHE construction costs and higher COP of the heat pump allow using significantly more boreholes for achieving an economically optimum design (72% more boreholes for lower GHE construction costs and 69% more boreholes for higher heat pump COP). A 20% reduction in the ground thermal conductivity results in a slight change in the number of boreholes (only by 14% from 29 to 33). In general, trends are difficult to observe because of the non-linear nature of the problem. It is thus also worth investigating the effect of the parameters on the optimization routine.

Table 5. Performance and NPV of case-specific optimal design.

Heading Number One	COP	HEAT(%peak/%tot)	COOL(%peak/%tot)	Case Optim Design NPV ($)
Base	3.80	35.4/82.8	52.4/80.2	1.45e+05
Case 1	4.37	46.8/91.4	100/100	9.59e+04
Case 2	3.71	34.4/82.0	52.0/80.0	1.87e+05
Case 3	4.31	45.3/90.7	100/100	2.44e+05
Case 4	3.77	31.0/77.8	46.2/74.0	7.94e+04
Case 5	3.76	34.4/81.7	51.6/79.7	9.39e+04
Case 6	4.34	46.2/91.2	100/100	1.86e+05
Case 7	3.31	30.5/77.2	43.8/71.2	1.30e+05
Case 8	4.70	48.2/92.0	100/100	1.75e+05

Building load

For Case 1, the optimization routine found an optimal NPV of $9.59e+04 which is lower than the Base case. As mentioned before this optimized solution consists of 40 boreholes connected to GSHPs that allow the system to cover 47% of the peak heating load (91.4% of the total requirement) and 100% of the cooling demand, throughout the 20 years. Based on the results of the optimal design for Case 1, using a chiller to generate auxiliary cooling cannot be justified economically and therefore the entire cooling is fulfilled using the GSHP. It is also noteworthy that the NPV of this case is improved by 69% compared to the NPV of Case 1 in Table 3 when the optimization is not used. If an optimization routine is used for Case 2 where the building load is 20% more than the base case, the NPV is improved by 30% compared to Case 2 listed in Table 3. For Case 2, the optimized solution consists of 17% more boreholes (34 boreholes) than the Base case allowing the GSHPs to provide relatively similar building heating/cooling load coverage despite the increase in the building load. It could also imply that using GSHP for bigger building load results in better economic performance and potentially shorter discounted payback.

GHE construction costs

If the GHE construction costs are lower by 20% (Case 3), results indicate that it makes a better economic sense to cover the whole building cooling load with the GSHPs and therefore eliminate the chiller as the costs are not any more justified. Furthermore, the load coverage by the GSHPs during the heating season increases, and therefore smaller boiler capacity is required. Case 3 appears to demonstrate the biggest impact on the project NPV by 68% improvement compared to the Base case. This is because the GHE construction costs are a significant portion (more than 50%) of the project investment and therefore a 20% reduction would generate a significant impact on the project NPV. It is also worth mentioning that the improvement in the NPV was reported 45% without performing the optimization and optimization can maximize the NPV improvement to 68% compared to the Base case. On the other hand, the increase in the GHE construction costs drops the NPV more than any other parameter by 45%. This again highlights the importance of the GHE construction cost certitude to design an economically optimum system for the project.

Ground thermal conductivity

In Case 5 where K_s is lower than the expected value by 20%, the building load coverage in both heating and cooling is not significantly influenced. Therefore, the optimized solution uses 4 more boreholes than the Base case to compensate for the GSHP capacity decline due to the lower K_s. However, the NPV is still reduced by 35% because the GSHP works at lower COP due to the lower design temperature limit. If K_s is 20% higher than the expected value (Case 6), both the COP and the building load coverage increase significantly. This allows eliminating the chiller unit and using a smaller boiler. The optimized solution improves the NPV of Case 6 further to 28% compared to the Base case from the 21% improvement reported in Table 4.

GSHP COP

If COP is lower by 20%, the optimized solution recommends using 4 boreholes less than the Base case to lower the construction costs and therefore compensate for the increase in the operation costs. Despite decreasing the number of boreholes, the NPV was still reduced by 10%. However, this is significantly better than using the base optimal design in which the NPV is reduced by 50% in Case 7 (Table 3). As shown in Table 5, in this case, both the building load coverage and the annual COP drop significantly. In Case 8, the optimized solution embraces the potential of higher COP by using 49 boreholes that allow increasing the building load coverage and eliminating the chiller unit in this case. The specific optimal design for Case 8 improves the NPV by 21% compared to the base optimal design whereas using the Base case with higher COP decreases the NPV by 12% (Case 8 in Table 3).

CONCLUSION

In this paper, the optimization routine developed by Nguyen et al. (2022) used to carry out a parametric analysis and assess the impact of uncertainty on the proposed optimal design. The effect of four parameters were studied: 1) the building load, 2) the construction cost of the GHE, 3) the ground thermal conductivity and 4) the heat pump COP. The results show that all the parameters have signifICnant impact on the optimization, but trends are difficult to observe due to the non-linear nature of the problem. It was shown that the GHE construction costs and GSHP COP had the most impact on the NPV, hence they would be key parameters for an optimal design that has to be evaluated carefully in advance. This work opens doors for more robust and stochastic optimization of hybrid GSHP systems under uncertainty.

ACKNOWLEDGMENTS

The authors would like to acknowledge the funding received by the Office of Energy Research and Development (OERD) of Canada through the Energy Innovation Program (EIP) to undertake this research.

NOMENCLATURE

COP	=	*Coefficient of performance (-)*
fun_{obj}	=	*Objective function (-)*
Q_b	=	*Building load (kW)*
NPV	=	*Net present value ($)*
F	=	*Relative distance (-)*
T_{min}	=	*Minimum fluid temperature (°C)*
T_{max}	=	*Maximum fluid temperature (°C)*
K_s	=	*Ground thermal conductivity (W/m°C)*

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