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2 **A Techno-economic Analysis of Heat-Pump Entering Fluid**
3 **Temperatures, and CO₂ Emissions for Hybrid Ground-Source**
4 **Heat Pump Systems**
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Abstract

Hybrid ground-source heat pumps (GSHPs) that include a ground loop for the base heating and cooling needs, and an auxiliary system (natural gas boiler and electric air conditioner) for peak loads, are an economical and environmentally cleaner alternative to conventional systems. For a ground-source heat pump (GSHP) system, the choice of entering fluid temperature (EFT) to the heat pump plays a crucial role in determining system efficiency and operating costs. To continue expanding the knowledge base of efficiently sizing GSHPs as a component of a hybrid system, this study explores the economic effects of choosing an EFT for a heat pump. In addition, system CO₂ emissions are calculated and analyzed for a variety of building types. Using a computational approach to size hybrid GSHP systems recently published in [Alavy *et al.*, Renewable Energy, 57 (2013) 404-412], the effects of optimizing EFT for a heat pump, and CO₂ emissions were studied for a variety of commercial installations. In the present study, using ten buildings situated in Southern Ontario, Canada, by varying cooling and heating EFTs for a heat pump, savings ranging from 0.47% to 3.6% can be achieved compared to using a fixed EFT pair for a heat pump. In addition, comparisons were made between the CO₂ emissions of optimally-sized (based on economic factors) hybrid GSHPs and those of non-hybridized GSHPs. Both the optimally-sized hybrid GSHPs, and the non-hybridized GSHPs significantly reduce CO₂ emissions compared to the use of conventional natural gas/electrical systems. The additional environmental benefit of the non-hybridized GSHPs over that of the optimally-sized hybrid GSHPs was found to be negligible in most cases analyzed.

1. Introduction

A ground-source heat pump (GSHP) system uses the ground, via a ground heat exchanger (a ground loop), as a heat-source (heat-sink) to provide space heating (cooling) to a building [1]. For a closed-loop system, the commonly used ground loop configurations include horizontal, vertical, and oblique [1]. Since the ground is a relatively stable medium for heat transfer throughout the year, compared to outdoor air, GSHP systems requires less electricity to operate and emit less greenhouse gas (GHG) relative to conventional heating and cooling methods due to high efficiency of the GSHP systems [2]. At soil depths less than two metres, the ground temperature is largely dependent on the outdoor air temperature. As the depth increases beyond two metres, the effect of seasonal changes in temperature is reduced and the ground temperature profile stabilizes to become constant, that of the local average annual outdoor air temperature [1, 3].

In a GSHP system, entering fluid temperature (EFT) to heat pump plays a crucial role in determining the efficiency of the heat pump and total costs of the system. The effects of various ground layers and single or double U-tube configuration on the borehole heat transfer performance is addressed in [4]. The authors in [4] find from their numerical model that the fluid temperature in the U-tubes varies non-linearly along the tubes with more heat transfer in the first stages than in the second stages of the U-tubes, as the temperature differences between the fluid and its surroundings are higher in the first stages. They also find that better heat transfer performance of the U-tubes can be obtained if the upper ground layers have high thermal conductivity. They conclude that although double U-tubes cost 22-29% more than single U-tube, the heat transfer performance of double U-tubes (in parallel or in series) are more superior than single U-tube by 26-29% (in parallel) or 42-59% (in series). For a given heat transfer from a heat pump in cooling mode, a more efficient ground loop will mean lower entering fluid temperature to the heat pump. Therefore, an appropriate design of ground loop is very important as the heat pump performance depends on the heat transfer efficiency of the ground loop.

In [5], hybrid GSHP systems with a supplemental cooling-tower loop, which is connected in parallel to the condenser of the heat pump or in series with the ground loop, were analyzed. The results show that the coefficients of performance (COPs) of the hybrid GSHP systems with the parallel and serial configurations are 18% and 6% higher than that of the GSHP alone, respectively, when the exiting fluid temperature of the ground loop is 40°C [5].

In [6], the effects of optimizing entering fluid temperature to a GSHP were studied. The authors utilized a building automation system to monitor the temperature of the liquid entering and leaving the heat pump. The GSHP system that they studied uses a primary-secondary system in which there are two loops to control the simultaneous heating and cooling demands in a building. The results of the study indicate that by optimizing the entering fluid temperature to a GSHP, there is an increase in the COP and energy efficiency rating (EER) of the system.

In [2], the author compares energy efficiency and CO₂ emissions of various heating systems. The systems include oil fired boilers, gas fired boilers, electrical heating, conventional electricity for cooling and a GSHP, and green electricity (*i.e.*, hydro, solar, wind) and a GSHP [2]. Electrical heating generates the highest CO₂ emissions of 0.9 kg CO₂/kWh and the lowest primary energy efficiency of 36% [2]. However, this result is dependent on location (United

Kingdom). The energy efficiency of 36% indicates that the output energy of the system is only 36% of the input. On the other hand, green electricity coupled with a GSHP system results in no GHG emissions and a primary energy efficiency of up to 400% [2]. Since GSHPs operate using electricity, green energy contributes to a much greater emissions savings than conventional electricity would otherwise.

As discussed by Soimakallio *et al.* [8], there are two types of CO₂ emissions, direct and indirect. Direct emissions are those that result during the operation of the heating and cooling system and indirect emissions are those that are connected such as the emissions that result from electricity production and consumption by the pumps and compressors. In [8], the authors acknowledge that there is a large uncertainty in determining emissions for GSHP systems. GHG emission calculations are greatly dependent on the following imitations: choice of heating method, actual COP of the heat pump, and electricity supply mix [9,10].

Similarly, in a study by Greening and Azapagic [7], a heat pump is used to completely replace the gas boilers inside a building. The direct CO₂ emissions of the heating system reduced from 0.220 kg CO₂_equivalent/kWh to 0.178 kg CO₂_equivalent/kWh [7]. It was concluded that replacement of the gas boiler with a GSHP resulted in a savings of 12.8% of direct GHG and only 2.4% in total GHG emissions [7]. Again, because of the dependence on the electricity supply mix, this result would be location dependent.

Although recent studies indicate that there are potential reductions in GHG emissions with the use of GSHPs, the studies are limited to complete replacements of conventional systems with that of a GSHP system. Similarly, in previous studies, the analyses on the effects of entering fluid temperature changes are limited to pure GSHP systems. There exists a knowledge gap in regards to analyses on optimizing entering fluid temperature to heat pump and CO₂ emissions savings for hybrid GSHPs. Entering fluid temperature to heat pump affects the COPs of a hybrid GSHP system. As such, improving the COP in turn reduces GHG emissions. The methodology outlined in Alavy *et al.* [11], which will be used in this study, automatically sizes hybrid GSHP systems with continuously variable ground loop and auxiliary system capacity, based on minimizing the net present value of total costs. The method has been applied to study the utility model of GSHPs [13] as well as the dependence on geographical location of hybrid system optimization [12].

Entering fluid temperature to the heat pump (EFT) affects the COPs of a hybrid GSHP system. As such, improving the COP in turn reduces GHG emissions. When GSHPs are sized, an EFT pair is selected. For Toronto, Canada, 35°F (1.7°C) and 85°F (29.4°C) are commonly used as the EFT pair for the heating and cooling modes, respectively. As an example, changing the EFT to 35°F (1.7°C) and 75°F (23.9°C) would result in an increased COP for the cooling mode. However, achieving an EFT of 75°F (23.9°C) would require a larger ground loop. As such, the initial costs of the system increases. This study investigates and quantifies the economic and environmental effects that varying the design EFT for GSHP capacities meeting 0% to 100% of building peak loads in 1% increments would have on hybrid GSHPs. Furthermore, GHG emissions is an important aspect for the growth of renewable alternatives such as GSHPs. By using the methodology outlined in [11], and incorporating a carbon emissions factor, the economic and environmental benefits of hybrid GSHPs is compared to that of a pure GSHPs and

131 of conventional systems. Finally, a techno-economic analysis of optimizing entering fluid
132 temperature to the heat pump, and CO₂ emissions for hybrid GSHP systems was performed to
133 determine and better understand the potential economic and environmental benefits.
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2. Methodology

In this study, the methodology outlined in Alavy *et al.* [11] will be used. In this methodology, a shave factor (the portion of peak demand met by the GSHP) based on the building's heating (cooling) demands is used to size and determine the optimal hybrid GSHP system design. By varying the shave factor between zero and one, the most economical design (based on the net present value of capital and operating costs) is selected as the optimal hybrid GSHP system design. For example, a shave factor of 0.70 denotes that 70% of the building's peak loads are met by the GSHP and the remainder by a conventional system. A building with all of its space heating and cooling demands met by a conventional system (no GSHP) would be represented by a shave factor value of 0.0. A building for which the entire demand is met by a GSHP would be represented by a shave factor of 1.0.

The methodology outlined in Alavy *et al.* [11] is based off of ASHRAE's design strategy [27] for sizing GSHPs. The procedure in determining the optimal design (optimal shave factor) outlined in Alavy *et al.* [11] is as follows:

1. Generate building hourly heating and cooling loads from building energy simulation software.
2. Determine the required GSHP capacity (and conventional system capacity) to meet the building's peak loads by varying the shave factor from 0.0 to 1.0, in increments of 0.01. The shave factor is defined as the portion of the building's peak load met by the GSHP.
3. Calculate the total costs, in net present value, for each shave factor (for the GSHP and conventional system). The total costs include both initial/installation costs, and annual operating costs. The shave factor with the lowest total costs in net present value is considered the most economical (optimal) design. The methodology assumes a twenty years maintenance cycle.

As described, in order to determine the most economical design, the methodology outlined in Alavy *et al.* [11] takes into consideration user defined inputs such as: heat pump EFT, COPs of the systems, properties of the working fluid, soil and piping properties, local utility rates, inflation rates, and long-term weather patterns (when generating building hourly data). The operation of the system is based on a simple on-off control strategy. As observed, using the outlined methodology, the optimal design of a hybrid GSHP system will have the GSHP operate throughout the year to meet base loads. The conventional system will be in off-mode and is only on during peak loads.

As this methodology was developed recently, a significant knowledge gap exists with regard to the best possible ways to use hybrid system optimization in GSHP design. Alavy *et al.* [11] focused on explaining and validating the methodology and Nguyen *et al.* [12] (using the same methodology) performed a series of sensitivity analyses to determine the effects of weather patterns and utility costs on the sizing of hybrid GSHP systems. A utility model was also investigated by Alavy *et al.* [13] to determine the feasibility of a common ground loop for multiple commercial and industrial buildings. As such, to continue expanding the knowledge base of automatically sizing GSHPs as a component of a hybrid system, two new algorithms have been created for the present study as discussed in sections 2.1 and 2.2. The parameters used in the present study are listed in Tables 1 and 2.

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Table 1: General design parameters (data courtesy of CleanEnergy™)

Parameters	Value
Cooling Design Entering Fluid Temperature to HP	29.4°C
Heating Design Entering Fluid Temperature to HP	1.7°C
Heat Pump	CleanEnergy Developments/ PC0018 (COP=3.1, EER=12.9)
Soil Thermal Conductivity	2.94 W/m·K
Soil Thermal Diffusivity	0.072 m ² /day
Duration of Operation	20 years
Borehole Thermal Resistance	0.136 m·K/W
Pipe Resistance	0.06 m·K/W
Pipe Size	32 mm
Borehole Diameter	127 mm
Grout Thermal Conductivity	1.47 W/m·K
Number of boreholes across	11
Number of boreholes down	4
Electricity rate	\$0.17/kWh
Natural gas rate	\$0.35/m ³
Inflation Rate	4%
Interest Rate	8%

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GSHP Configuration: closed-loop vertical single U-tube

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Table 2: General costs of hybrid GSHP system components (data courtesy of CleanEnergy™)

Item	Cost
Ground heat exchanger (installation and materials)	\$65.6/m
Cooling tower, plate heat exchanger including controls and auxiliary equipment (COP = 2)	\$14/kW of tower design capacity
Boiler (efficiency = 78%)	\$20/kW of boiler design capacity

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An important factor in the present analysis is the cost of installing the ground heat exchanger. In the present study, this cost is taken as \$65.6/m. Installation costs are normally determined based entirely on the system capacity, or total ground loop length. There is a relatively small but significant cost to starting the drilling process (drilling the first meter), associated primarily with the above-ground heat pump components and procuring the drilling equipment. After that cost, each additional meter costs approximately the same amount, due labour and materials.

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2.1 Heat-pump entering fluid temperature (EFT)

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Using the methodology in [11], total costs (in net present value) of a hybrid GSHP system was calculated as a function of shave factor. By varying the shave factors from zero to one – a two-dimensional optimization (total cost as a function of shave factor) – the most economical hybrid GSHP system is determined. However, the methodology in [11] sizes and determines the optimal hybrid GSHP system (optimal shave factor) based on a fixed pair of heat-pump EFTs (for the heating and cooling modes) specified by the designer [11]. For Toronto's weather patterns, a

fixed heat-pump EFT pair used for the heating and cooling modes were 35°F and 85°F (1.7°C and 29.4°C) respectively.

In this study, the methodology outlined in [11] was modified to consider an array of operational heat-pump EFT pairs with corresponding heat-pump COP values, since the COPs depend on the temperature pairs (higher COP values corresponds to less GHG emissions). For example, there would be a total of 121 possible heat-pump EFT pairs (22 COP values) if a particular heat pump model can operate in the EFT ranges of 35-45°F and 85-95°F (1.7-7.2 °C and 29.4-35°C) for the heating and cooling modes, respectively, considering 1.0°F increments. Each COP value will be used to calculate the operating costs of the hybrid GSHP system in the heating and cooling modes respectively. As such there would be 121 optimal shave factors calculated, one for each temperature pair, the temperature pair with the lowest net present value cost would be selected as the most economical design.

Using the methodology outlined in [11] but also varying the EFT pairs, the total cost of a hybrid GSHP system becomes a function of shave factor and heat-pump EFT pair (a three-dimensional optimization problem). As a result, a three-dimensional surface is generated, as shown for example in Figure 1, in which the total costs are plotted against the corresponding shave factors and heat-pump EFT pairs. The shave factors ranged from zero to one, and the temperature pairs range from 1 to the maximum number of EFT pair combinations. For a school located in Toronto (Figure 1), the assigned operational heat-pump EFTs were 25-42°F and 60-100°F (-3.9-5.6°C and 15.6-37.8°C) for the heating and cooling modes respectively (738 temperature pairs using 1.0°F increments).

Figure 1: EFT analysis for a school located in Toronto, Ontario.

In Figure 1, there are three low-lying areas. The first low-lying area occurs in the region nearby the shave factor value of 20% (or 0.20) and is the lowest at the EFT pair index 557 corresponding to 41°F and 90°F. The second low-lying area occurs near the shave factor value of 40% (0.40) and EFT pairs 100-200, which correspond to the temperature ranges 25-42°F and 65-71°F (-3.9-5.6°C and 18.3-21.7°C) for heating and cooling modes respectively. The third low-lying area occurs near shave factor value of 50% (0.50) and EFT pairs 400-700, which correspond to the temperature ranges 25-42°F and 82-98°F (-3.9-5.6°C and 27.8-36.7°C) for heating and cooling modes respectively.

At the time of this study, the cost of using natural gas to provide space heating for Ontario (per kWh of heating) was more economical than using a GSHP (due to high upfront costs of installing the system). As such, for heating dominant buildings, it was more economical to use a boiler to provide space heating. For cooling dominant buildings, such as the transit facility (Figure 2), using this EFT analysis results in only one low-lying region. This trend was consistent for all of the cooling dominant buildings analyzed.

Figure 2: EFT analysis for a transit facility located in Toronto, Ontario.

The contributing factors for the school's three low-lying areas, based on the parameters used in this analysis (*i.e.*, Toronto's utility costs), was due to the fact that the school is mildly cooling dominant. Its peak cooling and heating loads are 174 kW (total annual load: 247,180 kWh) and 146 kW (total annual load: 203,350 kWh) respectively. Unlike for the case of the transit facility (cooling dominant), the current low costs of natural gas in Ontario (used for heating) had a larger affect on the school's hybrid GSHP system's total costs. As such, the first low-lying area corresponds to the most economical design for implementing a hybrid GSHP system for the school (optimal EFT pair). For the second and third low-lying areas, by increasing the shave factor to 40% and 50%, this increase resulted in higher upfront costs (larger ground loop). This increase in costs was counteracted by using temperature pairs that improved the GSHP's COP for heating and cooling modes, thus generating other low-lying areas. By having a larger ground loop, better system COPs can be achieved (*i.e.*, higher heating and lower cooling EFTs).

These low-lying regions indicate that for this particular building (school), there might be three good design strategies that a designer might want to implement. The first low-lying region might be more economical and have a slightly lower payback, but the second and third low-lying regions would have more environmental benefit since it has a higher shave factor value.

Therefore analysing CO₂ emissions becomes important too. This methodology shows a designer what their design freedoms are and provides them with a tool to better analyse potential designs.

2.2 CO₂ Emissions

The total amount of CO₂ emitted as a result of using a hybrid GSHP system is dependent on the heating fuel that is used for the conventional system, the electricity consumed by pumps and compressors and the CO₂ emission factors of the local electricity supply mix. CO₂ emission factors are the factors indicating the amount (measured in kg/kWh and kg/m³) of CO₂ that is emitted into the air. The supply mix breakdown consists of percentage make-ups of each fuel source such as nuclear, hydro, coal, wind, gas/oil, and other electricity production sources. The breakdown used in this analysis corresponds to an averaged supply mix in Ontario between 2011 and 2012. The supply mix for Ontario is assumed as follows: 51.95% from nuclear energy, 23.05% from hydroelectricity, 13.74% from coal energy, 1% from wind energy, 9.45% from gas/oil combustion, and 0.81% from other sources [18].

In the present study, natural gas was assumed to be the fuel for the conventional component of the heating system. The CO₂ emissions factor for natural gas is 1.8750 kg-CO₂/m³ [19]. Similarly, for space cooling by a conventional or a GSHP system, the CO₂ emission factors are based on kg-CO₂ per kWh of electricity (kg-CO₂/kWh). For electricity production in Ontario, the emission factors used in this analysis are 0.002 kg-CO₂/kWh for nuclear [14], 0.023 kg-CO₂/kWh for hydro [14], 1.02 kg-CO₂/kWh for coal [15], 0.002 kg-CO₂/kWh for wind [14], 0.2786 kg-CO₂/kWh for oil [16], and 0.0261 kg-CO₂/kWh other electricity generation methods [17]. The emission factor of 0.0261 kg-CO₂/kWh by other electricity generation methods is associated with biomass (wood chips and pellets) electricity generation. The emission factor 0.0261 kg-CO₂/kWh from biomass electricity generation is achieved by taking the average of 0.0149 kg-CO₂/kWh for wood chips and 0.0373 kg-CO₂/kWh for wood pellets [17], assuming an equal mix of the two fuels. The constant emission factor value of 0.1730 kg-CO₂/kWh, based on Ontario's electricity supply mix, will be used in the present study for any kWh of electricity used or displaced by the GSHP.

Using these emission factors, CO₂ (or CO₂ equivalent) emission rates by a hybrid GSHP system can be determined. To quantify the effects GHG emissions have on hybrid GSHP systems, a carbon tax is implemented (section 4.1). Using the methodology outlined in Alavy *et al.* [11], the costs associated with GHG emissions is added with the annual operating costs. The most economical design is selected based on the shave factor which produces the lowest total costs in net present value (capital and operating costs). The process in determining the CO₂ emissions are outlined in the subsequent section (section 2.2.1).

2.2.1 Calculation of CO₂ Emissions

To quantify environmental benefits generated by a hybrid GSHP system, a process for calculating CO₂ emissions is used in the present study. It is illustrated in Figure 3.

Figure 3: CO₂ emission calculation process

3.1 Heat-pump EFT analysis

In this analysis, two ranges of operational EFTs of a heat pump are used to determine the effects they have on the economics of hybrid GSHP systems. Depending on the mode (heating or cooling), varying the heat pump's EFT, within its operational ranges, will affect its COP values (for the heating and cooling modes). The COPs of the heat pump used in this analysis, are based on the EFTs (CleanEnergy Developments, model PC0018. The parameters used in this analysis are listed in Tables 1 and 2 — an inflation rate of 4%, electricity rate of \$0.17/kWh, and natural gas rate of \$0.35/m³ are used. A total of ten real buildings are studied, with their data provided by CleanEnergyTM Developments Corporation. The buildings consists of a hospital, an office, a restaurant, a fast-food restaurant, a transit facility, a mid-rise multi-residential building, three high-rise multi-residential buildings, and a school.

The results of this three-dimensional optimization analysis are compared to that of the base case (fixed heat-pump EFT pair of 1.7°C and 29.4°C) presented in Table 3. In Table 3, the ten buildings are listed in the first column and the optimal shave factors corresponding to each building are listed in columns two and three. Columns two and three correspond to the optimal shave factors for the base case (fixed EFT pair) and variable EFT pairs, respectively. The corresponding EFT pairs are listed in columns four and five for the base case (fixed EFT pair) and column six and seven for the case of varying EFT pairs.

Table 3: Variable heat-pump EFT vs. base case (fixed EFT)

Buildings	Heating or Cooling Dominant	Optimal Shave Factor		Optimal Temperature Pair				Minimum Total Costs \$ (×10 ⁵)		Total Costs Savings (\$)
		Base Case	Variable	Base Case		Variable		Base Case	Variable	
				T _c (°C)	T _h (°C)	T _c (°C)	T _h (°C)			
1. School	Cooling Dominant*	0.22	0.24	29.4	1.7	32.2	5	4.36	4.20	15,667
2. Office	Heating Dominant**	—	—			—	—	—	—	—
3. Hospital	Heating Dominant**	—	—			—	—	—	—	—
4. Restaurant	Cooling Dominant	0.65	0.65			29.4	5	8.25	8.25	0
5. Fast food restaurant	Cooling Dominant	0.62	0.62			29.4	5	4.74	4.74	0
6. High-rise (I)	Cooling Dominant	0.25	0.27			33.9	5	6.45	6.4	5,447
7. High-rise (II)	Cooling Dominant	0.23	0.25			33.9	5	14.6	14.5	14,272
8. High-rise (III)	Cooling Dominant	0.39	0.41			32.2	5	11.6	11.5	5,830
9. Mid-rise	Cooling Dominant	0.34	0.36			32.2	5	8.71	8.66	4,092
10. Transit facility	Cooling Dominant	0.44	0.48			33.9	5	7.18	7.11	6,856

*The school is mildly cooling dominant. Heating (peak: 146 kW, total annual load: 203,350 kWh) and Cooling (peak: 174 kW, total annual load: 247,180 kWh)

**At the time of this study, the low price of natural gas used for space heating (per kWh heating) is much more economical compared to GSHPs. As such, it is uneconomical to install a GSHP system for heating dominant buildings.

Since the ground temperature in Toronto is approximated to be 50°F (10°C), using the COP values for the heat pump (CleanEnergy Developments, model PC0018), the heat-pump EFTs for the heating and cooling modes were varied in the ranges of 25-42°F and 60-100°F (-3.9-5.6°C and 15.6-37.8°C) respectively. The EFTs in the range of 43-49°F (6.1-9.4°C) for the heating mode were omitted to reduce computational time, because there were no savings when these specific temperatures were analyzed separately (due to the associated need for larger ground-loop lengths when operating in cooling mode).

The minimum total cost for the base case (column eight) and variable EFT analysis (column nine) are used to determine the total costs savings presented in column 10 associated with using a three-dimensional optimization. Of the ten buildings analyzed, the school in Table 3 produced the most savings compared to the base case. A total of 3.6% reduction in cost was achieved when all the possible combinations of heat-pump EFTs are assessed compared to the base case design standard. For a typical installation, this level of savings can translate to \$1,000 per year. However, the observed savings for the remaining buildings were less than 1%.

Based on the building's heating and cooling loads, two ground-loop lengths are calculated. If the cooling ground-loop length is larger than that of the heating ground loop, the building is cooling dominant (vice versa for heating dominant). Buildings, #1 and #4-10 are cooling dominant. As a result, although the optimal EFT for heating mode is 5°C compared to the base case of 1.7°C, the effects it has on the hybrid GSHP system's economics are negligible for certain buildings such as the restaurant and fast-food restaurant (the two most cooling dominant sample buildings). For the restaurant and fast-food restaurant, the optimal shave factors between the base case and the variable EFT scenario remained the same for these two buildings because they are very cooling dominant throughout the year, with negligible heating requirements.

Although there is some merit in continuously varying the heat-pump EFT pairs using the existing methodology in [11], the effects of varying heat-pump EFT has shown to be negligible (for buildings situated in Toronto) compared to other parameters such as weather patterns, operating costs, and inflation rates as investigated by [12]. In most cases, the effects of varying EFTs is modest as compared to shave factor. This analysis was repeated for many variations in EFT pairs, such as 33°F-37°F and 83°F-87°F (0.6-2.8°C and 28.3-30.6°C) for the heating and cooling mode respectively. The trends and conclusions remain the same.

3.2 CO₂ Analysis

By applying a CO₂ emissions module, Figures 4 and 5 plot the shave factors, *i.e.*, the portion of peak demand that could be met by the GSHP, against total annual CO₂ emission (kg). In Figure 4, the curved line represents the CO₂ emission (of a fast food restaurant) for each shave factor value from 0 to 1. To generate the curve, 100 different shave factors were considered, each corresponding to a differently sized GSHP system. The intersection point between the vertical and horizontal line represent the location of the optimal shave factor. Using Alavy *et al.*'s methodology [11], the optimal shave factor for the fast food restaurant, as presented in Figure 4, is 0.62. It can be observed that the CO₂ emitted when the system is sized with an optimal shave factor value of 0.62 (23,595 kg) is very near the minimum CO₂ emissions (21,750 kg). For the case of the fast food restaurant, the optimization based on Alavy *et al.*'s methodology [11] results in a CO₂ emissions reduction of 91.5% (compared to a conventional system) of that which would be achieved with a GSHP system meeting peak demand, but at a much lower cost (a savings of \$26,400 in net present value).

Figure 4: Annual CO₂ emissions of a fast-food restaurant located in Toronto, Ontario, as a function of shave factor.

In some cases, a design based on the optimal shave factor (based on net present value) results in a hybrid GSHP system that produces more than 20% more CO₂ than the minimum CO₂ emitting GSHP system (with a shave factor of 1.0). For example, in Figure 5, the optimal shave factor of a high-rise (II) building located in Markham, Ontario is 0.23 (most economical design in terms of

net present value). The corresponding annual CO₂ emission of the system is 87,119 kg (minimum CO₂ emissions is 65,250 kg). However, if reduction in CO₂ emissions were a higher priority, the installer can size the system to a shave factor of 0.6, the annual CO₂ emissions would reduce to 68,385 kg resulting in a 25% reduction in CO₂ emissions. The corresponding cost increase would be 4.2%. It can be seen that this method of plotting and analysis can give designers and engineers the ability to understand the trade-off between cost, payback period, and environmental impacts.

Figure 5: Annual CO₂ emissions of high-rise (II) building located in Markham, Ontario

A total of eight buildings are analyzed and the results are summarized in Table 4. In Table 4, the optimal shave factors are listed in the second row and the corresponding CO₂ emissions are listed in the third row. The CO₂ emissions for each building corresponding to a shave factor of 1 (GSHP meeting full demand) are listed in the fourth row, and represent the minimum CO₂ emissions that can be achieved using a full GSHP installation. The CO₂ emissions of the optimized hybrid GSHP systems are the closest to the minimum possible CO₂ emissions for buildings that are extremely cooling dominant, such as the fast food restaurant, for which the optimized shave factor results in emissions that are only 8.5% more than the minimum possible amount. There was no economically viable hybrid-GSHP design for the office building (most economical using a conventional system). As a result, the average percentage increase in CO₂ emissions for the office building using a conventional system is 326% (maximum percentage increase) compared to a full GSHP installation (shave factor value of 1). Using the optimal shave factor approach outlined in Alavy *et al.* [11] produces acceptable levels of CO₂ emissions even

when the optimal shave factors are below 0.50, as is often the case. For example, the shave factor for the high-rise (III) building is 0.39 and the corresponding percentage increase in CO₂ emissions is only 21% with respect to the shave factor of 1. Similarly, the transit facility and mid-rise building have optimal shave factor values of 0.44 and 0.34, respectively, while their average percentage increases in CO₂ emissions are 19.5% and 22.8%, respectively. For these buildings, much of the reduction in CO₂ emissions is still realized when switching from the conventional system to the hybrid GSHP system which is designed based purely on economic optimization.

Table 4: Summary of CO₂ emission for the 8 buildings, located in Toronto, Canada

Building	High-rise (I)	High-rise (II)	High-rise (III)	Office	Restaurant	Fast food Restaurant	Transit Facility	Mid-rise
Optimal Shave Factor	0.25	0.23	0.39	0	0.65	0.62	0.44	0.34
CO ₂ _optimal SF (kg)	36,427	87,119	61,934	624,291	21,035	23,595	37,603	46,490
CO ₂ _SF=1 (kg)	28,553	65,248	51,166	146,560	14,656	21,750	31,457	37,845

3.2.1 Applying a Carbon Tax

The reduction in carbon emissions provided by renewable energy sources is a benefit that is difficult for the end-use customer to quantify. Typically it is the savings related to any energy efficiency arising from the renewable energy technology that provides the potential for customer adoption. If those savings are marginal then the carbon reduction benefit is not likely to stimulate energy consumers into paying more for technologies that reduce emissions. However, by implementing policies that introduce a cost to the emitting of carbon, such as a carbon tax, then an incentive exists for customers to consider adopting costlier renewable energy technologies [23].

The use of a carbon tax has been identified in the climate policy literature as an effective tool for stimulating emissions reduction. It is preferred by most economists because it is seen as a mechanism for reducing carbon in the most economically efficient manner even though putting a carbon tax into practice can be problematic as the general public tends to reactive negatively to increased taxation [24].

Currently, Finland, Australia, Sweden, Great Britain, New Zealand, and some provinces in Canada have implemented a carbon tax as an initiative to reduce their carbon footprint [20, 21, 22]. In Canada, for every tonne of CO₂ (CO₂ equivalent), a cost is charged based on the regulations set by the province. Alternatively, some jurisdictions may impose a carbon incentive,

providing a tax break for companies that take measures to reduce their emissions. For example, a cost of \$30 is charged (pre-applied to fuel consumption) for every tonne of CO₂ emitted into the air in British Columbia, Canada [20]. The provinces of Quebec and Alberta, Canada have also begun adopting carbon taxes. In the present analysis, a carbon tax of \$30 for every tonne of CO₂ emitted is adopted (British Columbia's rate) in order to understand the effect that it has on the economic viability of hybrid GSHP installations. Using the value of a carbon tax as a proxy for the cost of carbon when undertaking the economic evaluation of renewable energy technologies is not uncommon in the recent literature [25, 26]

The total annual carbon tax costs were determined using the calculations outlined in Section 2.2. Using a 20 year system operating duration and the methodology outlined in Alavy *et al.* [11], the calculated annual carbon tax was added to the total annual costs (which includes operation and any overhead costs) for years 1 through 20 before they are all discounted into net present values. The shave factor that corresponds to the minimum total costs in net present value (NPV) was selected as the optimal shave factor. As the operating costs change with the consideration of a carbon tax, the optimal shave factor is expected to change. The main objective of this analysis is to determine to what extent the optimal shave factor varies, so as to understand how carbon taxation should be considered in hybrid GSHP design.

The results of implementing a carbon tax are presented in Table 5. Due to the carbon tax, the overall total costs as presented here in NPVs increase. As a result, in order to alleviate the increase in operation costs, the optimal shave factor increases (emitting less CO₂) as compared to the cases without the carbon tax. Furthermore, an increase in shave factor contributes to a reduction in payback periods due to savings in operating costs from the carbon tax incentive (especially for the case when the shave factor is 0, i.e. conventional system with no reduction in CO₂ emissions). For example, as presented in Table 5, the transit facility's shave factor increased from 0.44 (no carbon tax) to 0.47 (with a carbon tax) resulting in a reduction in payback period from 19.4 years to 18.7 years. As presented in Table 5, in some cases, a slight increase in shave factor values result in a moderate reduction in the payback period. The high-rise (I) and high-rise (II) buildings achieved a reduction in payback periods of 1.1 and 1.5 years, respectively, due to the impact of a carbon taxation. The restaurant and fast-food restaurant achieved a negligible reduction in payback periods of 0.32 and 0.28 years respectively. It can be concluded that if a carbon tax were to be applied, the shave factor would increase to offset the increase in operating costs (resulting in shorter payback periods), but in most cases the increase is modest. It is interesting to find that, for the heating-dominant office building, there is still no economically viable hybrid-GSHP design even with a carbon tax of \$30/tonne CO₂.

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Table 5: Changes in shave factors and payback periods due to a carbon tax

Building	High-rise (I)	High-rise (II)	High-rise (III)	Office	Restaurant	Fast Food Restaurant	Transit Facility	Mid-rise
No carbon tax:								
Shave Factor	0.25	0.23	0.39	0	0.65	0.62	0.44	0.34
Payback Period (years)	20.88	22.13	17.93	--	14.29	14.62	19.42	18.39
With a carbon tax (\$30/tonne CO ₂):								
Shave Factor	0.25	0.24	0.4	0	0.65	0.63	0.47	0.35
Payback Period (years)	19.79	20.61	17.36	--	13.97	14.34	18.73	17.83

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3.2.2 Operating Duration Analysis

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In the previous analyses, an operating duration of 20 years was used. However, depending on how long a building owner might plan to own a building, other operating durations may be of interest. If operating durations other than 20 years are assumed, then the algorithm will determine a different shave factor because it is factored into determining the net present value of the annual operating costs and/or possible equipment replacement costs. Therefore, depending on the assumed operating duration of the hybrid system, a different optimal shave factor, and therefore CO₂ emissions might be the desired design parameter. In this section, two analyses were carried out to determine the effects operating duration have on annual costs (net present value) and CO₂ emissions. In these two analyses, the conventional system and GSHP system are replaced every 20 and 40 years respectively.

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Operating Duration: NPV/year Analysis

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In this section, a new variable “NPV/operating duration” was calculated. The total cost (capital, operating costs, overhaul costs of cooling towers, heat pumps, boilers, and the ground loop) in net present value (NPV) is divided by the operating duration to determine the amortized system costs per year. The “NPV/operating duration” parameter, analogous to payback period, is useful in visually displaying the amortized system costs per year. Using the methodology outlined in Alavy *et al.* [11] will determine the payback period and corresponding total costs of a GSHP system in net present value for a particular optimal shave factor. However, if GSHPs are installed and rented out (a utility model), as is often the case with boilers and furnaces for residential and commercial buildings, by using this parameter the installer can determine the appropriate shave factor (system size) and operating duration in order to achieve the optimal NPV per operating year using the “NPV/operating duration” parameter.

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In Figure 6, the net present value cost per operating year is plotted against the operating duration (in years). As expected, as operating duration increases, the annual system costs decreases. This decrease is attributed to the fact that the capital cost is spread over a longer timeframe (when considered as an averaged costs). For most buildings, such as the fast food restaurant associated with Figure 6, net present value cost per operating year levels off after very long durations of

operation – greater than 100 years. However, sizing a hybrid GSHP system based on an economic analysis of 100 years is impractical.

Figure 6: Net present value per operating year vs. operating duration for a fast food restaurant located in Toronto, Ontario

Operating Duration: CO₂ Analysis

By varying the operating duration (investment timeframe) from 10 to 100 years, the annual CO₂ emissions asymptote at around 50 years of operation for most buildings. The costs in this analysis include replacement costs of components such as the heat pump, cooling tower, and boilers every twenty years and the ground loop every forty years. Table 6 illustrates the effects that operating duration have on the hybrid system economics. As the assumed operating duration increases, the shave factor and CO₂ emissions level off at values of 0.8 and 22,076 kg, respectively, (as shown in Table 6) for the fast food restaurant. This relationship is plotted in Figure 7. In Figure 7, it can be observed that the CO₂ emissions per operating year decreases with operating duration and begins to level off at around 20 years of operation. It can be concluded that the reduction of CO₂ emissions per operating year for operating durations greater than 20 years are not much greater than the operating duration of 20 years for buildings similar to that of the fast-food restaurant. Similar trends are also observed for the other buildings tested.

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Table 6: Operating duration and CO₂ analysis for a fast food restaurant

Operating Duration (Years)	Shave Factor	CO ₂ Emissions per Operating Year (kg/year)
10	0.01	40,744
20	0.62	23,595
30	0.73	22,494
40	0.75	22,355
50	0.77	22,233
60	0.78	22,178
70	0.79	22,125
80	0.8	22,076
90	0.8	22,076
100	0.8	22,076

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Figure 7: CO₂ emissions per operating year vs. operating duration for a fast food restaurant located in Toronto, Ontario

The relationship between payback period and operating duration is presented in Figure 8. In Figure 8, the solid line represents the payback period corresponding to the operating duration of the hybrid GSHP system and the dashed line tracks the assumed operating duration. When the payback period is greater than the assumed operating duration, the system is not economically

574 viable. When the payback period is shorter than the operating duration, an economically viable
575 system is feasible. The break-even point of the hybrid GSHP system is the point of intersection
576 between the two lines, for the fast-food restaurant being analysed in Figure 8, the break-even
577 point occurs at year 13. If the system operates for 13 years or less, there is no economic benefit.
578 The payback period is calculated as the total costs (discounted to net present value) divided by
579 savings. As a result, an inverse relationship exists between payback period and operating
580 duration before the break-even point (no economic benefit).

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584 Figure 8: Payback period vs. operating duration of a fast-food restaurant located in Toronto,
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4. Conclusions

The present study shows that although heat-pump EFT plays a crucial role in determining the efficiency of the system, the effects of varying the EFT pairs on the optimal design is unsubstantial compared to other parameters such as weather patterns and utility rates. Varying the heat-pump EFT directly affects the COPs of the heating and cooling modes of the heat pump (operating costs), as such, improving the COP in turn reduces GHG emissions. However, EFT pairs that improve the COPs require a larger ground loop which results in incrementally higher upfront costs associated with labour and materials. As a result, the largest savings achieved from the ten real buildings analyzed, compared to the base case (fixed EFT pair) was only 3.6% for a school located in Toronto, Canada. In cases for which CO₂ emissions are the primary motivating factor, increasing the GSHP capacity beyond that which is economically optimized can be used to gain additional environmental benefit at manageable incremental cost. ~~Although there is merit in varying EFT for sizing hybrid GSHPs, the largest savings in this study was for buildings that were mildly cooling dominant, such as the school.~~ Furthermore, the results from the EFT analysis were consistent with the carbon emissions analysis in that most of the environmental benefit for using a hybrid GSHP system, compared to a conventional or GSHP system, can be achieved using the outlined methodology used in this study.

Based on the algorithm used in this study to size hybrid GSHPs, a building with all of its space heating and cooling demands met by a conventional system (no GSHP) would be represented by a shave factor value of 0.0. A shave factor of 0.70 denotes that 70% of the building's peak loads are met by the GSHP and the remainder by a conventional system. As such, in the CO₂ emissions analysis, the operating costs of a hybrid GSHP system was increased when a carbon tax of \$30 per tonne of CO₂ emitted was applied. In order to account for this cost increase, a new optimal shave factor was determined. For all of the buildings analyzed, to accommodate for the increase in operating costs due to a carbon tax being applied, it becomes more economical to increase shave factor (larger GSHP system). Increasing the shave factor (GSHP capacity increases and conventional system capacity decreases) contributes to a reduction in CO₂ emissions and payback periods (especially for the case of a shave factor of 0.0).

In the analysis in which a carbon tax was not applied, using the optimization methodology outlined in *Alavy et al.* [11] yields CO₂ emission levels similar to that of a shave factor = 1.0 (a non-hybridized GSHP). In some cases, such as that of the fast-food restaurant, sizing a hybrid system in which the GSHP heat pump meets 62% of the building's peak load (more economical than 100%) produced only 8.5% more CO₂ emissions than the minimum possible amount. However, in a scenario in which both total costs and CO₂ emissions are important, sizing the system based on the optimal shave factor may result in higher CO₂ emissions than desired, whereas sizing the system to a shave factor of 1.0 might result in higher upfront costs than desired. An example would be the high-rise (II) building with an optimal shave factor of 0.23 for which sizing the system to a shave factor of 0.6 would reduce CO₂ emissions, comparable to that of shave factor = 1, at what might be considered an acceptable cost increase. The methods of analysis presented in this article empower a designer to understand the increment in NPV and payback period associated with such an adjustment so as to make an informed decision. For the ten buildings analyzed, the average reduction in CO₂ emissions for operating durations greater than 20 years (long term) are similar to those of 20 years operation, a difference of 5% (for buildings similar to that of the fast-food restaurant).

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The operating duration analysis was performed to determine its economic and environmental effects on sizing hybrid GSHP systems. Using the “NPV/operating duration” parameter, to determine the amortized system cost per year, reductions in annual amortized system costs are achieved as the assumed operating duration increases. However, the economic benefits of increasing a hybrid GSHP’s assumed operating duration (exceeding the break-even point) begins to asymptote at year 50. This analysis may be of particular interest when government owned buildings or schools are considered, as such buildings infrequently change ownership. Similar results are also observed for CO₂ emissions. For the case of the fast-food restaurant, when the operating duration exceeds the break-even point (13 years), the reduction in CO₂ emissions per operating year is greatest at the operation duration of 30 years and asymptotes thereafter.

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