ANALYSIS OF THE FACTORS AFFECTING HYBRID GROUND-SOURCE HEAT PUMP

INSTALLATION POTENTIAL

by

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Bachelor of Engineering, Ryerson University, Toronto, Canada, 2012

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Abstract

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Master of Applied Science, 2014

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Mechanical and Industrial Engineering

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A series of sensitivity analysis was performed to a variety of design parameters as a way of increasing the knowledge base of automatically sizing GSHPs as a component of a hybrid system. The present work investigates the effects of geographical location (weather patterns and utility rates), operating costs (fixed vs. time-of-use rates), inflation rates, the control strategies used, project life, heat pump entering fluid temperature (EFT), carbon taxation, and building retrofit on the sizing of hybrid GSHP systems in North America. Based on an economic approach to sizing hybrid GSHP systems by selecting the most economical design (based on minimizing the net present value of capital and operating costs), significant energy and cost savings and reductions in CO_2 emissions can be achieved.

Acknowledgements

Dedication

To my parents, Le, Jordan, Michelle, Dr. Dworkin, Dr. Leong, and my best friends for helping me become a better person every day. My current achievements and success are due to your undying support and encouragements.

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List of Terms and Abbreviations

AOPC	Annual Operating Costs
ASHP	Air Source Heat Pump
CD	Cooling Dominant
C_{fc} and C_{fh}	Correction factors accounting for the heat rejected or absorbed by the heat pump
CMHC	Canada Mortgage and Housing Corporation
CO_2	Carbon Dioxide
COP	Coefficient of Performance
CSA	Canadian Standard Association
CTMY	Canadian Typical Meteorological Year
DHP	Ductless Heat Pump (mini-split)
DX	Direct-Expansion
EER	Energy Efficiency Ratio
EFT	Entering Fluid Temperature
F_{sc}	Short-circuit heat loss
GHG	Green House Gas
GLD	Ground Loop Design (Geothermal Software)
GSHP	Ground Source Heat Pump
GHX	Ground Heat Exchanger
GTA	Greater Toronto Area
HD	Heating Dominant
HDD	Horizontal Directional Drilling
HDPE	High Density Polyethylene
IC Savings	Initial Cost Savings
L_c	Required ground loop length for cooling (m)
L_h	Required ground loop length for heating (m)
MURB	Multiunit Residential Building
NPV	Net Present Value
OD	Operating Duration (project life)

PBP	Payback Period
PLF_m	Part-load factor during design month
q_a	Net annual heat transfer to the ground (W)
q_{lc}	Building design cooling load (W)
q_{lh}	Building design heating load (W)
R_b	Thermal resistance of bore (m·K/W)
R_{ga}	Effective thermal resistance of the ground, annual pulse (m·K/W)
R_{gd}	Effective thermal resistance of the ground, daily pulse (m·K/W)
R_{gm}	Effective thermal resistance of the ground, monthly pulse (m·K/W)
SF	Shave Factor
TEDM	Percentage of Total Energy Demand Met by the ground-source heat pump system
TMY	Typical Meteorological Year (United States)
t_g	Undisturbed ground temperature (°C)
t_p	Temperature Penalty
t_{wi}	Liquid temperature at heat pump inlet (°C)
t_{wo}	Liquid temperature at heat pump outlet (°C)

Chapter 1

Introduction

When it comes to dealing with global warming and climate change, there are two approaches, through mitigation and/or adaptation [1]. With the major contributor of climate change being greenhouse gasses (GHGs), policies are created in attempts of reducing emissions. These policies are evaluated according to an economic analysis in order to determine the appropriate level of action in relation to the two mentioned approaches [1].

Based on the current progress in reducing GHG emissions, and a strong economic influence, the rate of change to reduce GHGs will be slow and will favour adaptation [1]. However, GHG emissions can be significantly reduced through mitigation. Electricity and natural gas consumption accounts for almost half of the required energy in Canada [2]. Space heating and cooling is responsible for a large portion, over 60% and 50% for Canadian residential and commercial sectors, respectively, of a building's total energy demands [3]. A substantial reduction in energy consumption, and emissions, can be achieved by providing heating and cooling energy demands to the residential and commercial sectors using clean renewable alternatives.

Due to increasing environmental concerns and potential resource shortages, there is an ongoing drive to develop and implement sustainable alternatives. Ground-source heat pump (GSHP) systems have shown great success and potential, making them a popular clean renewable alternative to consider [4-8]. GSHPs are versatile, economically preferable to conventional systems, and can be combined with other renewable alternatives [9-14].

1.1 Motivation and Objectives

High upfront costs and long payback periods are currently presenting obstacles to significant market penetration of GSHP systems. In many cases, market penetration impedance for GSHP systems can be alleviated with the use of appropriate computational tools for design analyses. Improving the economic outlook of potential installations can be addressed by hybridizing GSHP systems with an auxiliary system; the buildings' base load energy demands are met by the GSHP

system and any excessive peaks are met by an auxiliary system [15]. However, due to the highly variable nature of sizing GSHP systems, general standards currently used by the industry do not always correspond to an optimized design [15, 16]. Addressing the problem, Alavy *et al.* [15] developed a new computational approach, replacing the rule-of-thumb method of sizing hybrid GSHPs.

The methodology outlined in Alavy *et al.* [15] showed that rough standards currently used by the industry do not always correspond to an optimized design [15]. For example, in Sagia *et al.*'s study [17], the cooling tower (auxiliary cooling system) was sized to meet 20%, 30%, and 50% of a particular building's cooling load [17], with the balance met by a GSHP. By contrast, the methodology proposed by Alavy *et al*. [15] automatically sizes the heating and cooling systems, meeting the building's peak cooling and heating loads, with continuously variable auxiliary system capacity. The most economical design is selected based on the lowest net present value of capital and operating costs. Since this methodology was developed recently and is still poorly understood, a significant knowledge gap exists on how best to apply these new techniques. Furthermore, Alavy *et al.* [15] limited their study to ten buildings in the region of Southern Ontario, Canada. The ten real buildings in [15] were analyzed using Toronto, Canada's weather patterns, natural gas and fixed electricity rates. However, the paper focused on explaining and validating the methodology; as such, sensitivity analyses to a variety of design parameters remain valuable to explore as a way of increasing the knowledge base of automatically sizing GSHPs as a component of a hybrid system.

Using the methodology outlined in Alavy *et al.* [15], the present work investigates the effects that geographical location (weather patterns and utility rates), operating costs (fixed vs. time-of-use rates), inflation rates, the control strategies used, project life, heat pump entering fluid temperature (EFT), carbon taxation, and building retrofit have on the sizing of hybrid GSHP systems in North America. By performing a series of sensitivity analysis, based on the studies performed, a framework has been established and the algorithms and results can be used as tools and guides to complement existing ground loop design tools and aid the engineers during the design process.

1.2   Outline of the Thesis

This thesis includes data and information from two published journal articles and one submitted manuscript that is currently under review at the time of writing. A total of three studies were performed, the following chapters are organized as follows:

Chapter 2, a literature review on GSHPs, begins with an introduction to common GSHP system designs followed by design tools used to size GSHPs, hybrid GSHP systems, and knowledge gap/challenges.

Chapter 3, *Study #1*, analyzes the effects electricity rates (fixed vs. time-of-use), geographical location (weather patterns and utility rates), electricity and natural gas inflation, and a seasonality control strategy have on the sizing of hybrid GSHP systems in North America.

Chapter 4, *Study #2*, two new algorithms have been created for the methodology outlined in Alavy *et al*. [15]. The effects of optimizing entering fluid temperature for heat pump and carbon taxation were studied for a variety of commercial installations. Furthermore, the economic viability of varying the project life of a hybrid GSHP system was also studied.

Chapter 5, *Study #3*, a retrofit analysis was performed (hybrid GSHP system) for electrically heated and cooled buildings (baseboard heaters and air-conditioners/cooling towers), in order to investigate the viability of retrofitting existing buildings with a hybrid GSHP system.

Lastly, in Chapter 6, the overall conclusions for the thesis, recommendations, and future work are presented.

Chapter 2

Literature Review

2.1 Ground-Source Heat Pumps

GSHPs (also called earth-energy systems, and GeoExchange systems), based on an old technology, were originally developed for the residential sector [18]. A GSHP functions in the same manner as an air-source heat pump (ASHP). Instead of air, like for an ASHP, the ground is used as a heat source and heat sink. In a GSHP system, high-density polyethylene (HDPE) pipes are buried into the ground and a working fluid, usually water or a water-antifreeze solution, is used to extract or inject heat into the ground. In a direct-expansion (DX) system, refrigerant is used as the working fluid instead of an anti-freeze solution [5, 18]. A GSHP system consists of three major components, heat pumps, the ground heat exchanger (GHX or ground loop), and a heating/cooling distribution system [8, 18].

The advantage of using a GSHP system is that the ground's temperature is more stable than that of the air. This stability of the ground temperature allows the system to meet heating and cooling energy demands more efficiently throughout the year compared to ASHPs [18-19]. The heat pumps have a coefficient of performance (COP) value of three to four, in the heating mode. The COP of a heat pump is calculated as the heat supplied (removed) divided by the required work input (Equation 2.1). This means that, for 1 kWh of electricity, the heat pump can extract and supply 3 to 4 kWh of heat. The water-to-air heat pump is commonly used in a GSHP system [8, 18]. This designation indicates the system's connection are as follows: ground loop (water side), heat pump, and distribution system (in this case an air distribution system) [8, 18].

$$COP_{heat\ pump} = \frac{Heat\ Supplied}{Work\ Input} \tag{2.1}$$

Figure 2.1, reproduced from [8], is a graphical representation of the ground temperature variation as a function of depth. These profiles vary depending on geographical location and weather patterns. As a result, the configuration of the ground loop plays an important role in the

performance and economics of a GSHP system. The deep ground temperatures, corresponding to a location, can be approximated using the "long-term averages of annual average ambient air temperature" [59]. The deep ground temperature in Toronto is approximately 10ºC. By contrast, in Hawaii, due to warmer weather patterns, the deep ground temperature is approximately 25ºC [59].
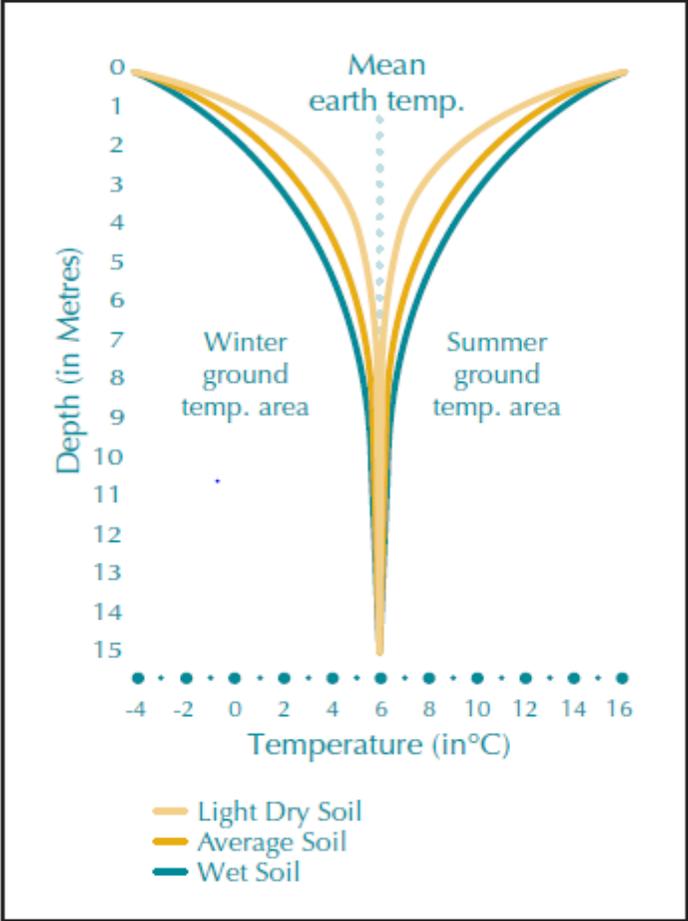
Figure 2.1: Graphical representation of the relationship between ground depth and ground temperature (reproduced from [8])

GSHP systems can reduce up to 66% of greenhouse gas (GHG) emissions compared to conventional heating and cooling systems [5]. The high initial costs of a GSHP system can be alleviated by hybridizing it with an auxiliary system [15]. In a hybrid GSHP system, the GSHP provides the buildings' base load energy demands and any excessive peaks are met by an auxiliary system [15]. Figure 2.2 is a simplified schematic of a hybrid-GSHP system. A ground loop is used

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to extract from or inject heat to the ground. Heat is transferred between the ground loop and distribution system by a heat pump. A common water loop was used as the distribution system in the study by Alavy *et al.* [15]. Similarly, the heating and cooling auxiliary systems are also connected to the common loop and heat is transferred by a heat pump and heat exchanger. For the case of a GSHP system (non-hybrid), the auxiliary heating and cooling systems do not exist.
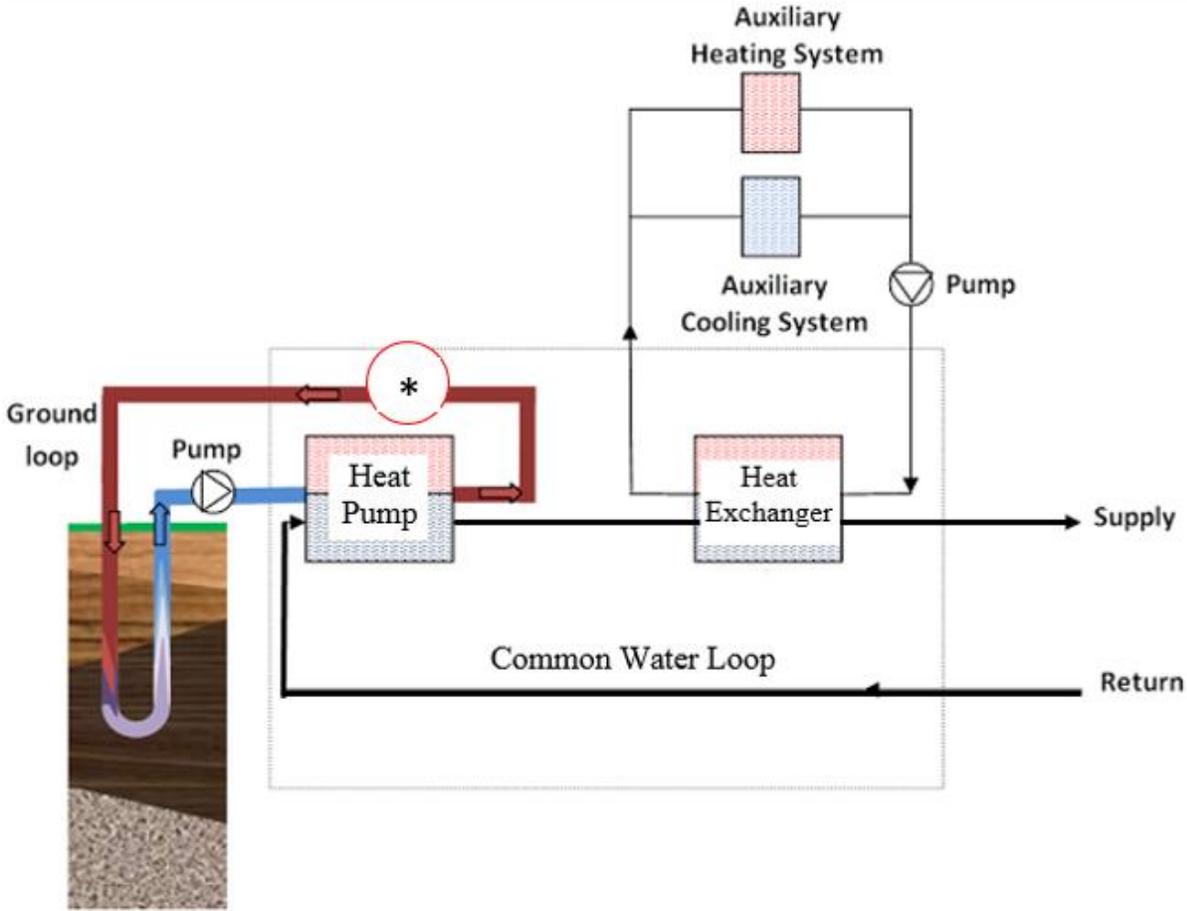
Figure 2.2: Simplified hybrid GSHP schematic

*Alternative placement of the auxiliary cooling systems. For example, a cooling tower would be placed here, the working fluid would be pre-cooled by the cooling tower before entering the ground loop.

2.1.1 Open-loop and closed-loop GSHP systems

GSHP systems can be classified as an open-loop or a closed-loop system [8, 18]. In an open-loop system, the working fluid (water) is extracted from the ground (or water bodies). Water is used as the medium with which heat will be transferred to and from the thermal sink [8, 18]. In order for such a system to operate, it will need a constant supply of fluid to circulate. These types of systems have been successfully implemented for decades and flourish in environments that have large bodies of water or sustainable aquifers [5, 8]. However, meeting the requirements for a sustainable water source may not be feasible for certain applications, such as buildings situated in urban environments, and/or any strict regulations that exist [18].

On the contrary, in a closed-loop system, a fixed volume of a working fluid is contained within the system; it continuously circulates and never exits the ground loop. Closed-loop systems can also be further classified based on the configuration of the ground loop (horizontal, vertical, and slinky) [5, 8, 18].

2.1.2 Horizontal configuration

A horizontal ground loop (Figure 2.3) is the simplest to install of the three configurations. Horizontal loops tend to be more desired where ample land is available such as buildings situated in rural areas [5]. Pipes are generally laid into relatively dense patterns. When trying to install these densely oriented configurations, the top surface of soil is typically required to be excavated. This will allow for the pipe configuration to be seated properly and the soil to redistribute evenly [5]. Typically 35-55 meters of pipe is installed per kW of heating/cooling capacity, at a depth range of 1.5 to 3 meters [8]. The primary thermal recharge, of the ground, for horizontal ground loops is mainly by solar radiation [5]. Table 2.1 outlines the advantages and disadvantages of a horizontal ground loop.

Figure 2.3: Horizontal ground loop configuration (reproduced from [5])

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Table 2.1: Horizontal ground loop advantages and disadvantages

Advantages [5, 8, 18]	Disadvantages [5, 8, 18]
Simplest to install	Requires large ground areas (may not be suitable for urban areas)
Low costs (trenching costs lower than drilling costs)	Longer pipe lengths compared to vertical ground loops
	At shallow depths, ground temperature subject to seasonal variance
	At shallow depths, soil thermal properties fluctuate

2.1.3 Slinky configuration

The slinky loop (Figure 2.4) generally requires more piping than the other loop configurations, but requires less trenching (compared to horizontal loops), approximately 500-1000 feet of pipe per ton of cooling [5]. For the installation of a horizontally oriented slinky, trench width typically ranges between 3 to 6 feet, with a spacing of 12 feet apart. When installing a vertically oriented slinky trench width is generally 6 inches [5]. The disadvantages of the slinky loop configuration are similar to that of the horizontal loop configuration.
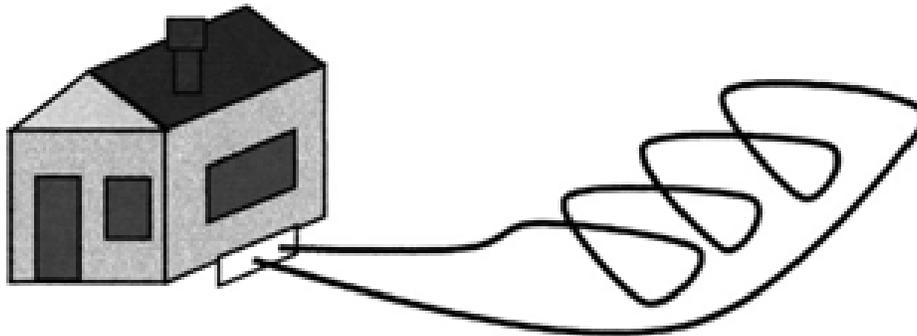
Figure 2.4: Slinky loop configuration (reproduced from [20])

2.1.4 Vertical configuration

The vertical loop (Figure 2.5) is the most commonly used configuration in GSHP applications [8]. The vertical loop configuration is well suited in applications with buildings that have bedrock close to the surface [8]. When little acreage is available, the vertical configuration is favorable compared to the slinky and horizontal loop configurations [5]. Boreholes are drilled 15 to 150 meters deep

into the ground. U-tubes are installed into the borehole. The borehole is then filled with grout to ensure good thermal conductivity between the pipes and the soil [5, 8]. The advantages and disadvantages of the vertical ground loop configuration are outlined in Table 2.2.
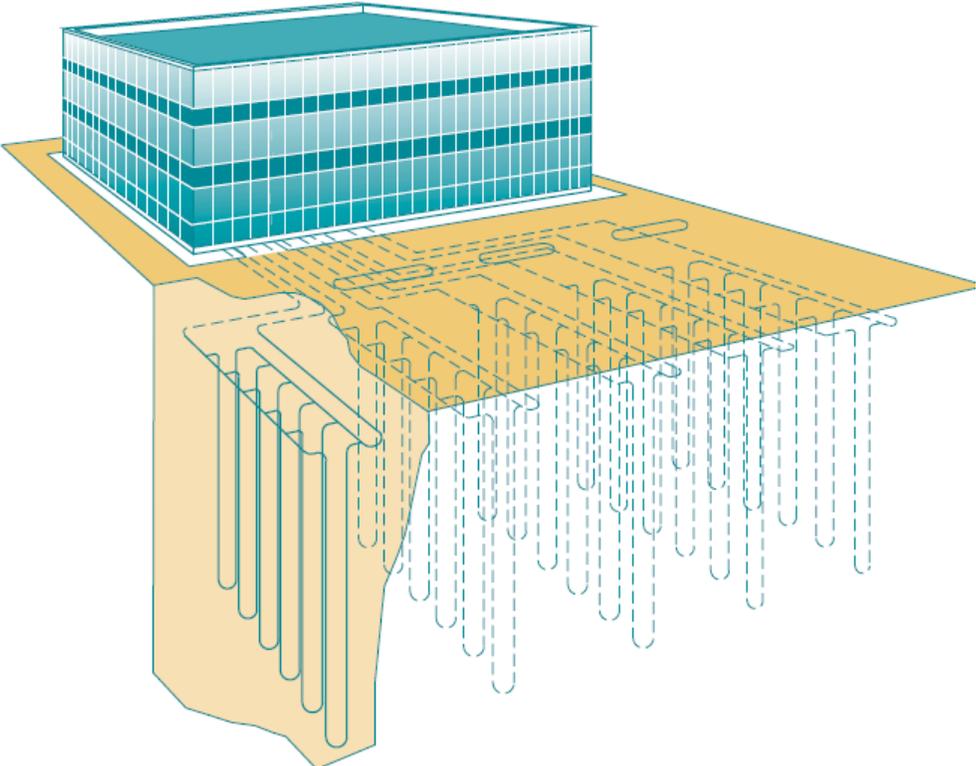
Figure 2.5: Vertical ground loop configuration (reproduced from [8])

Table 2.2: Vertical ground loop advantages and disadvantages

Advantages [5, 8, 18]	Disadvantages [5, 8, 18]
Requires less total pipe length	Higher upfront costs (*i.e.,* drilling, equipment costs)
Requires the least pumping energy	Long-term heat buildup if spacing between boreholes is inadequate
Low surface ground area requirement	
More consistent ground temperatures	

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2.1.5 Horizontal directional drilling

Horizontal directional drilling (HDD) is growing in popularity as an alternative approach for installing the ground heat exchanger. HDD is advantageous in urban areas, landscaped areas can be preserved, because it causes minimal disruption to the surface ground compared to trenching (horizontal) and vertical drilling [21]. However, HDD requires a full layout of the ground to avoid damaging utility lines and underground infrastructure. A simple schematic of HDD is presented in Figure 2.6, a ground pit is used for drilling and installation of the pipes. The costs of HDD is cheaper than that of vertical drilling [personal communication with Mr. Duynhoven and Mr. Rad, June 19, 2013]. The pipes installed by HDD are generally deeper than that of the horizontal configuration. For the case of an HDD ground loop installation outlined in [21], six 250 ft loops at a depth of 35 ft were installed for a residential house located in Rock Hill, South Carolina (resulting in no damage to the house's backyard).
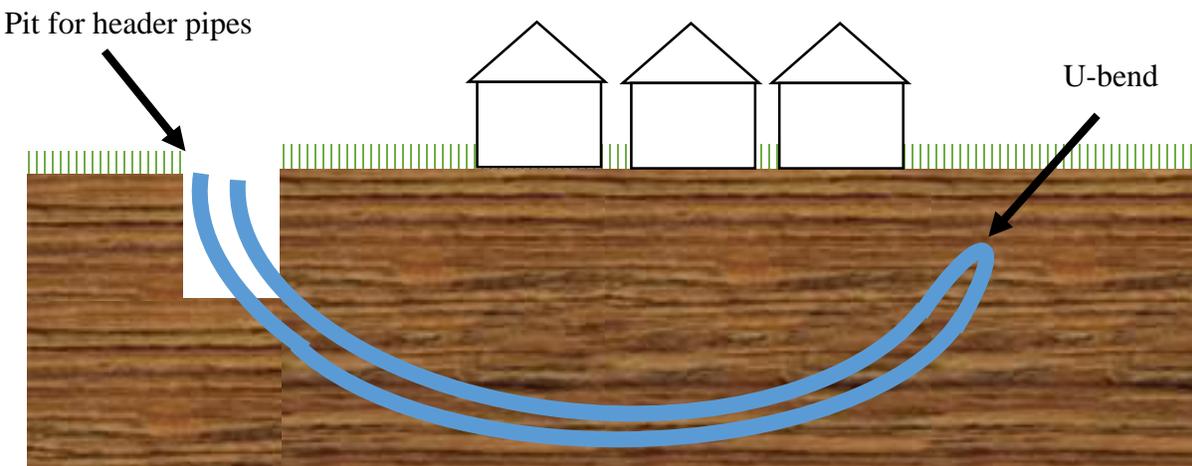
Figure 2.6: Horizontal directional drilling schematic

2.2 GSHP Design Tools

Sizing GSHPs is usually a two-stage process. Building energy modelling software (first stage), such as eQUEST [27], TRNSYS [28], and EnergyPlus [29], is commonly used in the industry to simulate a particular building's energy demands. These programs are used to generate a building's hourly heating and cooling loads for a given year based on user defined inputs such as building geometry, insulation materials, thermostat setting, occupancy patterns, and local weather patterns.

To size the ground loop (second stage), a GSHP ground loop sizing software is typically used. The building's annual hourly loads (8760 hourly loads) are imported into the program and the ground loop is sized based on the loop configuration and other user defined inputs such as heat pump EER/COP, properties of the working fluid, heating and cooling inlet temperatures, soil properties, and piping properties. There are several design software programs available, such as:

- Ground Loop Design (GLD) [22] is the industry leading software for designing GSHPs, it can design GSHP systems of any kind. It is capable of AutoCad integration, and has a system analyzer module for energy/cost analysis.

- GeoAnalyser [23] is a web-based, eliminating the software installation requirements and the use of a USB dongle (*e.g.*, GLD). GeoAnalyser is capable of designing horizontal and vertical GSHPs for residential projects.

- GLHEPRO [24] designs the GSHPs, most suited for vertical configuration, based on monthly heating and cooling loads. GLHEPRO currently is not capable of horizontal or open loop designs.

- RETScreen [25] is a free software provided by the Government of Canada. It can be used for vertical and horizontal closed-loop systems [26].

2.3   Hybrid GSHP Systems

Since 2005, the total installed capacity of GSHPs has increased by 78.9% [34]. Qi *et al.* [34] emphasizes the importance of addressing the problem of imbalance between heating and cooling loads, especially for buildings situated in extreme hot or cold climate, which in turn affects system performance and economics [34]. Implementing proper control strategies is important in optimizing GSHP system performance [35-38]. High upfront costs and long payback periods are currently presenting obstacles to significant market penetration. For large buildings that require large amounts of cooling/heating (cooling/heating dominant), there is a potential long term thermal imbalance of the ground. To address this problem, and account for ground temperature subject to seasonal variance (for horizontal configurations), it is required to have a larger ground loop and/or distance between boreholes. However, in doing so would result in higher upfront costs. In many cases, market penetration impedance for GSHP systems can be alleviated with the use of appropriate computational tools for design analyses. Improving the economic outlook of potential installations can be addressed by hybridizing GSHP systems with an auxiliary system [15, 39-44]; a building's base load energy demands are met by the GSHP system and any excessive peaks are met by an auxiliary system, addressing the problem of long-term thermal imbalance of the ground.

2.3.1   Sizing hybrid GSHP systems

The study in Alavy *et al.* [15] shows there are few research papers available on design strategies of hybrid GSHP systems in an automated manner. To increase the knowledge base of automatically sizing GSHPs as a component of a hybrid system, Alavy *et al.* [15] developed a computerized approach to automatically size hybrid GSHPs. The results by [15] shows that current rules-of-thumb used, such as that proposed by the CSA (Canadian Standard Association) [54], to size hybrid GSHP systems does not always correspond to an optimized design. For example, CSA suggests (for residential buildings) sizing the ground loop to meet 70% of the building's peak energy demands and the remainder by auxiliary heating and cooling systems. Furthermore, there are no rules-of-thumb to size GSHPs for commercial buildings, and most often the economics of a conventional system is compared to that of a full GSHP installation.

The methodology outlined in Alavy *et al.* [15], for sizing vertical ground loop lengths, produces comparable results to that of the leading ground loop design software GLD. In recent versions of GLD (*i.e.,* 2014 version [22]) there is an option to size hybrid GSHPs; however, this functionality is very limited and time consuming compared to the automated approach outlined in Alavy *et al.* [15]. In GLD the user defines what portion of the building's peak energy demands are met by the ground loop and auxiliary system. By contrast, the methodology outlined in Alavy *et al.*, [15] automatically sizes the heating and cooling systems, meeting the building's peak cooling and heating loads, with continuously variable auxiliary system capacity. The most economical design (optimal design) after 20 years of operation (or any other project life) is automatically determined.

The calculations for the computerized approach in Alavy *et al.* [15] are based on the governing equations outlined in ASHRAE's design strategy [18]. Using an energy modelling software (*i.e.,* eQuest, TRNSYS) to obtain the building's annual hourly cooling and heating loads, 8760 hourly loads, which are used towards sizing the ground loop lengths for the cooling and heating loads. Based on the assumption of long-term GSHP operation, the approach uses averaged values of equipment EER (energy efficiency ratio) and COP (coefficient of performance) [18]. For example, the COP and EER of the heat pump are based on the entering fluid temperature as illustrated in Figure 2.7.
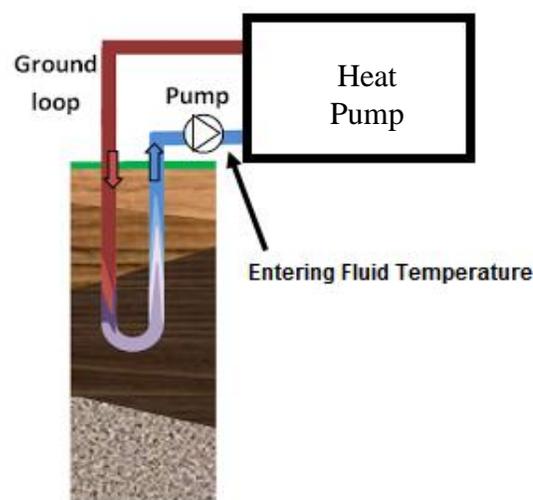
Figure 2.7: Entering fluid temperature to heat pump

The long-term temperature change in the ground due to excessive extraction or injection of heat is accounted for in the ground loop length calculations using a temperature penalty (t_p) parameter. By introducing a shave factor [15] for the portion of peak demands met by the GSHP, the hybrid design can be determined by varying it between 0 and 1. A shave factor value of 0.6 indicates that 60% of the building peak demands are met by the GSHP and the remainder by an auxiliary system (*i.e.*, conventional system). Two sets of ground loop lengths are determined, based on varying the shave factor, for the heating and cooling loads respectively.

The equations used to determine the vertical borehole length for the cooling loads (L_c) and heating loads (L_h) are respectively presented by Equations 2.2 and 2.3, as outlined by Kavanaugh and Rafferty [18]. If L_c is greater than L_h for peak demands, then the building is classified as cooling dominant and the analysis in varying the shave factor (Chapter 2.3.2) will be based on L_c (*vice versa* for heating dominant). For further calculation details, refer to [18].

$$L_c = \frac{q_a R_{ga} + (C_{fc} q_{lc})(R_b + PLF_m R_{gm} + R_{gd} F_{sc})}{t_g - \frac{t_{wi} + t_{wo}}{2} - t_p} \tag{2.2}$$

$$L_h = \frac{q_a R_{ga} + (C_{fh} q_{lh})(R_b + PLF_m R_{gm} + R_{gd} F_{sc})}{t_g - \frac{t_{wi} + t_{wo}}{2} - t_p} \tag{2.3}$$

where [18],

L_c	=	Required ground loop length for cooling (m)
L_h	=	Required ground loop length for heating (m)
q_a	=	Net annual heat transfer to the ground (W)
R_{ga}	=	Effective thermal resistance of the ground, annual pulse (m·K/W)
C_{fc} and C_{fh}	=	Correction factors accounting for the heat rejected or absorbed by the heat pump
q_{lc}	=	Building design cooling load (W)
q_{lh}	=	Building design heating load (W)
R_b	=	Thermal resistance of borehole (m·K/W)
PLF_m	=	Part-load factor during design month

R_{gm}	=	Effective thermal resistance of the ground, monthly pulse (m·K/W)
R_{gd}	=	Effective thermal resistance of the ground, daily pulse (m·K/W)
F_{sc}	=	Short-circuit heat loss
t_g	=	Undisturbed ground temperature (°C)
t_{wi}	=	Liquid temperature at heat pump inlet (°C)
t_{wo}	=	Liquid temperature at heat pump outlet (°C)
t_p	=	Temperature penalty for interference of adjacent boreholes (°C)

The constant values for the parameters listed can be found in Table 3.3.

2.3.2 Sizing hybrid GSHP systems (approach used in the thesis)

Peak cooling and heating demands, as observed in Figures 2.8 and 2.9 for a transit facility located in Toronto, Ontario only occur on the hottest and coldest days in a given year. Since GSHP systems are cheaper to operate but more expensive to install compared to conventional heating and cooling systems, it is not always economical to size the GSHP system to meet peak demands [15]. By introducing a shave factor which is the portion of peak demands met by the GSHP system, the high upfront costs of a GSHP system can be reduced.
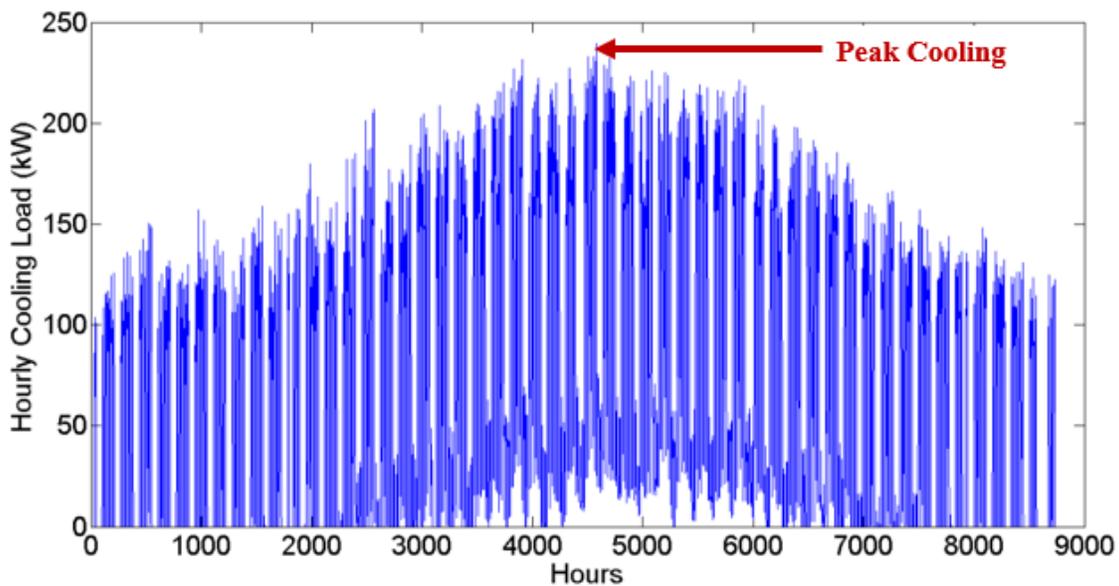
Figure 2.8: Sizing hybrid GSHP systems – Hourly cooling loads for a transit facility located in Toronto, Ontario. The hours in a year (8760 hours in a year) are along the abscissa.

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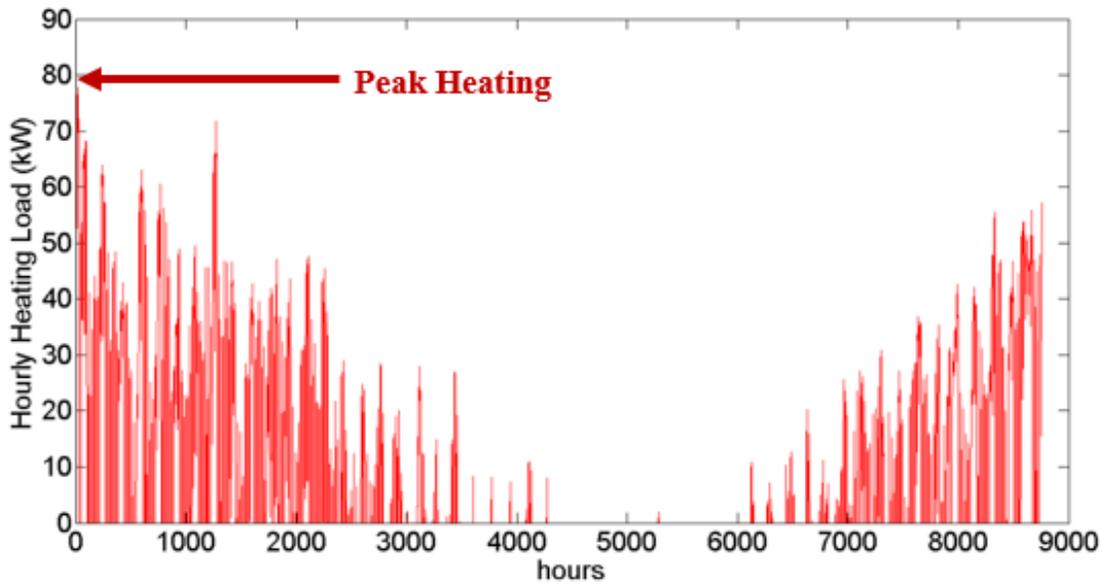
Figure 2.9: Sizing hybrid GSHP systems – Hourly heating loads for a transit facility located in Toronto, Ontario. The hours in a year (8760 hours in a year) are along the abscissa.

Figure 2.10 illustrates the use of the shave factor parameter in order to reduce the high upfront costs of the GSHP system for a transit facility located in Toronto, Ontario. The dashed line represents the shave factor (*SF*). For this particular example the shave factor is set at 60% of the transit facility's peak demands for the cooling and heating curves respectively. This set point indicates that 60% of the peak demands are met by the GSHP (base load) and the remainder by an auxiliary system (peak demands). It can be observed that a large portion of the building's energy demands are still met by the GSHP without the high upfront costs of sizing it to meet 100% of peak demands. By varying the shave factor between 0% and 100% of the building's peak cooling and heating demands, the hybrid GSHP system corresponding to the lowest cost in the net present value (NPV) is the most economical (optimal) design.
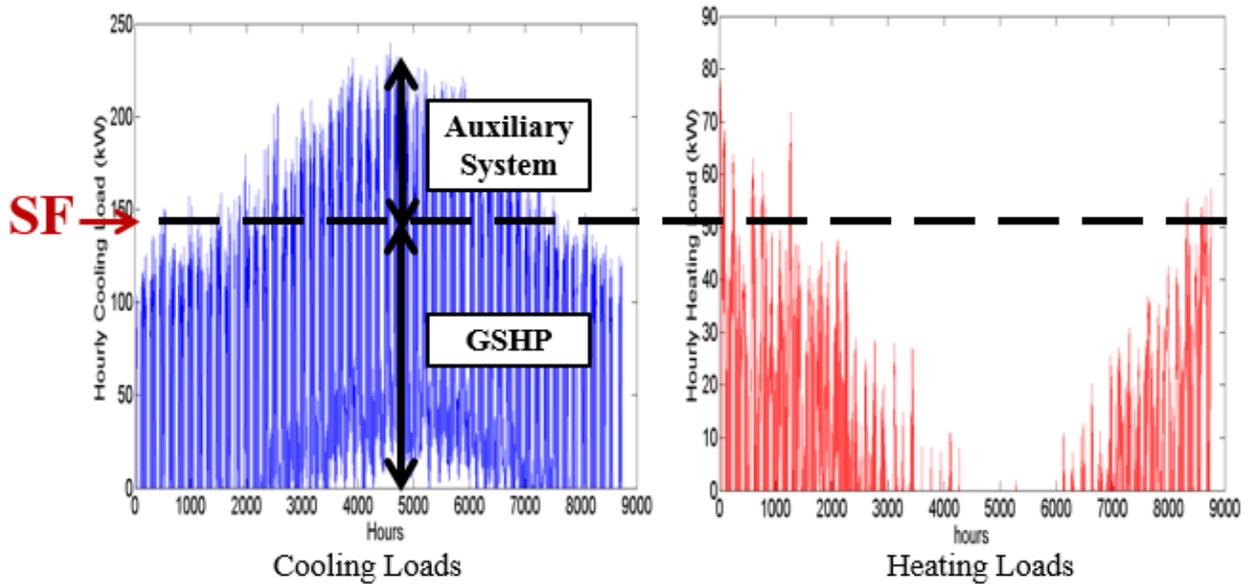
Figure 2.10: Sizing hybrid GSHP systems – Shave factor schematic for a transit facility located in Toronto, Ontario. The hours in a year (8760 hours in a year) are along the abscissa and hourly cooling/heating loads are along the ordinate.

In this thesis, hybrid GSHPs are sized using the methodology in [15] which defines optimal for hybrid GSHPs in terms of costs as presented in Figure 2.11. The costs consists of the initial costs, the operating/maintenance costs, and inflation. In Chapter 3 (Study #1), Chapters 4 (Study #2) and 5 (Study #3) of this thesis, the costs associated with utilities, carbon tax, and building retrofit costs will be considered. Discounting these costs into a total cost in net present value (NPV) dollars, by varying the shave factor between 0% and 100% of peak demands, the shave factor corresponding to the lowest total cost is deemed to be the most optimal hybrid GSHP system design (most economical design). In Figure 2.12, the total costs corresponding to each shave factor value are plotted. The upfront costs and operating costs of the hybrid GSHP system are represented by the blue and red curves, respectively. The total costs in net present value (green curve) is obtained by combining the costs upfront and operating costs (blue and red curves). For the case of the transit facility, the most economical design occurs at the shave factor value of 0.48 (48% of peak demand) at the minimum NPV.
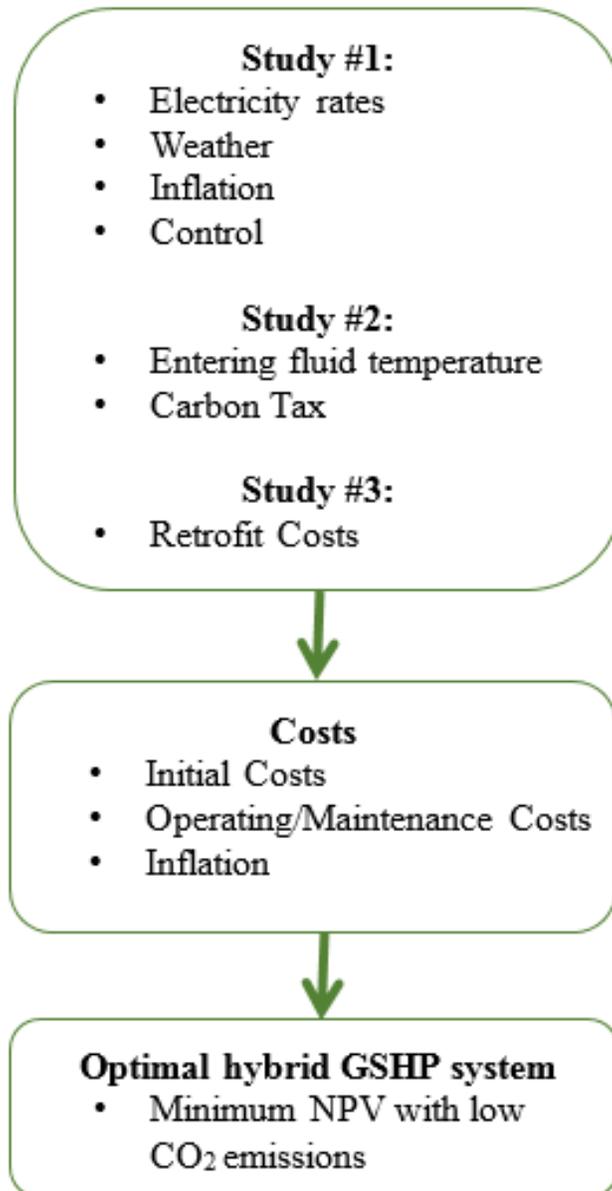
Figure 2.11: Sizing GSHPs based on costs
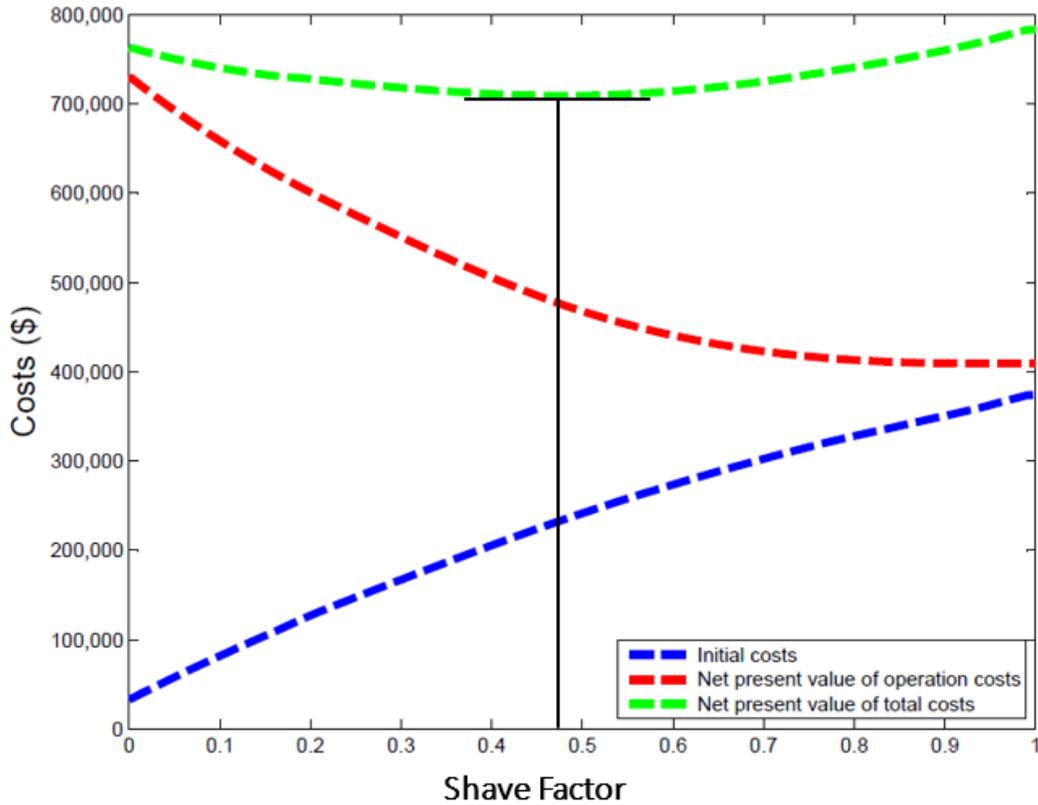
Figure 2.12: Sizing hybrid GSHP systems – Optimal design of a transit facility located in Toronto, Ontario (reproduced from [15]). The total costs in net present value are along the ordinate.

The procedure in determining an optimal design in this thesis consists of the following steps [15]:

- The building is modelled in accordance with an established building code through the use of a building energy modelling software (*i.e.*, eQUEST or TRNSYS). The building's annual energy demands, 8760 hourly heating and cooling loads (8760 hours/year), are generated using the long-term averaged weather data available in most building modelling software.

- The building's hourly heating and cooling loads are imported into the recently developed algorithm in [15] in order to determine the ground loop lengths L_c and L_h as explained in section 2.3.1 (equations 2.2 and 2.3). If $L_c > L_h$ the building is defined as cooling dominant, and the shave factor is varied (between 0% and 100% of peak demands) based on the building's cooling loads (*vice versa* for heating dominant).

- The capital and operating costs for each shave factor value are calculated and discounted into a net present value cost. The shave factor with the lowest total costs in net present value is deemed to be the optimal design.

2.4   Knowledge Gap and Challenges

Using the methodology outlined in Alavy *et al.* [15], a sensitivity analysis for a variety of design parameters will be explored as a way of increasing the knowledge base of automatically sizing GSHPs as a component of a hybrid system. In doing so, time consuming and tedious processes in sizing hybrid GSHP systems can be eliminated. For example, it can take several hours to obtain the ground loop lengths and determine upfront costs for all shave factors from 0 to 1 for a particular building, using existing software such as GLD.

The present work using the methodology outlined in [15], consisting of three studies, will investigate the economic viability of GSHPs based on various parameters such as geographical location, operating costs, inflation rates, operating duration (or project life), heat pump entering fluid temperature (EFT), carbon taxation, and building retrofit.

2.4.1   Heat pump entering fluid temperature and carbon taxation

In a GSHP system 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 [5]. 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 [20, 64].

In a GSHP system, 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 [65]. The authors in [65] find from their numerical model that the fluid temperature in the U-tubes varies non-linearly

along the tubes. More heat is transferred in the first stage (down-flow tube) than in the second stage (up-flow tube) of the U-tube, as the temperature differences between the fluid and its surroundings are higher in the first stage. 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 [39], 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 [39].

In [66], 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 [5], the author compares energy efficiency and CO_2 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 [5]. Electrical heating generates the highest CO_2 emissions of 0.9 kg CO_2/kWh and the lowest primary energy efficiency of 36% [5]. However, this result is dependent on location and the source of electricity (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% [5]. Since GSHPs operate using electricity, green energy contributes to a much greater emissions savings than conventional electricity would otherwise.

The study by Soimakallio *et al.* [68], there are two types of CO_2 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 [68], the authors acknowledge that there is a large uncertainty in determining emissions for GSHP systems. GHG emission calculations are greatly dependent on the following limitations: choice of heating method, actual COP of the heat pump, and electricity supply mix [69, 70].

Similarly, in a study by Greening and Azapagic [67], a heat pump is used to completely replace the gas boilers inside a building. The direct CO_2 emissions of the heating system reduced from 0.220 kg $CO_{2\_equivalent}$/kWh to 0.178 kg $CO_{2\_equivalent}$/kWh [67]. It was concluded that replacement of the gas boiler with a GSHP resulted in a savings of 12.8% of direct GHG emissions and only 2.4% in total GHG emissions [67]. 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 CO_2 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.* [15], which is 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 [97]. Using the methodology outlined in [15], a techno-economic analysis of optimizing entering fluid

temperature to heat pump, and carbon taxation for hybrid GSHP systems in Toronto, Canada was performed to determine and better understand the potential economic and environmental benefits.

2.4.2 Building retrofit

The literature shows that there is a challenge in retrofitting buildings with GSHP systems. For example, in the UK, there is a lack of understanding in determining the advantages of heat pumps for a particular house [30]. A growing body of evidence suggests the lack of determining the advantages for a heat pump system, for new builds and retrofits, is a result of poor installation and operating performance such as poor underestimation of the ground area for horizontal GSHP systems. Sizing heat pumps remain a challenge, in which oversizing the system would result in higher capital cost and longer payback periods [30].

Zhu *et al*. [31] performed a ground water heat pump retrofit case study for a hotel situated in Wuhan, China. The system was sized to replace a conventional air-to-water system and meet the building's cooling and heating loads of 208 kW and 170 kW respectively (total air conditioning area of 1,862 m^2). The retrofit proved to be economical, with the heat pump's COP ranging between 3.1 and 6.8 [31]. Although the installation was economically viable, it may be of interest to further optimize the system by continuously varying the capacity of an auxiliary system.

Between the 1960's and 1980's, many multiunit residential buildings (MURBs) used electric baseboard heaters as the main source of heating because of low capital cost, easy installation/non-intrusive, and low electricity costs [32]. However, current regulations for more efficient HVAC (heating, ventilation, and air conditioning) systems and high electricity rates make electric baseboards undesirable. As a result, there exist a large demand to economically retrofit buildings (*i.e.*, MURBs) with existing electric baseboard heaters. In 2002, a study was performed by the Canada Mortgage and Housing Corporation (CMHC) [32] to retrofit baseboard heaters with water-to-water GSHPs. The GSHP was sized to meet all of the building's heating demands; however, the building's cooling demands were not accounted for in the study resulting in long payback periods of over twenty years [32].

Similarly, Larson *et al.* [33] retrofitted electric baseboard heaters with ductless mini-split heat pumps (DHPs/ASHPs) for multifamily and commercial buildings. However, the buildings' heating energy demands were estimated based on the buildings' energy-use billing history. As a result, several buildings were rejected from the study due to unavailable/incomplete billing histories. Furthermore, buildings that underwent major envelope upgrades were excluded from the study because it would be difficult to attribute DHP savings [33].

There exists a knowledge gap to retrofit buildings heated by electric baseboard heaters with GSHP systems and in several instances space cooling was not accounted for by the heat pump. To fill the knowledge gap, using the methodology outlined in Alavy *et al*. [15], the retrofit designs can be optimized in an automated manner.

2.4.3 Other energy efficient systems

Much work has been done on implementing renewable alternatives to provide heating and cooling energy for the residential sector. For example, a typical single-family house designed for very low energy consumption, located in Germany, has all of its heating and electricity demands met by renewable energy sources [98]. All water consumption used for toilet flushing, garden irrigation, and washing machines are met by a 5500 L rainwater storage tank. Heating and electricity demands are met by a solar heating system and PV system respectively. Similar systems are installed in residential houses in France, Switzerland, Sweden, and the Netherlands [98]. However, these systems still lack space cooling capabilities.

Alternatively, cogeneration systems which simultaneously produce electricity and heat (for space heating and hot water production) can be considered. These systems are suitable in temperate and arctic regions of North America and are often referred to as CHP (combined heat and power) systems [99-100]. In a CHP system, a Stirling engine is commonly used to generate electricity using natural gas. However, in the summer months there is very little demands for space heating. A lot of the generated heat, by the Stirling engine, becomes waste heat. With the addition of an absorption chiller a co-generation system becomes a tri-generation system (combined heat, cooling and power). The waste heat becomes a heat source for the absorption chiller [99-100].

Hasib [100] investigated the performance of a tri-generation system using a ClimateWell® absorption chiller. The experiment was carried out in Vaughan, Ontario, using a Toronto and Regional Conservation Authority (TRCA) house. This project is the first of its kind to use a Tri-generation system for residential purposes, in Canada, using ClimateWell® technology [100]. In addition to the tri-generation system, a ground loop is installed at the TRCA house. The results obtained from this study can be used towards incorporating the ground loop for the TRCA house in an optimized manner.

Chapter 3

Study #1: Hybrid-GSHP Sensitivity Analysis

To better understand optimization factors in sizing hybrid GSHP systems, a series of sensitivity analysis have been performed. Using a rigorous mathematical, computational approach to size hybrid GSHP systems recently published in [15], the use of sensitivity analyses has allowed for a better determination of the impact that variations in input parameters have on the performance of GSHPs. A total of five analyses were performed to determine the effects that operating costs, inflation, geographical location within North America, and a seasonality control strategy have on sizing hybrid GSHP systems.

3.1 Sensitivity Analysis: Parameters Used

The literature on environmental modelling supports the need for sensitivity analysis when undertaking a model-based study [46]. In particular, the application of sensitivity analysis is useful when the parameters employed in the model are impacted by uncertainties related to the parameter data [47] and can provide for a better understanding of the impact of changes in input data on a model's results. Decisions arising from performance modelling are better informed by the results of sensitivity analysis. Otherwise, a risk of misunderstanding the behaviours suggested by the model may result in inferences leading to improper choices [48].

When evaluating performance modelling of GSHP and hybrid-GSHP energy systems, the more recent literature has recognized the need for the use of sensitivity analysis related to model parameters such as electricity and natural gas pricing, interest rates, annual operating hours and ground temperatures when presenting the results of modelled outcomes [49-53].

For the purpose of sensitivity analysis, ten real buildings ranging from large multi-residential to commercial were analyzed as detailed in Table 3.1, data courtesy of CleanEnergy^{TM}. Based on these buildings a total of five sensitivity cases are investigated using the parameters, such as heat pump inlet temperature, boiler cost, interest and inflation rates, listed in Tables 3.2 and 3.3. The

criteria in determining the optimal GSHP size is based on one which produces the minimum total costs in net present value dollars, considering both installation and operating costs (Chapter 2.3.2).

Based on a building's energy demands, for space heating and cooling, two ground loop lengths are calculated [15]. If the ground loop length required to meet peak heating demand is greater than that required to meet peak cooling demand, then the building is heating dominant (and *vice versa*). If a building is heating (cooling) dominant, the ground loop length is sized as a function of shave factor (the portion of peak demand met by the GSHP) based on the building's heating (cooling) demands (Chapter 2.3). The most economical design is selected, based on the optimal shave factor, corresponding to the lowest net present value of capital (of the entire hybrid system) and operating costs [15].

Table 3.1: Building information

Building Info*	Sector
1. Hospital (Hosp.)	Commercial
2. Office	Commercial
3. Restaurant (Rest.)	Commercial
4. Fast-Food Restaurant (FF Rest.)	Commercial
5. Transit Facility (TF)	Commercial
6. Mid-rise, Multi-residential (MR)	Residential
7. High-rise, Multi-residential A (HR A)	Residential
8. High-rise, Multi-residential B (HR B)	Residential
9. High-rise, Multi-residential C (HR C)	Residential
10. School	Commercial

Refer to Appendix A for full building details.

Table 3.2: General costs of hybrid GSHP system components (data courtesy of CleanEnergy[TM])

Item	Cost
Ground heat exchanger (installation and materials)	$65.6/m ($20/ft)
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

Table 3.3: General design parameters (data courtesy of CleanEnergy^{TM})

Parameters	Value
Cooling Design Entering Water Temperature to HP	29.4°C
Heating Design Entering Water Temperature to HP	1.7°C
Heat Pump	CleanEnergy Developments/ PC0018 (COP$_{heating}$=3.1, COP$_{cooling}$=3.78)
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
Inflation Rate	4%
Interest Rate	8%
C_{fc} and C_{fh} [18]	1.04

GSHP Configuration: single U-tube vertical closed-loop

It is important to note that several factors (*i.e.*, insulation, and occupancy patterns) contribute to determining the buildings' heating or cooling dominance. Based on the definition of heating/cooling dominance, using Toronto's weather patterns, only the hospital and office building were found to be heating dominant [15]. For example, occupancy activities such as cooking is accounted for as heating which results in residential buildings requiring less heating from a GSHP (during the winter months) and more cooling during the summer months.

The building's TEDM (percentage of Total Energy Demand Met by the GSHP) can be determined by varying the shave factor. As the shave factor increases so does the TEDM, however, this relationship is not linear. For example, Figures 3.1 and 3.2 illustrate the relationship between shave factor and TEDM for a school situated in Toronto, Ontario. For this particular example, a shave factor of 0.78 is capable of providing close to 100% of the building's TEDM (Figure 3.2); there are only a few days in a year where a building's peak loads occur and exceed the GSHP's capacity, which can be negligible compared to the total annual loading (Figure 3.1).
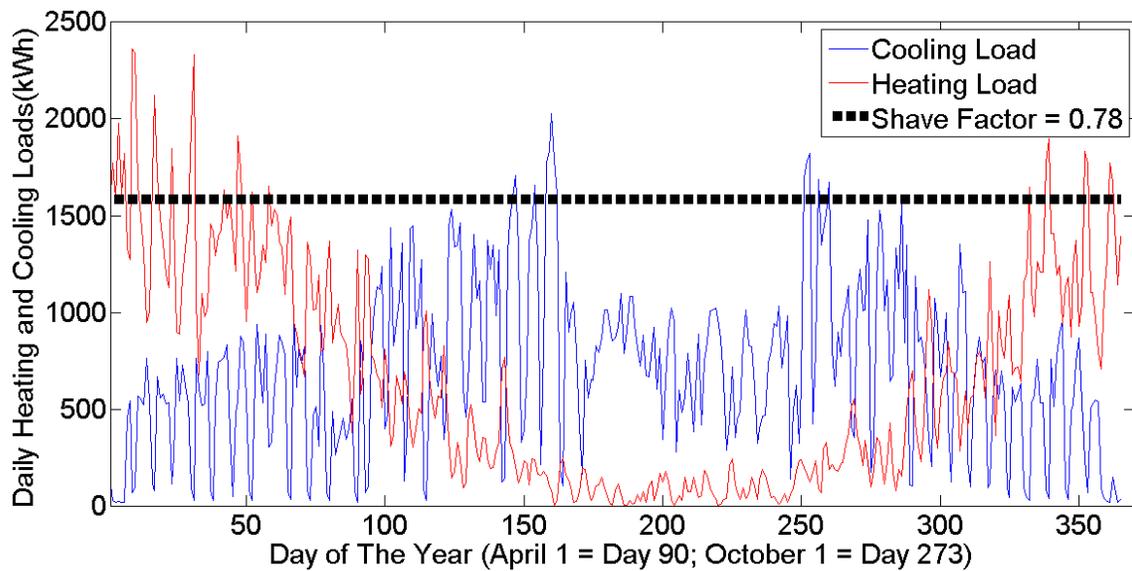
Figure 3.1: Daily heating and cooling loads of a school in Toronto, Ontario, Canada
The abscissa represents the days of the year (365 days). The blue and red line represents the
cooling and heating loads (kWh) respectively.
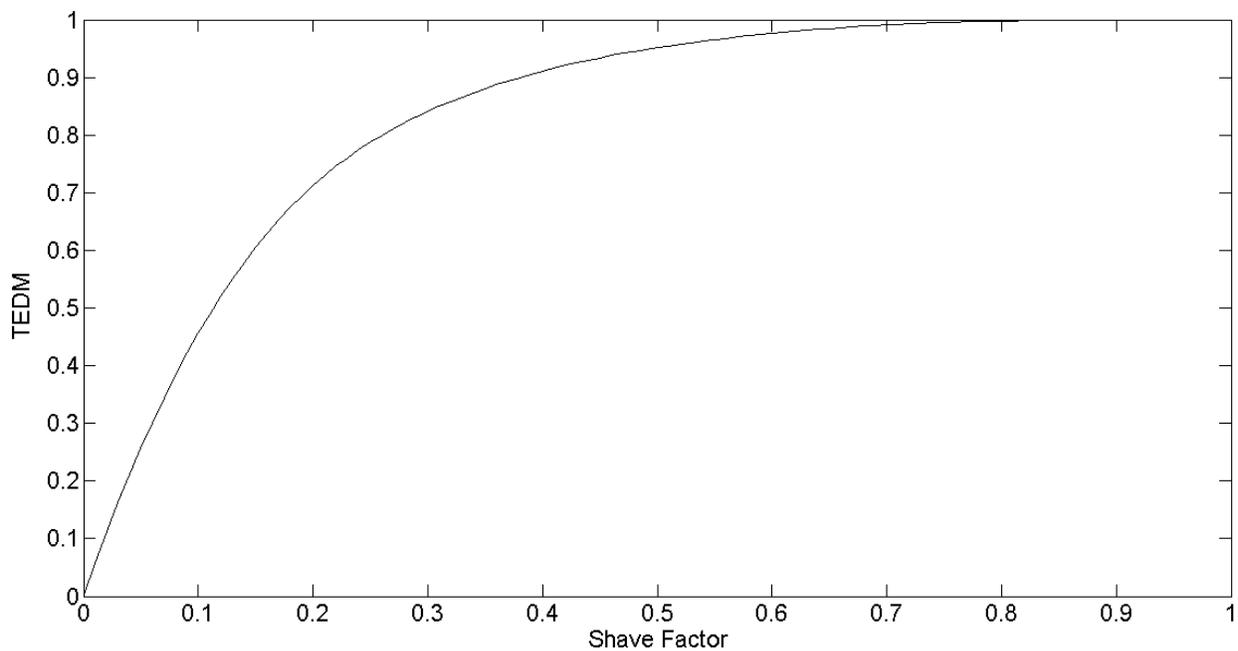
Figure 3.2: shave factor vs. TEDM for a school located in Toronto, Ontario

Although economics determine the optimal sizing of the systems, the incurring annual maintenance costs for these systems are not considered. Furthermore a project life of 20 years was

selected on the notion that payback periods exceeding this would be unappealing, since boilers, cooling towers and heat-pumps operate for approximately 20 years before needing major overhaul or replacement [5]. In this study inflation of electricity and natural gas prices, interest rates and constant values were taken into consideration in determining the annual savings and payback periods.

To determine the optimal hybrid GSHP size for the buildings listed in Table 3.1, the requirements are [15]:

1. The mentioned parameters (Tables 3.2 and 3.3).
2. The buildings' hourly cooling and heating loads (8760 hours/year).
3. Electricity and natural gas rates.
4. Project life (20 years)

3.2 Base Case

Toronto's weather patterns and fixed rates will be used as the base case for comparison. The ten real buildings (Table 3.1), will be analyzed using a project life or operating duration (OD) of 20 years, natural gas and electricity rates of $0.35/m^3 and $0.17/kWh respectively.

In [15], payback period was calculated using the annual operating costs (AOPC) of the first year ($i = 1$), as given by Equations 3.1a and 3.1b. The first and second terms on the right hand side of equation 3.1b correspond to the annual operating costs for $SF=0$ and $0 < SF \leq 1$ respectively. In this analysis the annual savings calculations is modified, as shown in Equation 3.1c. The new annual savings is calculated using the averaged AOPC discounted into net present value (NPV).

$$\text{Payback Period} = \frac{\text{Initial Cost}}{\text{Annual Savings}} \qquad (3.1a)$$

where:

$$Annual\ Savings_{[18]} = AOPC(SF = 0, i = 1) - AOPC(SF, i = 1) \qquad (3.1b)$$

$$Annual\ Savings_{Present} = \frac{\sum_{i=1}^{OD} AOPC_{NPV}(SF = 0, i) - \sum_{i=1}^{OD} AOPC_{NPV}(SF, i)}{OD} \qquad (3.1c)$$

Note that, in Equation 3.1b and 3.1c, i denotes the year and *SF* is the shave factor. The shave factor is defined as the portion of the peak building cooling (heating) demand that is to be supplied by a GSHP, and the remaining portion is supplied by conventional equipment [15]. *SF* = 0 represents a purely conventional system (*i.e.*, no GSHP). *SF* = 1 represents a GSHP system only (*i.e.*, no conventional equipment). For 0 < *SF* < 1, a hybrid-GSHP system is considered.

For demonstrative purposes, using the new payback period calculations, building #6 a mid-rise multi-residential building (Table 3.1) will be discussed. Applying the fixed electricity rate of $0.17/kWh resulted in an optimal system size with a shave factor of 0.37. The optimal hybrid-GSHP size (optimal shave factor) is compared to shave factor values that correspond to 0 and 0.7 for residential buildings, which denotes 0% and 70% of the building's peak demand to be supplied by the GSHP respectively [15]. For non-residential buildings, the optimal hybrid-GSHP size is compared to hybrid shave factor of 0 and 1.

The results are illustrated in Table 3.4. As expected, it is apparent that the conventional system prevailed in achieving minimum upfront costs ($81,694). However, the optimal hybrid-GSHP system proved to be the most cost effective (total costs) after 20 years of operation; meeting 77.7% of the building's total energy needs, even though the GSHP is only sized to meet 37%.

Table 3.4: Mid-rise multi-residential building (cooling dominant)

Shave Factor	Ground loop Length (meter)	TEDM (%)	Total Costs NPV ($)	Initial Costs ($)	AOPC ($)	Payback Period (years)
0	0	0	975,414	81,694	44,686	-
0.37*	3,743	77.7%	868,766	279,598	29,458	13
0.7 (Standard)	6,130	98.4%	917,800	418,400	24,970	17

TEDM (percentage of total energy demand met by GSHP)   AOPC (annual operating costs)

*Optimal system size

In terms of total and initial cost (IC) savings, Equations 3.2 and 3.3 are used respectively:

$$\text{Total Savings} = (\text{Total Costs NPV})_{\text{Standard}} - (\text{Total Costs NPV})_{\text{Optimal } SF} \qquad (3.2)$$

where: net present value is abbreviated to NPV

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IC Savings = (IC)$_{Standard}$− (IC)$_{Optimal\ SF}$ (3.3)

In this analysis, the standard systems which are referred to in Equations 3.2 and 3.3 are for *SF* = 0.7 and 1.0 for residential and non-residential buildings, respectively.

Applying Equations 3.2 and 3.3, the optimal design for the mid-rise multi-residential building provided significant savings; with initial cost savings of $138,800, a total savings of $49,000 and the payback period reduced by four years from 17 to 13. The remaining analyses will focus on comparing the net changes between the optimal-design determined by the methodology to that of the standard shave factors currently used in the industry (0.7 for residential, 1 for non-residential). A positive value, in Equations 3.2 and 3.3., denotes net savings by the optimal design compared to standard sizing.

The results of the base case are illustrated in Table 3.5 and Figure 3.3. GSHP installations for buildings #1 and #2 (hospital and office) were uneconomical and excluded from the figure. The current low rates of natural gas in Toronto make it uneconomical to install a GSHP system for the heating dominant buildings (the hospital and office). Although the standard shave factor for sizing GSHP for residential buildings is 0.7 [54], the shave factor for buildings #6-9 did not exceed 0.42. For example, substantial initial cost savings and total savings ($136,000 and $46,000) can be achieved using the optimal shave factor design which produces a minimum TEDM (percentage of total energy demand met by the GSHP) of 71% for high-rise A (building #7). The same patterns are observed for non-residential buildings. The optimal shave factor are well below 0.7 (70%) and the minimum TEDM is 83%. It is established that if the payback period is greater than the duration of operation (20 years), the system is uneconomical. For buildings #5, #7, #8 and #10, using the standard *SF*s resulted in long payback periods. According to Table 3.5, if an optimal shave factor exists, its payback period will be shorter than the payback period associated with the rule-of-thumb design standard.

Table 3.5: Payback periods – Toronto fixed electricity rates

Payback Period (Years)	Building							
	#3 Rest.	#4 FF-Rest	#5 TF	#6 MR	#7 HR-A	#8 HR-B	#9 HR-C	#10 School
Optimal Payback Period	12.5	12.8	14.4	13	12.7	13.5	12.7	15.8
Standard Payback Period	14.5	15	20	17	18.7	18.1	15.9	30
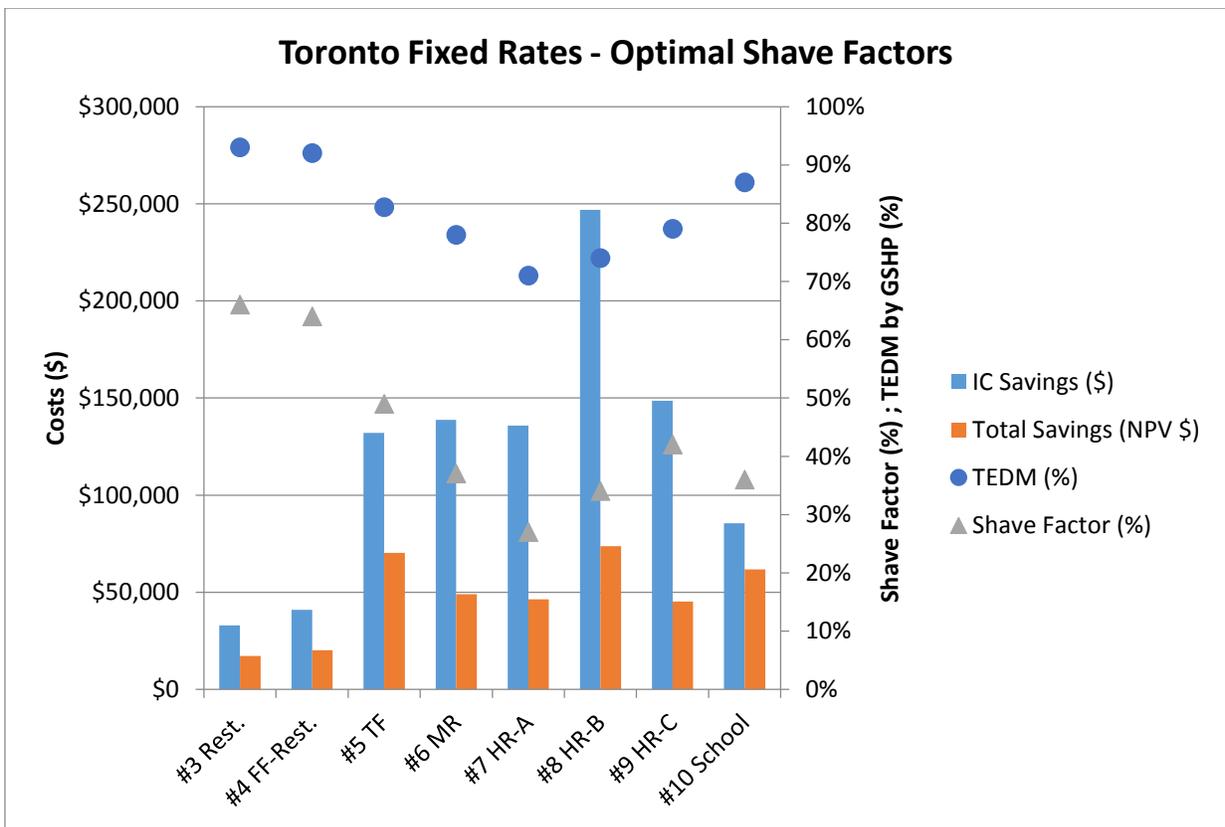
Figure 3.3: Hybrid GSHP data for eight buildings (base case) in Toronto, Ontario, Canada.

With regard to Figure 3.3, building #3 is a restaurant, building #4 is a fast food restaurant, building #5 is a transit facility, building #6 is a mid-rise (multi-residential building), building #7-9 are high-rises (multi-residential buildings), and building #10 is a school. The blue bars represent the savings in initial costs (IC) associated with using an optimized hybrid GSHP system as compared to using industry design rules-of-thumb. The orange bars represent the net present value (NPV) of total

savings associated with using an optimized hybrid GSHP system as compared to using industry design rules-of-thumb. The triangles and circles represent the *SF* (shave factor) and total energy demands met (TEDM), respectively, associated with using an optimized hybrid GSHP system.

3.3   Analysis #1 - Electricity Rates: Fixed vs. Time-of-Use

Conventional heating and cooling consume large amounts of natural gas and electricity, with operating costs affected by rising costs of resources. It is imperative to understand the effects of fixed vs. time-of-use electricity rates, which has become prevalent in North America. The most recent weather data, the CTMY2 (Canadian typical meteorological year) [55], was used to simulate the buildings' hourly loads using eQUEST Version 3.64 [27].

Due to the ease of obtaining data for weather, electricity and natural gas costs, and as it is representative of many North American and European locales in terms of climate and GSHP potential, the present study considers Toronto, in the province of Ontario, Canada. Table 3.6 presents the operating costs and conditions used in this analysis. Since the electricity tax rates vary depending on many factors, it was impractical to derive a mathematical algorithm to approximate these taxes and fees. However, based on information available from the Ontario Energy Board [56], electricity prices used in this analysis, the adjusted values are also presented in Table 3.6. If a building operates for twenty-four hours in a day, using the time-of-use rates, the average electricity rate is $0.17/kWh (the same as fixed rate). However, most buildings operate during peak demands and the weighted average cost based on time-of-use rates would exceed that of the fixed rate of $0.17/kWh.

Table 3.6: Toronto operating costs and conditions

Project Life	20 years[†]
Ground Temperature	10°C[†]
Natural Gas	$0.35/m^{3}[†]
2012 Electricity Fixed Rate	$0.87/kWh[57]
2012 Time-of-Use Rates[58]	
Peak	$0.117/kWh
Mid-Peak	$0.1/kWh
Off-Peak	$0.065/kWh
Adjusted: 2012 Electricity Fixed Rate	$0.17/kWh
Adjusted 2012 Time-of-Use Rates	
Peak	$0.228/kWh
Mid-Peak	$0.195/kWh
Off-Peak	$0.127/kWh

[†]Data courtesy of CleanEnergy^{TM}

The net difference from the results (fixed and time-of-use rates) are calculated as follows:

$$\Delta \text{Total Savings} = (\text{Total Savings})_{\text{time-of-use}} - (\text{Total Savings})_{\text{Fixed}} \qquad (3.4)$$

$$\Delta \text{Initial Cost Savings} = (\text{IC Savings})_{\text{time-of-use}} - (\text{IC Savings})_{\text{Fixed}} \qquad (3.5)$$

$$\Delta \text{Payback Period} = (\text{PBP}_{\text{Optimal Design}})_{\text{Fixed}} - (\text{PBP}_{\text{Optimal Design}})_{\text{time-of-use}} \qquad (3.6)$$

$$\Delta SF_{\text{Optimal Design}} = (SF_{\text{Optimal Design}})_{\text{time-of-use}} - (SF_{\text{Optimal Design}})_{\text{Fixed}} \qquad (3.7)$$

Based on Equations 3.4 to 3.7, time-of-use rates are more economical than fixed rates if values for ΔTotal Savings, ΔIC Savings (initial cost) or ΔPBP (payback period) are positive. For the case of ΔSF (shave factor, the portion of peak demand met by the GSHP), a positive value indicates the time-of-use's GSHP system capacity is larger than the fixed rates' and smaller if it is negative.

Similar to the base case in Figure 3.3, optimal GSHP size for Toronto time-of-use rates are presented in Figure 3.4. Implementing Equations 3.4-3.7, the results for this analysis are presented in Figure 3.5. Time-of-use electricity pricing was an incentive to reduce peak power usage by rewarding cheaper rates during off-peak times. However, this strategy may have adverse effects on buildings with GSHPs. The restaurants showed reduced costs due to long operating hours and

high cooling demands during cheaper off-peak times. This reduction contributed to downsizing of the GSHP system for these buildings; reducing the upfront costs contributed to a positive ΔTotal Savings and ΔInitial Cost Savings. However, it also resulted in a decrease in annual operating costs savings which contributed to longer payback periods.

For the case of the school, most of the cooling demands occur during peak rates. As a result, the GSHP size was increased (increasing the shave factor: ΔSF=0.03), resulting in a negative ΔTotal Savings and ΔInitial Cost Savings. However, during the summer months (holiday months) it is common for schools to not provide space cooling. The hospital's and office's heating dominance prevents feasibility for a GSHP system as in the electricity fixed-rate scenario. As observed in Figure 3.5, comparing between fixed and time-of-use rates, an increase in shave factor results in poorer economics.
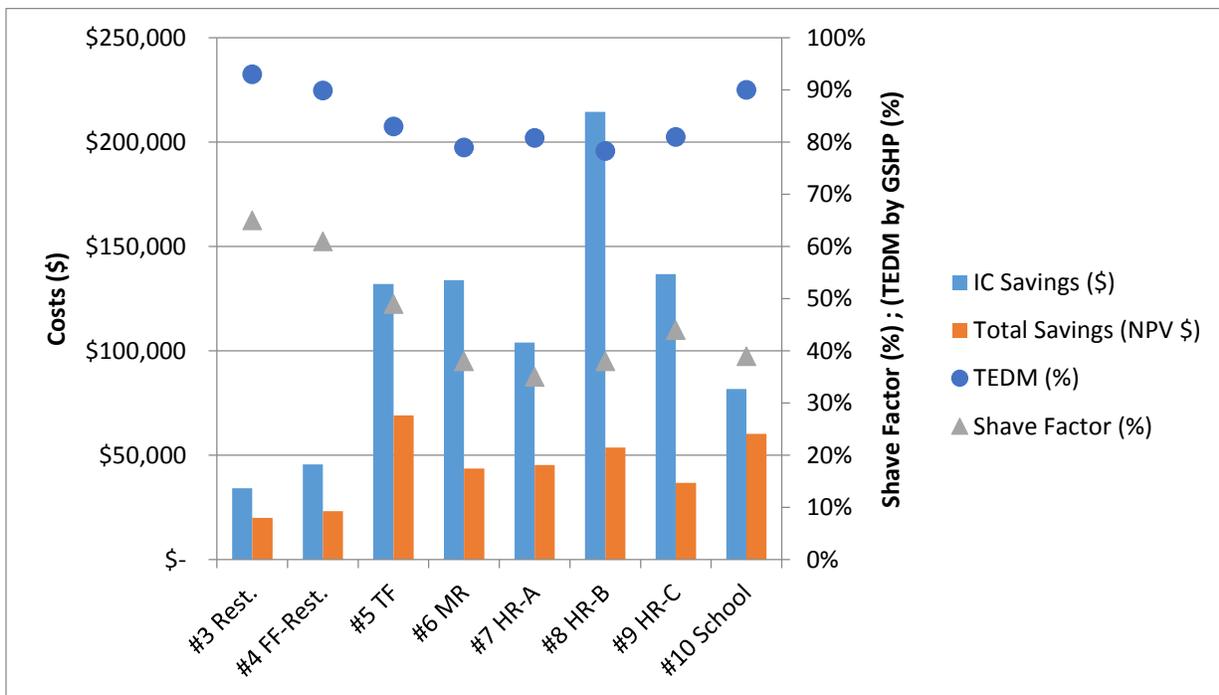
Figure 3.4: Toronto time-of-use electricity rates results for eight buildings in Toronto, Ontario, Canada

In Figure 3.4, the buildings are the same as those depicted in Figure 3.3. The blue bars represent the savings in initial costs (IC) associated with using an optimized hybrid GSHP system as compared to using industry design rules-of-thumb. The orange bars represent the net present value

(NPV) of total savings associated with using an optimized hybrid GSHP system as compared to using industry design rules-of-thumb. The triangles and circles represent the *SF* (shave factor) and total energy demands met (TEDM), respectively, associated with using an optimized hybrid GSHP system.
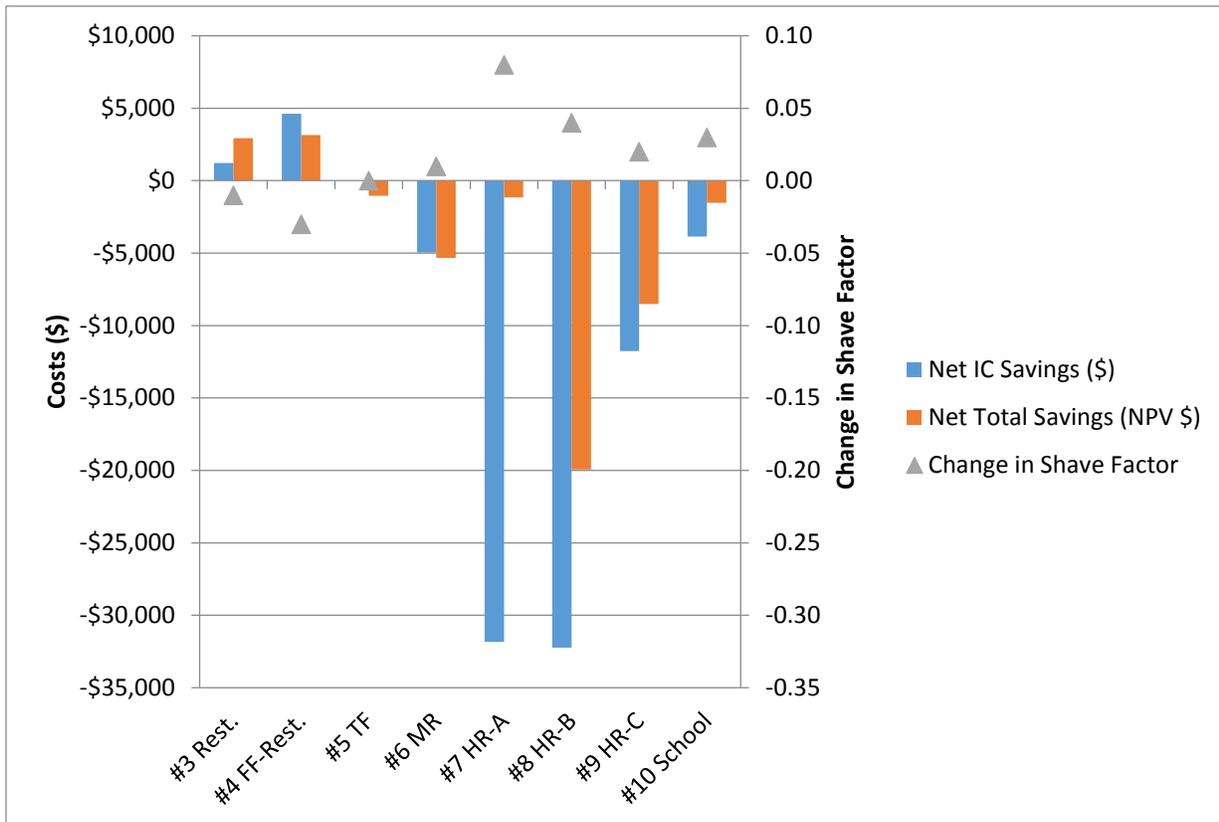
Figure 3.5: Δinitial cost (IC) savings, Δtotal savings, and Δshave factor for Toronto fixed vs. time-of-use electricity rates

3.4   Analysis #2 - Toronto Fixed Rates with Variable Weather

A weather sensitivity test was conducted in this analysis using weather data from other North American cities. A total of 11 US locations focusing on weather extremities were considered. Since the effect of weather is analyzed here, Toronto's fixed rates, the same rates used in Analysis #1, were applied. If the local rates were also considered, the effect of weather may not be clearly shown.

The hourly cooling and heating demands for buildings #1-6 and #10 were simulated in eQUEST using the TMY3 weather data [55]. The ground temperatures corresponding to each of the 11 locations are approximated using the "long-term averages of annual average ambient air temperature" retrieved from [59].

The optimal hybrid-GSHP system designs are rivalled to the standards currently used in the industry (in prior discussion: 0.7 for residential and 1 for non-residential buildings). With varying weather patterns, the savings can be compared as follows:

$$\Delta\text{Total Savings} = (\text{Total Savings})_{\text{Other}} - (\text{Total Savings})_{\text{Reference Location}} \qquad (3.8)$$

$$\Delta\text{Initial Cost Savings} = (\text{IC Savings})_{\text{Other}} - (\text{IC Savings})_{\text{Reference Location}} \qquad (3.9)$$

$$\Delta\text{PBP} = (\text{PBP}_{\text{Optimal Design}})_{\text{Reference Location}} - (\text{PBP}_{\text{Optimal Design}})_{\text{Other}} \qquad (3.10)$$

$$\Delta SF_{\text{Optimal Design}} = (SF_{\text{Optimal Design}})_{\text{Other}} - (SF_{\text{Optimal Design}})_{\text{reference}} \qquad (3.11)$$

$$\Delta GroundLoopLength = \frac{(GroundLoopLength)_{other} - (GroundLoopLength)_{reference}}{(GroundLoopLength)_{reference}} \qquad (3.12)$$

The results are compared to those using Toronto's weather patterns (reference location). The alternative location is more economical than Toronto's if values for ΔTotal Savings, ΔInitial Cost Savings or ΔPBP (payback period) are positive. For the case of Δ*SF* (ΔShave Factor), a positive value indicates the system size for the building situated with that particular weather pattern is larger than that which would be in Toronto; smaller if Δ*SF* is negative.

In the following figures, only buildings with an optimal shave factor are plotted. Since the hospital and office were heating dominant in Toronto's weather, resulting in a shave factor value of zero (most economical by a conventional system), they were omitted from the figures. Based on the results, weather patterns have a strong effect on payback periods and costs. In warmer weather there is a larger initial cost savings which contributes to a net positive total savings (Figure 3.6).

This savings was achieved by downsizing the GSHP and expanding the conventional equipment to meet the peak demands (Figure 3.7).
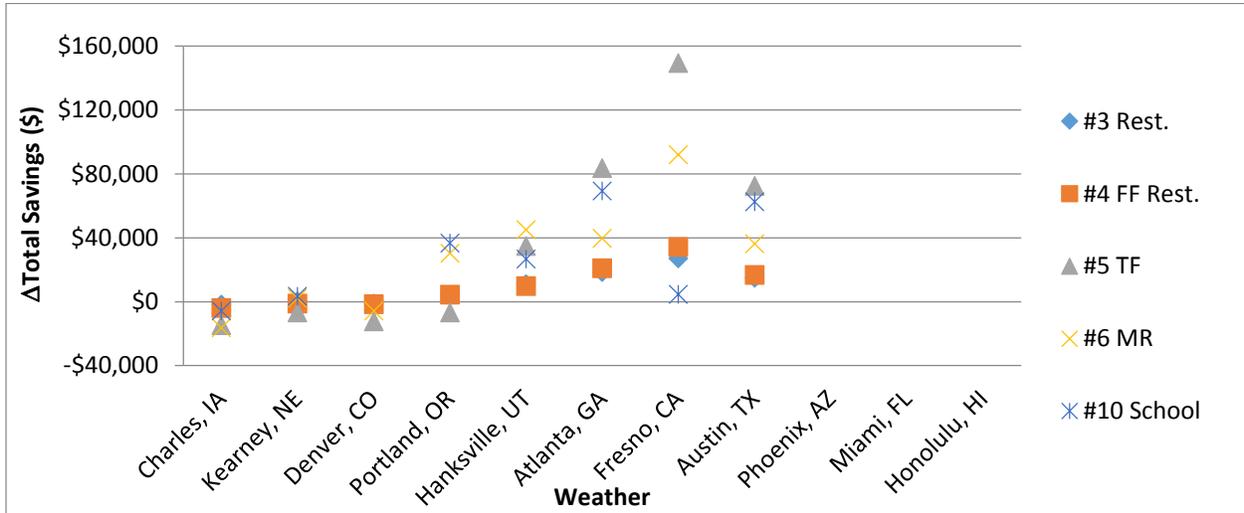
Figure 3.6: ΔTotal Savings: variable weather, Toronto rates. The base case, Toronto's weather patterns and fixed rates, was used for comparison. The ordinate represents the change in savings in net present value (NPV) associated with using an optimized hybrid GSHP system as compared to using industry design rules-of-thumb.
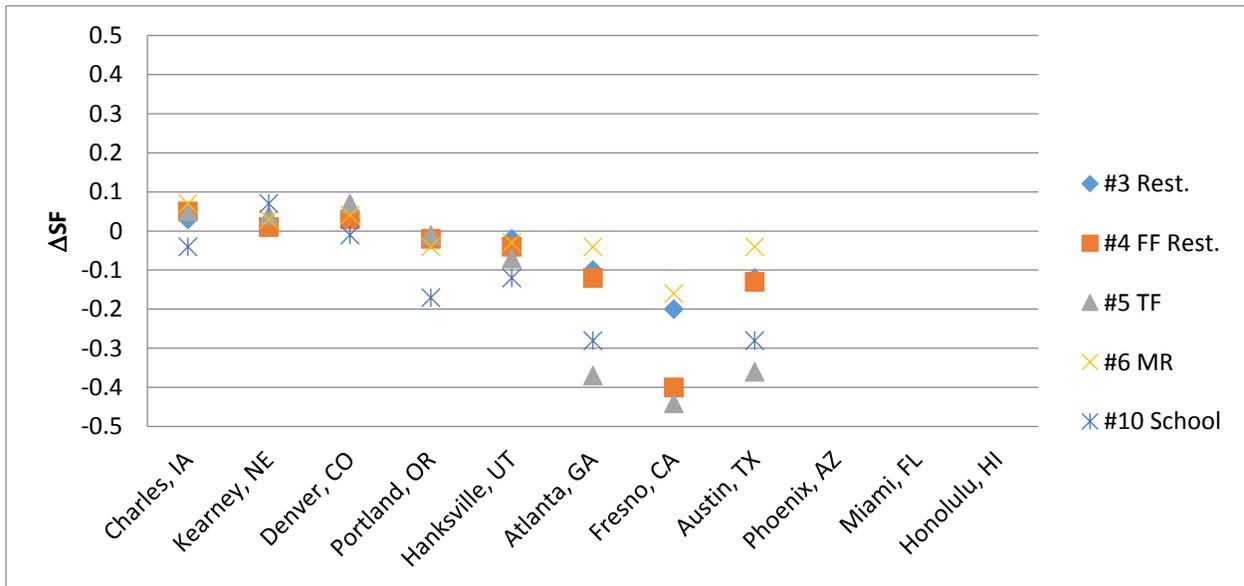
Figure 3.7: Δ*SF*: variable weather, Toronto rates. The base case, Toronto's weather patterns and fixed rates, were used for comparison.

There are several factors contributing to smaller shave factors (Figure 3.7). Firstly, in warmer weather (states: AZ, FL, HI) the average ground temperature is significantly higher than that of Toronto. As a result, this increase in ground temperature requires a longer ground loop length to meet the buildings' energy demands. In Figure 3.8, the fast-food restaurant was used to compare the effects warmer weather have on ground loop lengths using a shave factor of 1 (*SF*=1 for Equation 3.12). For Honolulu's weather patterns, the fast-food restaurant requires a ~70% longer ground loop in order to provide 100% of the building's total energy demands compared to if it were subject to Toronto weather. For a larger building such as the school, it requires a 140% longer ground loop if the school were to be located in Arizona, instead of Toronto.

Although buildings require more cooling in warmer weather, due to higher ground temperatures, downsizing the ground loop length and expanding the cooling tower was most economical. Based on California's and Atlanta's mild winter, heating demands are kept minimal which helps to produce large savings compared to Toronto. Denver, Charles and Kearney have similar weather patterns to that of Toronto. As a result, after applying Toronto's rates, the net change in ground loop length, savings and payback periods (Figure 3.9) were not as substantial compared to other locations. Using Toronto's rates no optimal shave factor exists for Phoenix, Miami and Honolulu (uneconomical to install GSHP system).
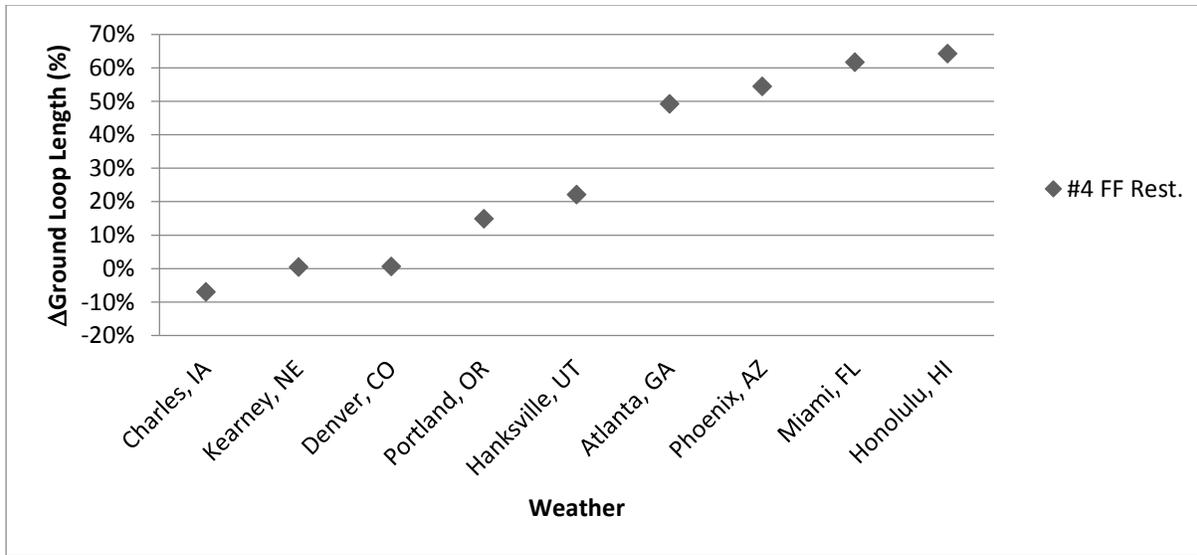
Figure 3.8: ΔGround loop length - fast food restaurant. The abscissa represents the weather patterns, for the US cities, used in this analysis. The base case, Toronto's weather patterns and fixed rates, was used for comparison. The ordinate represents the change in ground loop length, for *SF*=1, associated with using Toronto's weather patterns as the base case for comparison.
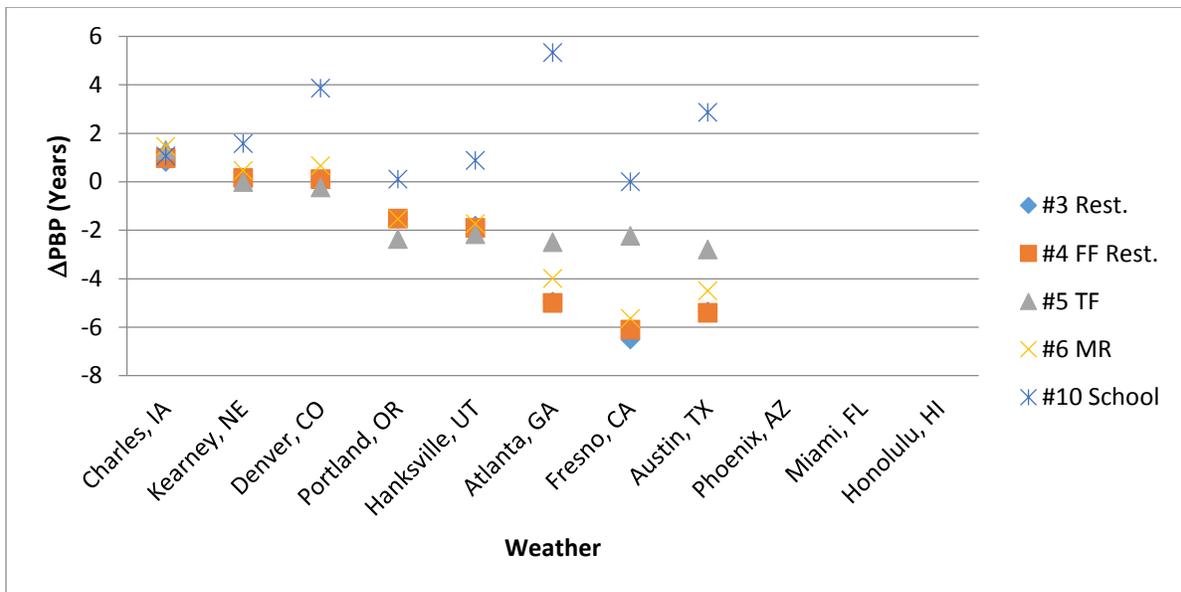
Figure 3.9: ΔPBP: variable weather, Toronto rates. The ordinate represents the change in payback period (ΔPBP) associated with using an optimized hybrid GSHP system as compared to using industry design rules-of-thumb. If the payback period for the US cities in the abscissa is shorter than that of the base case, ΔPBP is positive.

It is interesting to note some unique cases where a very small optimal shave factor produces significant savings compared to the standard shave factor (Table 3.7). For example, with a shave factor of 0.09 meeting 48% TEDM (percentage of total energy demand met by the GSHP), the office with Austin's weather patterns and Toronto's rates produces significant savings (over $1,000,000) compared to a standard shave factor of 1 (SF =1). About half of the building's energy demands are met, requiring only 13% of the standard's ground loop length.

Table 3.7: Low optimal shave factor cases using Toronto's fixed rates

Building (Weather Patterns)	Shave Factor	TEDM (%)	Total Savings ($)	Initial Costs Savings ($)	Payback Period (years)
Hospital (Atlanta, GA)	0.14*	44	117,411	236,463	12.2
Hospital (Portland, OR)	0.14*	61	88,324	146,225	12.8
Office (Austin, TX)	0.09*	48	1,014,326	1,440,203	8.0
School (Austin, TX)	0.08**	28	124,376	278,055	12.9

*To meet peak heating **to meet peak cooling

3.5   Analysis #3 - Variable Weather and Local Rates

In this analysis, the same approach and conditions were used as that of Analysis #2. The only exception is that, instead of using Toronto's rates, the most recent local rates for the cities tested were used (Tables 3.8 and 3.9) [60-62]. In this analysis, only the local natural gas and electricity rates are considered; labor, supplies, installation and other rates are still assumed to be the same as in Toronto, so that the effects of local natural gas and electricity prices can be studied. The exchange rates between the Canadian and US currency were assumed to be the same when this study was performed (June, 2012).

Table 3.8: Natural gas prices for 2011 (US dollars)

		Natural Gas Price (2011)	
State	City	Residential Average Price ($/m³)[60]	Commercial Average Price ($/m³)[61]
Arizona	Phoenix	0.53	0.35
California	Fresno	0.35	0.29
Colorado	Denver	0.29	0.28
Florida	Miami	0.65	0.39
Georgia	Atlanta	0.54*	0.37
Hawaii	Honolulu	1.95	1.61
Iowa	Charles	0.34	0.27
Nebraska	Kearney	0.32	0.23
Oregon	Portland	0.44*	0.36*
Texas	Austin	0.38*	0.26
Utah	Hanksville	0.3	0.25

*2010 prices were used (unavailable 2011 prices)

Table 3.9: Average electricity prices for 2010 (US dollars)

		Average Electricity Prices (2010)	
Location	City	Residential ($/kWh) [62]	Commercial ($/kWh) [62]
Arizona	Phoenix	0.1097	0.0947
California	Fresno	0.1475	0.131
Colorado	Denver	0.1104	0.0913
Florida	Miami	0.1144	0.0976
Georgia	Atlanta	0.1007	0.0906
Hawaii	Honolulu	0.281	0.2593
Iowa	Charles	0.1042	0.0791
Nebraska	Kearney	0.0894	0.0763
Oregon	Portland	0.0887	0.0759
Texas	Austin	0.116	0.0919
Utah	Hanksville	0.0871	0.0715

This analysis produced similar results to that of Analysis #2. Higher ground temperatures were a significant factor for the downsizing of the system's ground loop and longer payback periods. Since shave factor (the portion of peak demand met by the GSHP) is a measure of the building's peak demands met, it can be uneconomical to increase the shave factor (increasing ground loop increases initial cost) for cooling dominant buildings in warmer climates. However, the effects can be alleviated if the local rates were high enough. This can be observed for the case of Honolulu, Hawaii. In Analysis #2, installation of a GSHP system in Honolulu proved to be uneconomical,

but by applying the actual local electricity rates, which are quite high ($0.281/kWh and 0.2593/kWh for residential and commercial respectively), an optimal design is found. Similar patterns are obtained for the case of Phoenix and Miami. Previously, using Toronto's rates there was no shave factor for any buildings with Phoenix's or Miami's weather patterns; applying the actual local rates produces optimal shave factors and improved payback periods.

Thus far, this methodology has provided valuable insight in sizing hybrid GSHPs compared to the standards currently used by the industry. Based on the assumed COP_{GSHP} and $COP_{cooling\_tower}$, warmer climates lead to total savings when compared to Toronto's climate (reference) — the optimal design produces a shave factor that would otherwise be undetermined by installers using current standards of 0.7 or 1. As a result, high upfront costs from large ground loops are minimized. Locations with warmer climate than in Toronto have poorer payback periods due to ground temperatures and loop lengths (except Hawaii, which has predominating electricity prices). For example, for the case of the fast-food restaurant building situated in Phoenix, it has an optimal shave factor of 0.16 and 27% TEDM (optimal shave factor of 0.64, 92% TEDM for Toronto's weather and rates). This is a substantial drop in shave factor due to the weather and higher ground temperature. Another example would be the office located in Phoenix (Table 3.10). Installers would likely overlook the optimal shave factor of 0.23 using current sizing standards. Approaching the problem with a shave factor of 0.7 or 1 would lead the installer to believe that a GSHP is unfeasible since it would be costlier than a conventional system. However, this is not true, and implementing a shave factor of 0.23 (compared to 0) leads to a savings of over $330,000 in net present costs.

Table 3.10: Office building – Phoenix, Arizona (weather and local rates)

Shave Factor	TEDM (%)	Total Costs (NPV) ($)	Initial Cost ($)	Annual Operating Cost ($)	Payback Period (years)
0	0	2,532,587	185,575	177,167	0
0.23*	62.06	2,202,834	1,163,198	78,478	11.79
0.7	98.81	2,797,625	2,673,894	9,340	15.93
1	100	3,412,982	3,318,836	7,107	19.52

Optimal shave factor

The effects local weather and rates have on payback periods are summarized in Table 3.11. Only payback periods from the buildings that have an optimal shave factor are summarized. Toronto, Denver, Kearney and Charles have similar weather patterns and rates, thus their payback periods are similar. Higher ground temperatures lead to longer payback periods with Hawaii as the exception due to high electricity rates. The location with the longest payback period is Phoenix and the shortest is Hawaii.

Table 3.11: Optimal design – mean and median payback periods

Location	Mean Payback Period (Years)	Median Payback Period (Years)	Ground Temperature [59] (°C)
Charles, IA	13.9	12.8	8
Kearney, NE	14.2	14	10
Denver, CO	12.9	12.1	10
Toronto, ON	13.7	13	10
Portland, OR	13.2	14.9	12
Hanksville, UT	14	15.6	13
Atlanta, GA	15.4	16.8	17
Fresno, CA	14.7	14.5	18
Austin, TX	15.7	16	20
Phoenix, AZ	18.1	18.6	24
Miami, FL	16.7	16.9	25
Honolulu, HI	9.4	9	25

Actual weather patterns and rates are used for each corresponding location

3.6 Analysis #4 - Effects of Inflation

The analyses performed thus far assumed an inflation rate of 4% for both natural gas and electricity. In this analysis, the effects of inflation for electricity and natural gas are tested. The average annual inflation rate for the past 20 years was calculated using data provided in [60], [61] and [62] for the 11 US locations. Hawaii's highest average electricity cost inflation rates were 13.4% in the residential sector between 2002 and 2008, and 15.2% in the commercial sector between 2004 and 2008. For natural gas [60], Georgia experienced the worst average inflation of 28.2% (1999-2008).The residential average inflation for natural gas and electricity, for the 11 US locations between 1990 and 2010, are 4.4% (4.5% for commercial) and 2.3% (2.0% for commercial), respectively. The locations with the lowest average residential natural gas and

electricity are: 3% for Utah (3.8% for commercial in Texas) and 1% in Arizona (0.7% for commercial in Arizona). Although unlikely, the effects of inflation will be analyzed using the worst case scenario of 10% and 20% for electricity and natural gas, respectively. The data from Analysis #3 (standard rates) will be compared to its worst case scenario inflation counterpart.

In this analysis, a discount rate of 8% was used. However, it is interesting to note that by increasing the discount rate from 4% to 8% the payback period will increase. For example, based on a discount rate increase from 4% to 8% the payback period for the fast-food restaurant, mid-rise multi-residential building, and transit facility increased by 3.7, 3.2, and 2.3 years respectively.

3.6.1 Electricity inflation

In this analysis, the worst inflation of 10% for electricity will be used while the standard inflation rate of 4% for natural gas will remain. The results are compared to its counterpart, standard 4% natural gas and electricity inflation rates.

It is predictable that as electricity rates increase, so does the GSHP system size in order to counter the high operating costs as observed in Figure 3.10. However, the increase in optimal shave factor (the portion of peak demand met by the GSHP) results in higher upfront costs (increased ground loop length). Furthermore, by increasing the optimal shave factor, in most cases, the difference between the optimal shave factor and the standard shave factor reduces. As this gap reduces, the savings potential in using an optimization methodology (optimal vs. standard) is reduced. In Figure 3.11, the overall payback period is improved (ΔPBP is positive) when larger electricity inflation occurs; lower annual operating costs are achieved from increasing the ground loop thereby achieving a larger TEDM (percentage of total energy demand met by the GSHP) by the system.
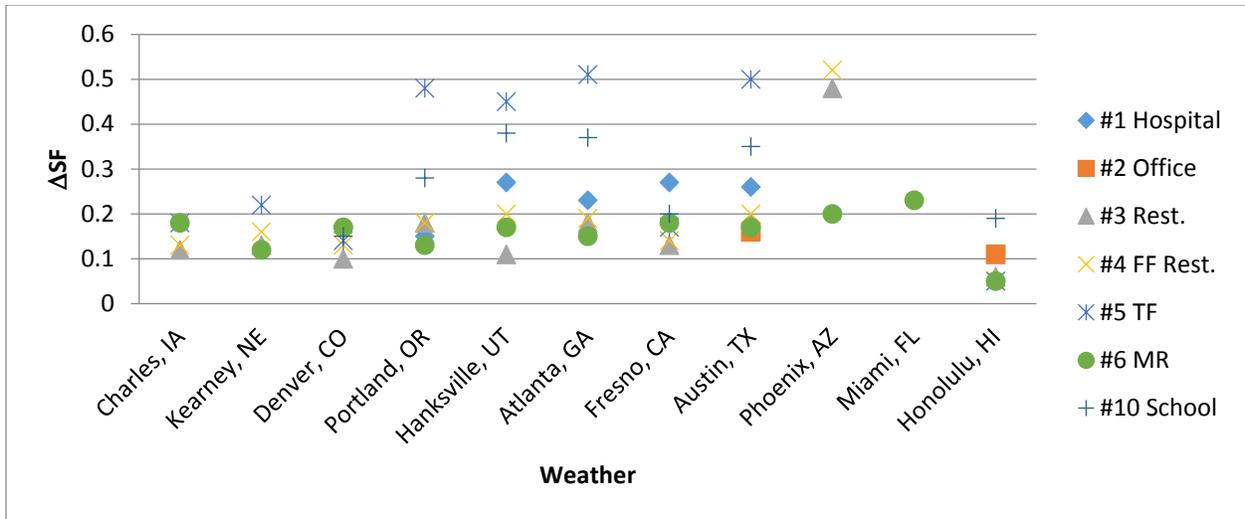
Figure 3.10: ΔSF - standard vs. 10% electricity inflation. The ordinate represents the change in shave factor (*SF*) associated with using an optimized hybrid GSHP system as compared to using industry design rules-of-thumb.

The cause of the increased payback periods (negative ΔPBP) in Figure 3.11 results from several factors. For example, in the case of the school with electricity inflation of 4%, the optimal shave factor was 0.08 (Δ*SF = 0.28)* and 0.07 (Δ*SF*=0.37) for Portland's and Hanksville's weather, respectively. The optimal shave factor substantially increases in the 10% inflation scenario. As a result, higher upfront costs lead to longer payback periods. Furthermore, Hanksville would require a building similar to the school to have a heating component. Since the heat pump is powered by electricity, inflation of electricity rates will have adverse effects on the economics on GSHP systems that are required to provide heating. Because of these factors, inflation in electricity may benefit or disadvantage a GSHP system, depending on the building needs.
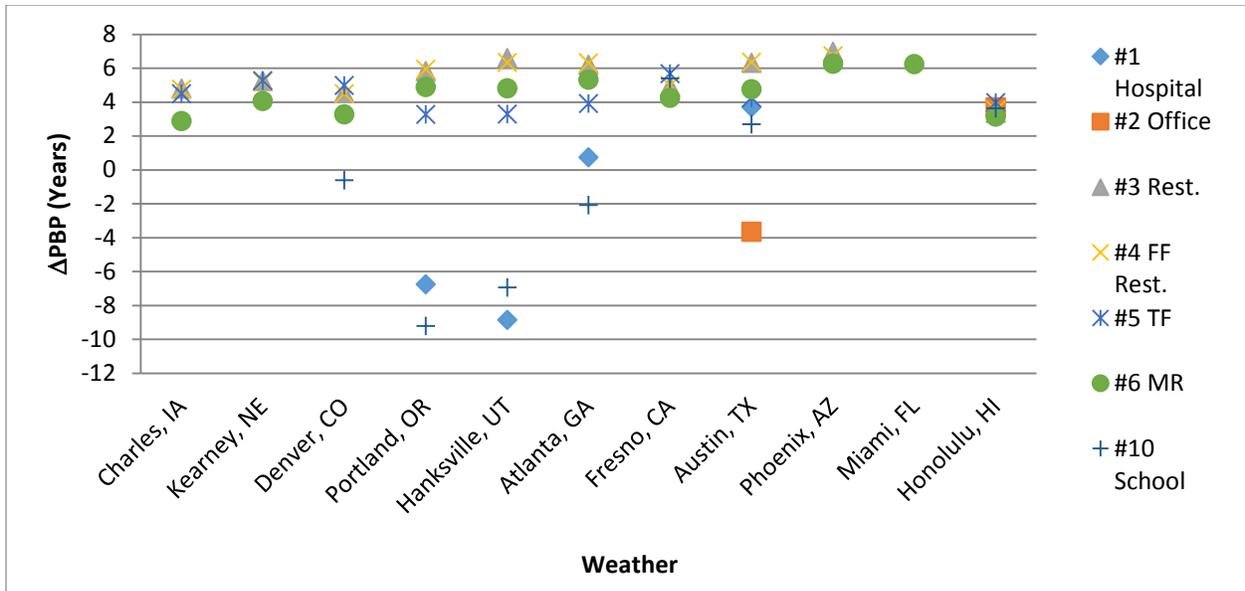
Figure 3.11: ΔPBP: standard vs. 10% electricity inflation. The ordinate represents the change in payback period (ΔPBP) associated with using an optimized hybrid GSHP system as compared to using industry design rules-of-thumb. If the payback period for the 10% inflation is shorter compared to standard inflation ΔPBP will be positive.

It is interesting to note that a higher electricity inflation rate produces viable non-zero shave factor in cases that otherwise would be uneconomical for cities with high ground temperatures like Phoenix, AZ. Table 3.12 lists some scenarios where a shave factor exists from 10% electricity inflation. For example, if the office building was located in Phoenix, 75% of the building's energy demands can be met using an optimal shave factor of 0.32, resulting in a payback period of 16.3 years and total savings of $515,000. The results shows that in locations with warmer climate and high ground temperatures, inflation in electricity makes GSHP more appealing due to the high cooling demands. Similar trends are observed for the case of Toronto's weather patterns and rates when a 10% electricity inflation was applied.

Table 3.12: Economical cases due to 10% electricity inflation

Building (Weather Patterns)	Shave Factor	TEDM (%)	Total Savings ($)	Initial Costs Savings ($)	Payback Period (years)
Hospital (Phoenix)	0.47	82.2	$80,800	$164,800	13.7
Hospital (Miami)	0.48	85	$66,600	$133,000	13
Office (Phoenix)	0.32	75	$515,400	$882,900	16.3
Office (Miami)	0.3	77.7	$870,600	$1,262,200	14
Restaurant (Miami)	0.69	93.5	$26,300	$50,600	13
School (Phoenix)	0.48	83.5	$95,000	$170,600	15.1

Savings are compared between optimal SF and standard SF, using 10% electricity inflation

All buildings listed are "Cooling Dominant"

3.6.2 Natural gas inflation

Similar to section 3.6.1, the worst inflation rate of 20% for natural gas was used (4% electricity inflation rate). This inflation increase affects heating dominant buildings the most. Locations with high ground temperatures were unaffected because very little to no heating was required (extremely cooling dominant). For example, the restaurant and fast-food restaurant require only cooling. The only two buildings that are heating dominant are the hospital and office.

Unlike electricity inflation in which heating requirements would counteract the benefits, natural gas inflation does not contribute to the GSHP's operational costs. Thus unlike with electricity, which can have either a positive or negative effect, natural gas inflation only serves to increase the viability of GSHP systems as observed in Table 3.13. In addition, using the methodology outlined in Alavy *et al.* [15] shows a clear advantage in heating dominant cases where natural gas inflation is high. Most shave factors listed (Table 3.13) are below 0.5 and the GSHP is still capable of providing most of the building's total energy demands (TEDM). Furthermore, payback periods are substantially less than the case where *SF*=1. For the office building with Hankville's weather patterns, the optimal design yields a payback period of 4.8 years whereas using a shave factor of

0.7 and 1.0 yields payback periods of 12 (not shown) and 18.8 years respectively. The most notable shave factor for the office occurs in Hanksville where SF=0.22 yields a TEDM of 88.1%, total savings of $675,700 and a payback period of 4.8 years (compared to 18.8 years for SF=1). Similar trends are observed for the case of Toronto's weather patterns and rates when a 20% natural gas inflation was applied.

Table 3.13: Economical cases due to natural gas inflation rate of 20%

Building	Weather Patterns	Optimal Shave Factor	TEDM (%)	Total Savings (x$1,000)	Initial Costs Savings ($)	PBP (Years)	PBP SF=1 (Years)
Office	Denver	0.41	95.1	620.7	776,000	6.2	12.4
	Charles	0.43	92.7	853.7	1,157,800	6.6	13.4
	Kearney	0.37	92.1	892.8	1,141,400	7.4	16.4
	Portland	0.64	98.6	136.4	183,800	2.9	4.3
	Hanksville	0.21	88.1	675.7	687,400	4.8	18.8
Hospital	Denver	0.48	93.1	42.6	58,000	3.9	7
	Charles	0.42	95.6	129	155,700	7.5	18.7
	Kearney	0.37	75.9	95.8	96,100	4.7	18.6

3.7   Analysis #5 - Control Strategy: Seasonality

The final analysis is to determine the effects of a control strategy on the sizing of the hybrid-GSHP system. Some buildings in Toronto produces demands for simultaneous heating and cooling, especially during the shoulder seasons. For example, in Figure 3.1, the school requires a moderate amount of space heating and cooling during the shoulder seasons.

In prior analyses (Analysis #1 to Analysis #4) the hybrid-GSHP system was sized based on the 8760 hourly loads.The system provided all the heating and cooling demands throughout the year. In this analysis instead of sizing the system for all 8760 hourly loads, during the winter months, all cooling demands (building cooling loads) will be set to zero. Similarly, during the summer months all heating

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demands (building heating loads) will be set to zero. This control strategy assumes the building will obtain free cooling (heating) during winter (summer) from outdoor air. The cooling season will begin at the start of May and ends on the last day of October. For the purposes of this analysis, in cooling mode (summer months) all heating demands are assumed to be achieved through free heating from hot outdoor air. Conversely, the remaining months will be considered the heating season and all cooling demands will be provided from cold outdoor air (no costs). Realistically, such a control strategy could not be implemented in most buildings, however, this analysis is useful in demonstrating the sensitivity of optimal design to the potential use of free heating or cooling.

Using the above-mentioned definition for seasonality, Toronto's fixed electricity rates and a project life of 20 years, the results for the optimal shave factor (the portion of peak demand met by the GSHP) and associated costs are produced in Table 3.14. Interestingly, under this condition, a GSHP system is only economical for residential buildings. The hospital and office are heating dominant, regardless if seasonality was considered it still remains a fact that heating by a conventional system is cheaper than by a GSHP due to the current low rates of natural gas. For all the remaining non-residential buildings, although they are cooling dominant, the summer is the only period for the system to generate savings. Due to the high upfront costs and short cooling season, the savings are hindered during the winter months where heating by the GSHP produces expenses instead of savings. All these factors make a conventional system cheaper to install and operate for twenty years than a hybrid-GSHP system. However, for residential buildings (buildings #6 to #9), a substantial savings in net present value dollars can be achieved compared to either a conventional system or installing hybrid GSHPs using the standard shave factor of 0.7. The midrise multi-residential building achieved the greatest savings ($55,500) using an optimal shave factor value of 0.31. Similarly, for the high-rise A (SF=0.12), high-rise B (SF=0.11), and high-rise C (SF=0.36) a savings of $58 000, $130 000, and $52 500 can be achieved.

Table 3.14: Test #6 – Seasonality results

Building	HD/CD	Optimal *SF*	TEDM (%)	Total Savings (NPV $)	IC Savings ($)	PBP (Years)
1. Hospital	HD	0	0	N/A	N/A	N/A
2. Office	HD	0	0	N/A	N/A	N/A
3. Restaurant	CD	0	0	N/A	N/A	N/A
4. Fast-Food Restaurant	CD	0	0	N/A	N/A	N/A
5. Transit Facility	CD	0	0	N/A	N/A	N/A
6. Mid-rise, Multi-residential	CD	0.31	67.9	55,500	169,900	16.4
7. High-rise, Multi-residential A	CD	0.12	44.51	58,000	206,059	13.3
8. High-rise, Multi-residential B	CD	0.11	41.3	130,000	457,000	10.6
9. High-rise, Multi-residential C	CD	0.36	72.5	52,500	185,200	16.2
10. School	CD	0	0	N/A	N/A	N/A

Savings are compared between optimal SF and standard SF

HD (Heating Dominant)   CD (Cooling Dominant)

3.8 Chapter Summary

In this chapter the relationship between two parameters, shave factor and TEDM, were presented for a school located in Toronto, Canada. For most of the buildings analyzed the relationship between the two parameters are non-linear, making the shave factor an important parameter to consider for optimization of hybrid GSHPs, as presented in Alavy *et al.* [15]. If an optimal shave factor exists, its payback period will be shorter than the payback period associated with the rule-of-thumb design standard.

Extremely cooling dominant buildings had longer payback periods in weather warmer than Toronto (*i.e.* California, Georgia, and Hawaii). This is due to the higher ground temperatures which requires a larger ground loop to meet the buildings' energy demands. However, based on the assumed COP_{GSHP} and $COP_{cooling\_tower}$, hybrid GSHP systems become more favorable when electricity rates or inflation is increased. For heating dominant buildings, the current low rates of natural gas make it uneconomical to install a GSHP system; the cost of natural gas per kWh heating is cheaper than electricity.

In Analysis #1, the effects of fixed and time-of-use electricity rates were explored. Net differences were computed in terms of changes in total savings, initial cost savings, payback period, and shave factor. The time-of-use rates varied depending on the time of electricity usage; rates increased during peak hours and decreased during off-peak hours. In buildings with long operating hours during off-peak periods, the GSHP system was downsized, reducing initial costs. However, downsizing the system caused a decrease in annual operating cost savings, which resulted in longer payback periods.

In Analysis #2, fixed rates (Toronto) were applied on 11 US locations to study the effects of varying weather patterns. Results of the study showed that in warmer weather where ground temperatures were higher, it was most economical to downsize the ground loop length and expand the cooling tower.

In Analysis #3, both the local rates and local weather were used to determine the trends in optimal design of GSHPs. The results of the analysis demonstrated that the widely varying electricity rates in North America significantly affect the shave factor values – in some cases generating much more economically viable designs.

In Analysis #4, the effects of electricity and natural gas inflation were studied. As electricity rates increased, the GSHP system size also increased to counter the high operating costs. As a result of the optimal shave factor, upfront costs also increased. The economics for buildings with GSHPs that provided heating were worsened when electrical prices increased but were improved when natural gas prices increase. As a result, inflation for natural gas or electricity rates can benefit or adversely affect the hybrid GSHP system depending on the building and weather patterns; the shave factors generally increase proportionally with rate increases, but nonetheless, designs should be tailored to each specific building.

In Analysis #5, a control strategy of seasonality was applied to study the effects on sizing hybrid-GSHP system. In the winter months, all cooling demands were set to zero and in the summer months, all heating demands were also set to zero. Under these conditions, a GSHP system is only economical for the residential buildings that were considered. For all non-residential buildings considered, although some are cooling dominant, the summer is the only period for the system to generate savings. Due to the high upfront costs, and short cooling season, the savings are hindered during the winter months where heating by the GSHP produces expenses instead of savings. All these factors make a conventional system less expensive to install and to operate for twenty years compared to a hybrid-GSHP system when a sophisticated seasonal control strategy is being implemented.

Chapter 4

Study #2: Analysis of Heat-Pump Entering Fluid Temperatures, and CO_2 Emissions

For a GSHP system, the choice of entering fluid temperature (EFT) to the heat pump plays a crucial role in determining the efficiency of the heat pump and operating costs of the system. To continue expanding the knowledge base of efficiently sizing GSHPs as a component of a hybrid system, the effect of choosing an EFT for a heat pump and the system CO_2 emissions are analyzed in the present study. Using a computational approach to size hybrid GSHP systems recently published in [15], the effects of optimizing EFT for heat pump and CO_2 emissions were studied for a variety of commercial installations.

4.1   Methodology

In this study, the methodology outlined in Alavy *et al.* [15] 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.

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.* [15] focused on explaining and validating the methodology. A utility model was also investigated by Alavy *et al.* [97] 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 4.1.1 and 4.1.2. The parameters used in the present study are listed in Tables 4.1 and 4.2.

Table 4.1: General design parameters (data courtesy of CleanEnergy^{TM})

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 ($COP_{heating}$=3.1, $COP_{cooling}$=3.78)
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%

GSHP Configuration: closed-loop vertical single U-tube

Table 4.2: General costs of hybrid GSHP system components (data courtesy of CleanEnergy^{TM})

Item	Cost
Ground heat exchanger (installation, materials, and heat pump)	$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

4.1.1 Heat-pump entering fluid temperature (EFT)

Using the methodology outlined in [15], 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 [15] 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 [15]. 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.

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In this study, the methodology outlined in [15] 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 35-45ºF and 85-95ºF (1.7-7.2 ºC and 29.4-35ºC) for the heating and cooling modes, respectively, considering 1.0ºF 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 [15] 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 4.1, 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 4.1), the assigned operational heat-pump EFTs were 25-42ºF and 60-100ºF ([-3.9ºC, 5.6ºC] and [15.6ºC, 37.8ºC]) for the heating and cooling modes respectively (738 temperature pairs using 1.0°F increments).

In Figure 4.1, 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 41ºF and 90ºF. 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 25-42ºF and 65-71ºF ([-3.9ºC, 5.6ºC] and [18.3ºC, 21.7ºC]) 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 25-42ºF and 82-98ºF ([-3.9ºC, 5.6ºC] and [27.8ºC, 36.7ºC]) for heating and cooling modes respectively. These low-lying regions indicate that for this particular building, 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 analyzing CO_2 emissions becomes important too. This methodology shows a designer what their design freedoms are and provides them with a tool to better analyze potential designs.
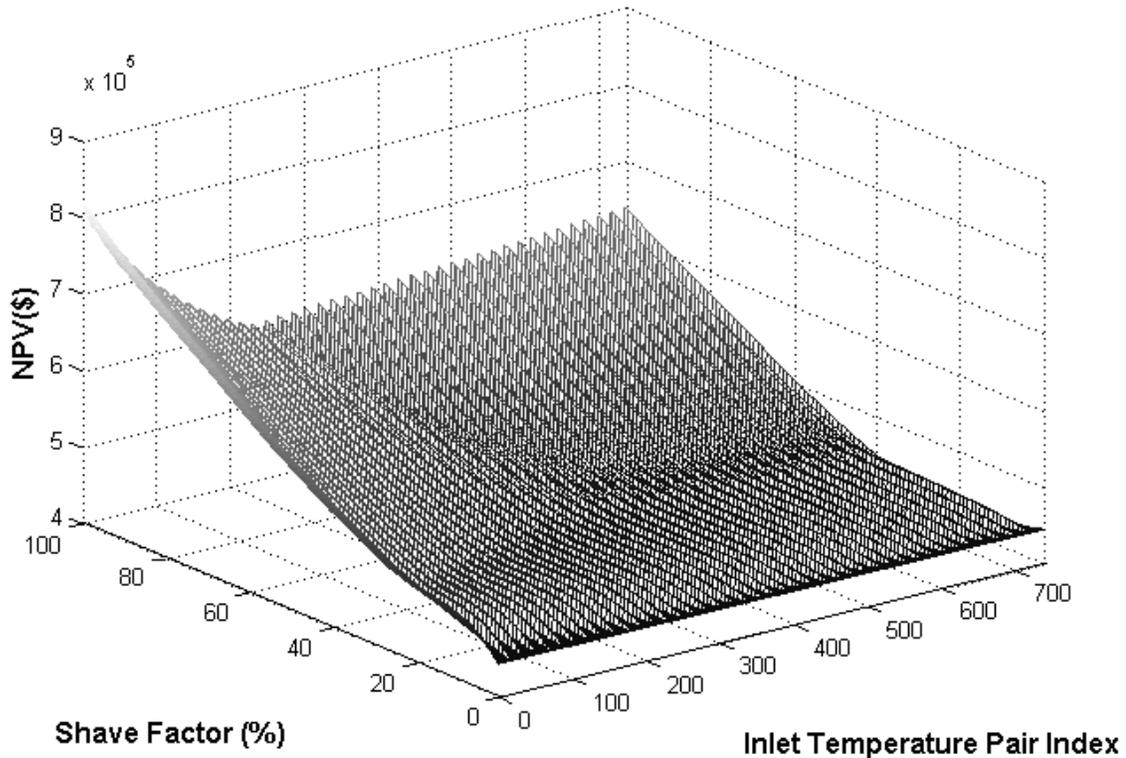
Figure 4.1: EFT analysis for a school located in Toronto, Ontario.

4.1.2 CO_2 emissions

The total amount of CO_2 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 CO_2 emission factors of the local electricity supply mix. CO_2 emission factors are the factors indicating the amount (measured in kg/kWh and kg/m^3) of CO_2 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 [75].

In the present study, natural gas was assumed to be the fuel for the conventional component of the heating system. The CO_2 emissions factor for natural gas is 1.8750 kg-CO_2/m^3 [76]. Similarly, for space cooling by a conventional or a GSHP system, the CO_2 emission factors are based on kg-CO_2 per kWh of electricity (kg-CO_2/kWh). For electricity production in Ontario, the emission factors used in this analysis are 0.002 kg-CO_2/kWh for nuclear [71], 0.023 kg-CO_2/kWh for hydro [71], 1.02 kg-CO_2/kWh for coal [72], 0.002 kg-CO_2/kWh for wind [71], 0.2786 kg-CO_2/kWh for oil [73], and 0.0261 kg-CO_2/kWh other electricity generation methods [74]. The emission factor of 0.0261 kg-CO_2/kWh by other electricity generation methods is associated with biomass (wood chips and pellets) electricity generation. The emission factor 0.0261 kg-CO_2/kWh from biomass electricity generation is achieved by taking the average of 0.0149 kg-CO_2/kWh for wood chips and 0.0373 kg-CO_2/kWh for wood pellets [74], assuming an equal mix of the two fuels.

Using these emission factors, CO_2 (or CO_2 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 4.4.1). Using the methodology outlined in Alavy *et al*. [15], 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 CO_2 emissions are outlined in the subsequent section (section 4.1.3).

4.1.3 Calculation of CO_2 emissions

To quantify environmental benefits generated by a hybrid GSHP system, a process for calculating CO_2 emissions is used in the present study. It is illustrated in Figure 4.2.
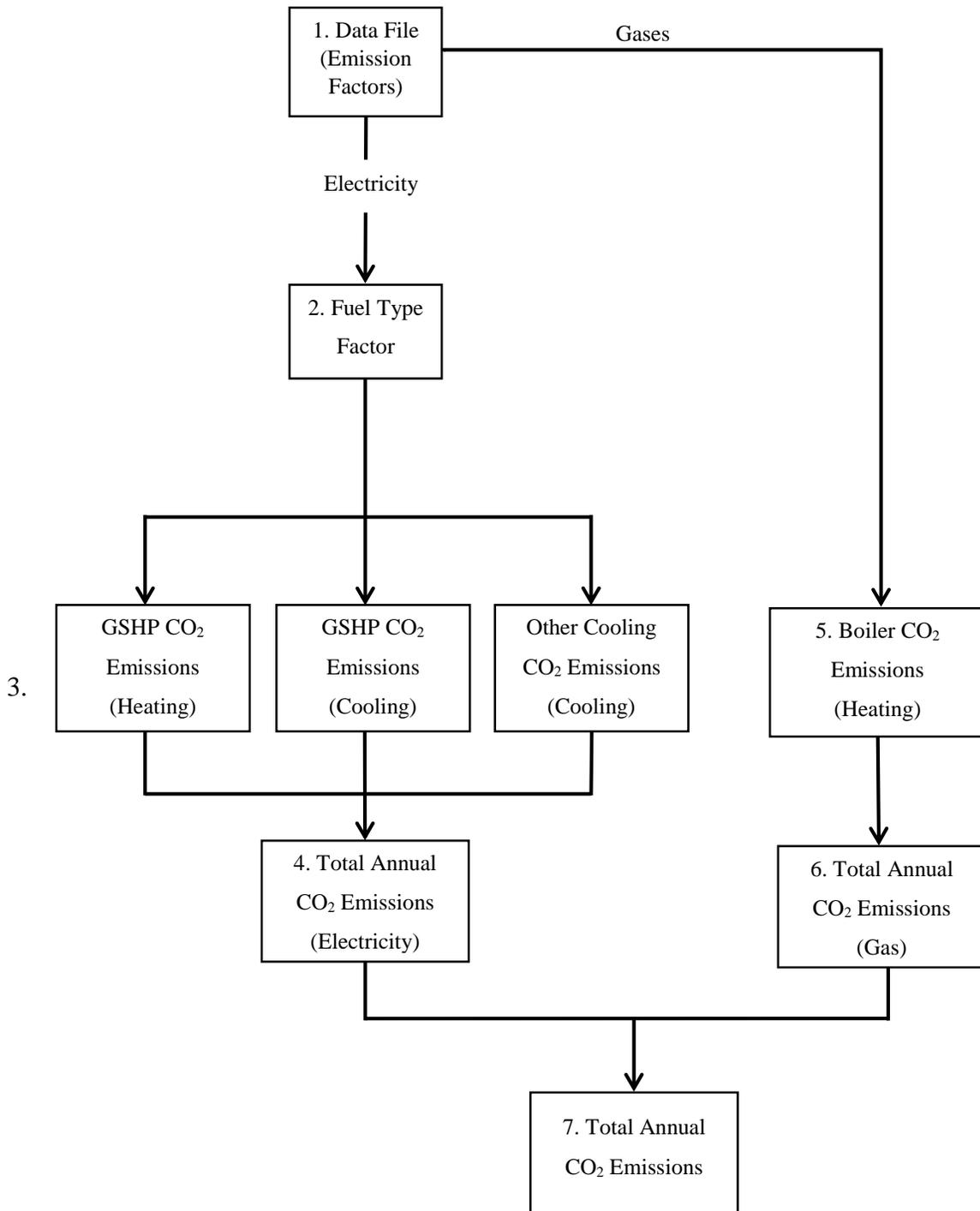
Figure 4.2: CO_2 emission calculation process

In step 1, the CO_2 emission factor values are entered into the module. The intermediate fuel type factors can be calculated in step 2 for each fuel source type using Equation 4.1. For example, the nuclear fuel type factor is calculated by multiplying the CO_2 emission factor for nuclear energy

(0.002 kg-CO_2/kWh) with the electricity supply mix of nuclear energy (51.95% of total electricity supply).

$$Fuel\ type\ factor_i = CO_2\ emission\ factor_i \times electricity\ supply\ mix\ break\ down_i \quad (4.1)$$
$where:$

$\quad i = nuclear, hydro, coal, wind, gas/oil, and\ other\ electricity\ generation\ methods$

In a hybrid GSHP system, the conventional systems (boiler and cooling tower) and GSHP system (heat pump) are the major components that use electricity and natural gas to provide space heating and cooling. In step 3, the CO_2 emissions emitted from each component are calculated using Equation 4.2. For example, for the cooling tower (other cooling CO_2 emissions), the CO_2 emissions contributed from nuclear energy can be calculated by multiplying the nuclear factor with the electricity consumed by the cooling tower.

$$CO_2 emission_{j,i} = Fuel\ type\ factors_i \times electricity\ consumed_j \quad (4.2)$$
$where:$

$\quad i = nuclear, hydro, coal, wind, gas/oil, and\ other\ electricity\ generation\ methods$

$\quad j = heating\ (heat\ pump), cooling\ (heat\ pump), cooling\ (cooling\ tower)$

In step 4, the total annual CO_2 emission from electricity consumption is calculated by the summation of all the CO_2 emissions in Equation 4.3 (step 3).

$$Total\ CO_2\ emission\ (electricity) = \sum_j CO_2\ emission_j \quad (4.3)$$
$where:$

$\quad j = heating\ (GSHP), cooling\ (GSHP), cooling\ (conventional)$

In step 5, a similar equation to that of step 3 is used to calculate the CO_2 emitted from natural gas consumption. In Equation 4.4, the CO_2 emission factor of natural gas (or other gases used for heating) is multiplied with the volume of natural gas or other heating gases used for space heating by the boiler.

$$CO_2\ emission_{gas} = CO_2\ emission\ factor_{gas} \times\ volume\ consumed_{gas} \qquad (4.4)$$

In step 6, the CO_2 emissions are summed up to find the total CO_2 emissions from all heating gases. Since the only gas used in the analysis is natural gas, the result of step 6 is the same as step 5. The total CO_2 emissions are calculated in step 7, by summing up the electricity and natural gas CO_2 emissions from steps 4 and 6, respectively.

4.2 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, based on the EFTs, are shown in Figure 4.3. The plot represented by squares and triangles corresponds to the COPs of the heat pump operating in the cooling and heating modes, 60-100ºF and 25-60ºF ([15.6ºC, 37.8ºC] and [-3.9ºC, 15.6ºC]) respectively.
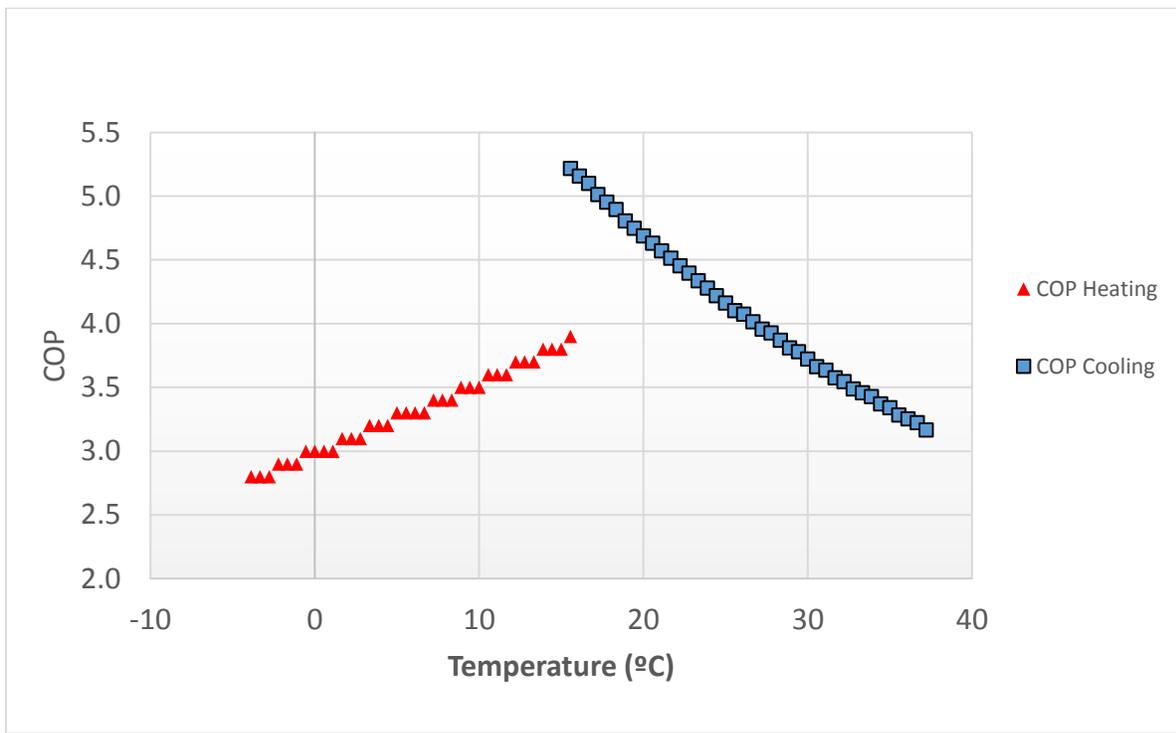
Figure 4.3: Coefficient of performance of a heat pump (CleanEnergy[TM], model PC0018)

The parameters used in this analysis are listed in Tables 4.1 and 4.2 — an inflation rate of 4%, electricity rate of $0.17/kWh, and natural gas rate of $0.35/m^3 are used. A total of ten real buildings are studied, with their data provided by CleanEnergy^{TM}. 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 1.7ºC and 29.4ºC) presented in Table 4.3. In Table 4.3, 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 4.3: Variable heat-pump EFT vs. base case (fixed EFT)

Buildings	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 (ºC)	T_h (ºC)	T_c (ºC)	T_h (ºC)			
1. School	0.22	0.24	29.4	1.7	32.2	5	4.36	4.20	3.6
2. Office	—	—			—	—	—	—	—
3. Hospital	—	—			—	—	—	—	—
4. Restaurant	0.65	0.65			29.4	5	8.25	8.25	0
5. Fast food restaurant	0.62	0.62			29.4	5	4.74	4.74	0
6. High-rise (I)	0.25	0.27			33.9	5	6.45	6.4	0.84
7. High-rise (II)	0.23	0.25			33.9	5	14.6	14.5	0.98
8. High-rise (II)	0.39	0.41			32.2	5	11.6	11.5	0.5
9. Mid-rise	0.34	0.36			32.2	5	8.71	8.66	0.47
10. Transit facility	0.44	0.48			33.9	5	7.18	7.11	0.96

Since the ground temperature in Toronto is approximated to be 50ºF (10ºC), using the COP values in Figure 4.3, the heat-pump EFTs for the heating and cooling modes were varied in the ranges of 25-42ºF and 60-100ºF ([-3.9ºC, 5.6ºC] and [15.6ºC, 37.8ºC]) respectively. The EFTs in the range of 43-49ºF (6.1-9.4ºC) 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 4.3 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 as outlined in Alavy *et al.* [15]. 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 5ºC compared to the base case of 1.7ºC, 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 [15], 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 in Chapter 3. 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 33ºF-37ºF and 83ºF-87ºF (0.6-2.8ºC and 28.3-30.6ºC) for the heating and cooling mode respectively. The trends and conclusions remain the same.

4.3 CO_2 Analysis

By applying a CO_2 emissions module, Figures 4.4 and 4.5 plot the shave factors, *i.e.*, the portion of peak demand that could be met by the GSHP, against total annual CO_2 emission (kg). In Figure 4.4, the curved line represents the CO_2 emission (of a fast food restaurant) for each shave factor value from 0 to 1. To generate the curve, 100 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 the methodology outlined in Alavy *et al.* [15], the optimal shave factor for the fast food restaurant, as presented in Figure 4.4, is 0.62. It can be observed that the CO_2 emitted when the system is sized with an optimal shave factor value of 0.62 (23,595 kg) is very near the minimum CO_2 emissions (21,750 kg). For the case of the fast-food restaurant, the optimization based on Alavy *et al.*'s methodology [15] results in a CO_2 emissions reduction of 74% (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).
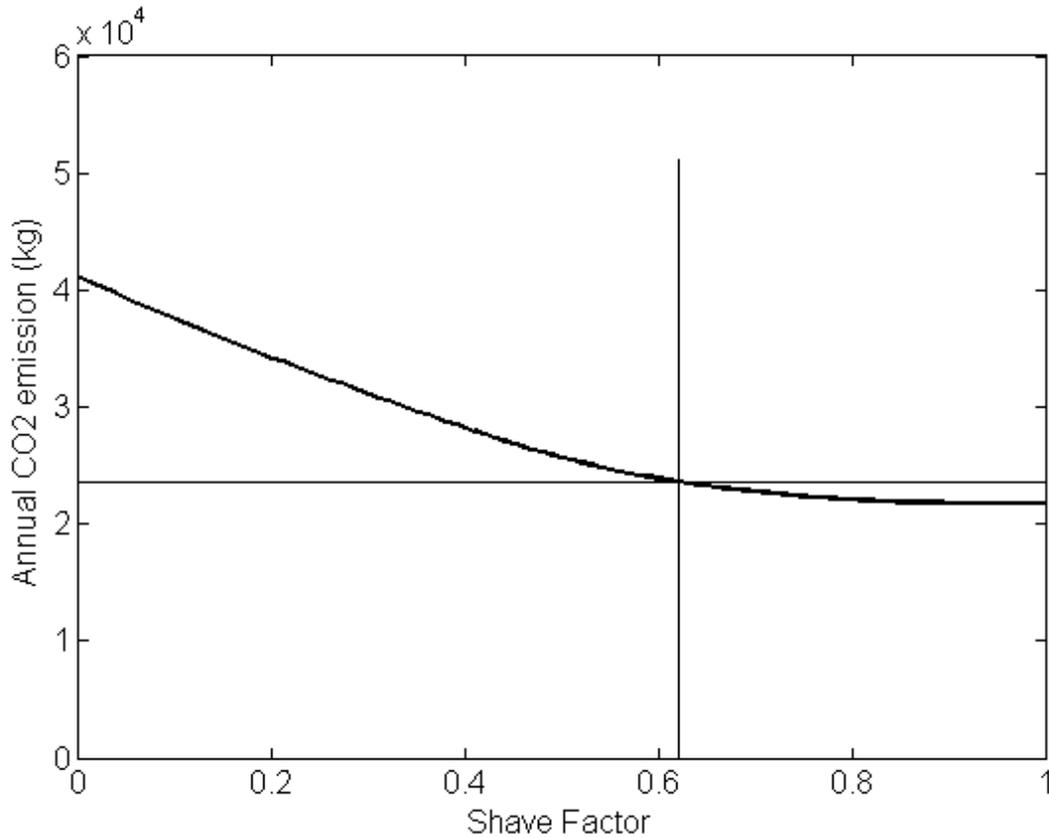
Figure 4.4: Annual CO_2 emissions of a fast-food restaurant located in Toronto, Ontario, as a function of shave factor.

In some cases, a design based on the optimal shave factor (based on net present value) results in a hybrid GSHP system that produces 20% or more CO_2 than the minimum CO_2 emitting GSHP system (with a shave factor of 1.0). For example, in Figure 4.5, the optimal shave factor of a high-rise (II) building located in Toronto, Ontario is 0.23 (most economical design in terms of net present value). The corresponding annual CO_2 emission of the system is 87,119 kg (minimum CO_2 emissions is 65,250 kg). However, if reduction in CO_2 emissions were a higher priority, the installer can size the system to a shave factor of 0.6, the annual CO_2 emissions would reduce to 68,385 kg resulting in a 25% reduction in CO_2 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.
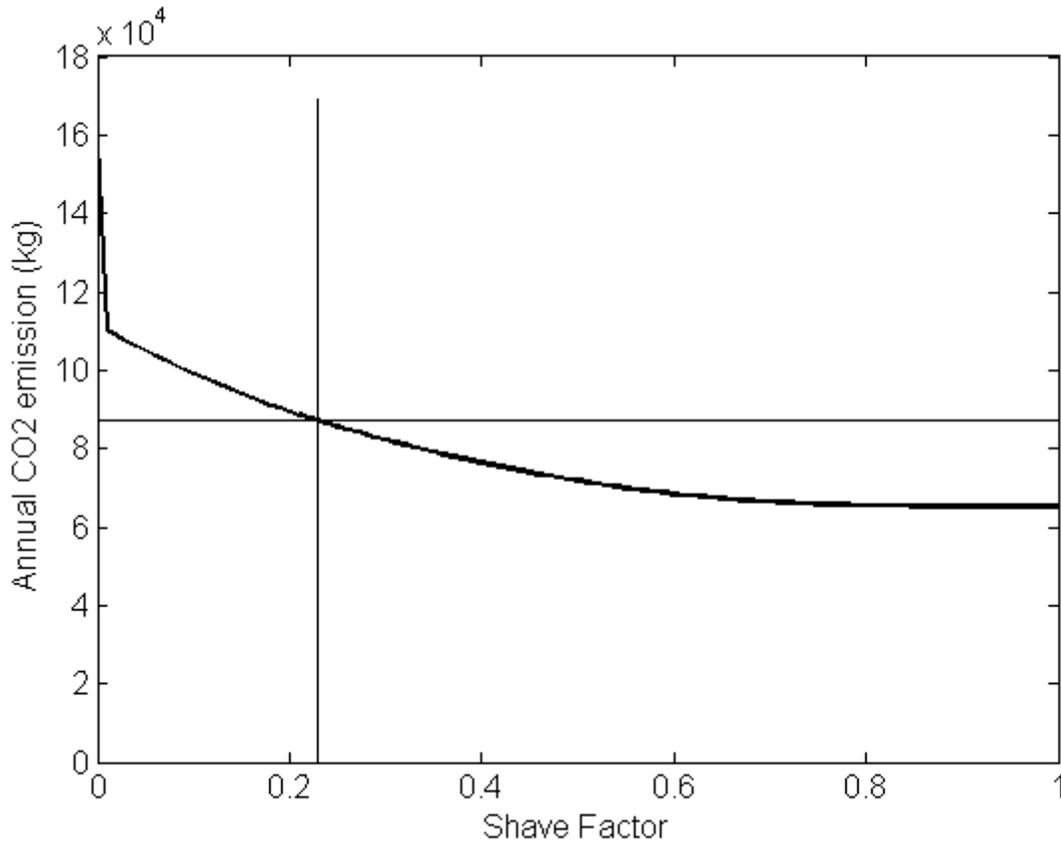
Figure 4.5: Annual CO_2 emissions of high-rise (II) building located in Markham, Ontario

A total of eight buildings are analyzed and the results are summarized in Table 4.4. In Table 4.4, the optimal shave factors are listed in the second row and the corresponding CO_2 emissions are listed in the third row. The CO_2 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 CO_2 emissions that can be achieved using a full GSHP installation. The CO_2 emissions of the optimized hybrid GSHP systems are the closest to the minimum possible CO_2 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 CO_2 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.* [15] produces acceptable levels of CO_2 emissions even when the optimal shave factors

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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 CO_2 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 CO_2 emissions are 19.5% and 22.8%, respectively. For these buildings, much of the reduction in CO_2 emissions is still realized when switching from the conventional system to the hybrid GSHP system which is designed based purely on economic optimization. Based on the optimal design, all the buildings reduced their CO_2 by at least 70% compared to a purely conventional system. The mid-rise building and transit facility reduced the minimum (70%) and most (84.6%) CO_2 respectively.

Table 4.4: Summary of annual CO_2 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	N/A	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
$CO_{2\_SF=0}$ (kg)	67,001	159,010	108,616	624,291	37,287	41,121	69,411	79,067

4.4.1 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 [80].

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 [81].

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 [77-79]. In Canada, for every tonne of CO_2 (CO_2 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 CO_2 emitted into the air in British Columbia, Canada [77]. 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 CO_2 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 [82-83]

The total annual carbon tax costs were determined using the calculations outlined in section 4.1.3. Using a 20 year system project life and the methodology outlined in Alavy *et al.* [15], 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 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 4.5. Due to the carbon tax, the overall total costs increase. As a result, in order to alleviate the increase in operation costs, the optimal shave factor increases (emitting less CO_2) 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 CO_2 emissions). For example, as presented in Table 4.5, 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 4.5, 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 CO_2.

Table 4.5: 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	0.40	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

4.4.2 Project life analysis

In the previous analyses, a project life of 20 years was used. However, depending on how long a building owner might plan to own a building, other project life may be of interest. If operating durations (project life) 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 project life of the hybrid system, a different optimal shave factor, and therefore CO_2 emissions might be the desired design parameter. In this section, two analyses were carried out to determine the effects project life have on annual costs (net present value) and CO_2 emissions. In these two analyses, the conventional system and GSHP system are replaced every 20 and 40 years respectively.

Project life: NPV/year analysis

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 (project life) 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*. [15] 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 project life in order to achieve the optimal NPV per operating year using the "NPV/operating duration" parameter.

In Figure 4.6, the net present value cost per operating year is plotted against the project life (in years). As expected, as project life 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 4.6, net present value cost per operating year levels off after very long durations of operation – greater

than 70 years. However, sizing a hybrid GSHP system based on an economic analysis of 70 years or more is impractical.
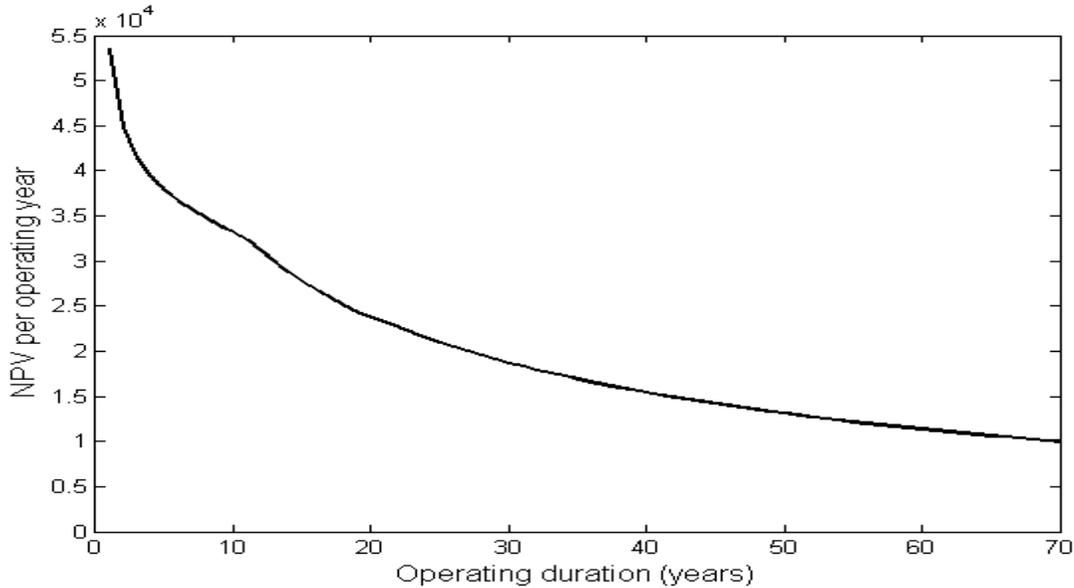
Figure 4.6: Net present value per operating year ($/year) vs. operating duration (project life) for a fast food restaurant located in Toronto, Ontario

Project life: CO_2 analysis

By varying the project life (investment timeframe) from 10 to 100 years, the annual CO_2 emissions asymptote at around 50 to 100 years of operation for all the buildings analyzed. The costs in this analysis include replacement costs of components such as the cooling tower, and boilers every twenty years and the ground loop every forty years. Table 4.6 illustrates the effects that project life have on the hybrid system economics. As the assumed project life increases, the shave factor and CO_2 emissions level off at values of 0.8 and 22,076 kg, respectively, for the fast food restaurant. This relationship is plotted in Figure 4.7. In Figure 4.7, it can be observed that the CO_2 emissions per operating year decreases with project life and begins to level off at around 20 years of operation. It can be concluded that the reduction of CO_2 emissions per operating year for project life greater than 20 years are not much greater than the project life 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 4.6: Project life and CO_2 analysis for a fast-food restaurant

| Project Life (Years)	Shave Factor	CO_2 Emissions per Operating Year (kg-CO_2/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
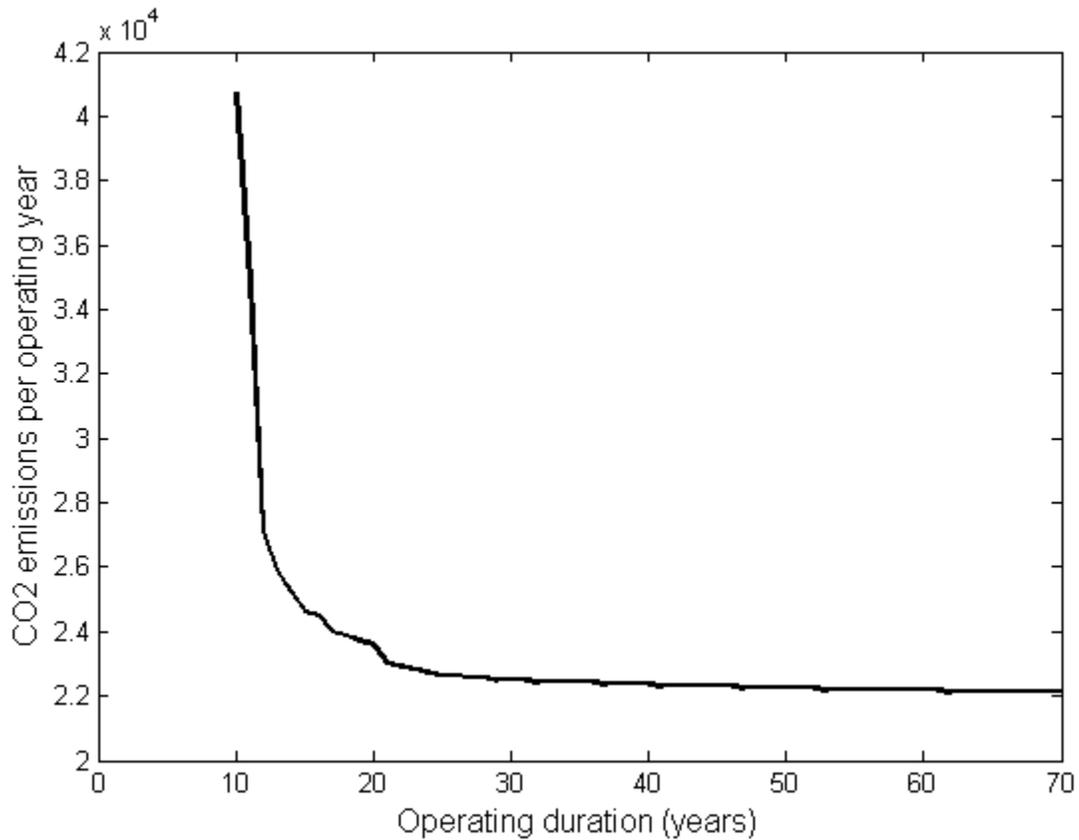
Figure 4.7: CO_2 emissions per operating year vs. operating duration (project life) for a fast-food restaurant located in Toronto, Ontario

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The relationship between payback period and project life is presented in Figure 4.8. In Figure 4.8, the solid line represents the payback period corresponding to the project life of the hybrid GSHP system and the dashed line tracks the assumed project life. When the payback period is greater than the assumed project life, the system is not economically viable. When the payback period is shorter than the project life, an economically viable system is feasible. The break-even point of the hybrid GSHP system is the point of intersection between the two lines, for the fast-food restaurant being analyzed in Figure 4.8, the break-even point occurs at year 13. If the system operates for 13 years or less, there is no economic benefit. The payback period is calculated as the total costs (discounted to net present value) divided by savings. As a result, an inverse relationship exists between payback period and project life before the break-even point (no economic benefit).
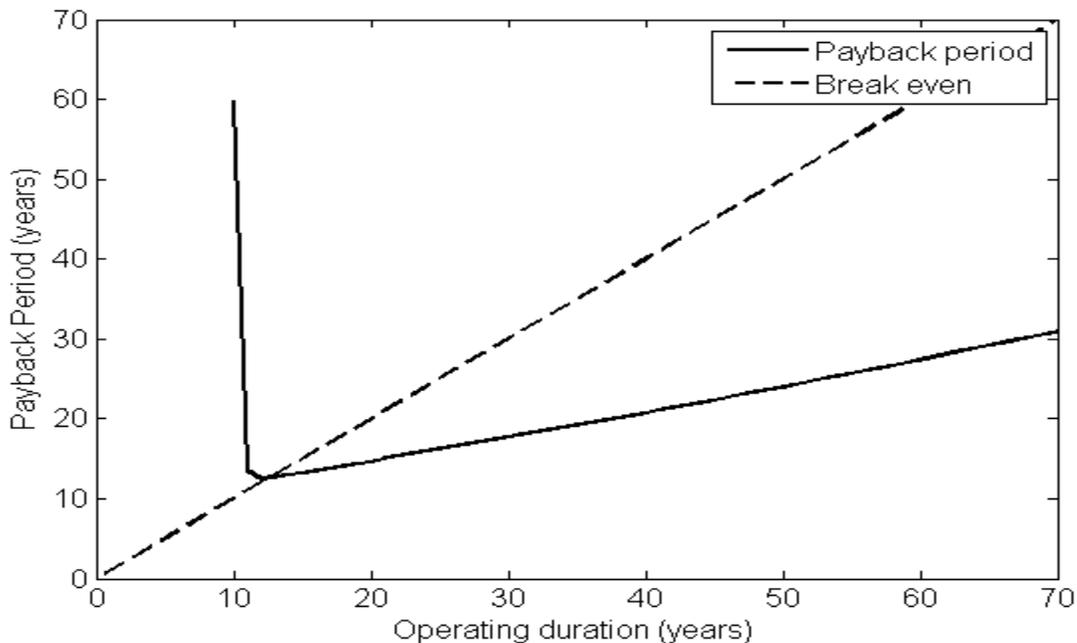
Figure 4.8: Payback period vs. operating duration (project life) of a fast-food restaurant located in Toronto, Ontario

Table 4.7 summarizes the buildings' project life. As observed, between 20 and 25 years of operation, most of the environmental benefit can be achieved compared to that of 100 years; the three high-rises all produce only 9% more CO_2.

Table 4.7: CO_2 emissions percent increase summary

Building	Project life (Years)	CO_2 emissions percent increase compared to 100 years (%)
High-rise I	20	9
High-rise II	24	9
High-rise III	21	9
Fast-food restaurant	20	7
Restaurant	20	10
Transit facility	22	7
Mid-rise	25	5

The values are rounded (up) to the nearest percent

4.4   Chapter Summary

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 requires a larger ground loop which results in higher upfront costs (*vice versa* for reducing upfront costs). 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 the CO_2 emissions analysis, based on a carbon tax of $30 per tonne of CO_2 emitted, a carbon tax increases the operating costs of a hybrid GSHP system. To accommodate the increase in operating costs, for all of the buildings analyzed the optimal shave factor increased, contributing to a reduction in CO_2 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.* [15] yields CO_2 emission levels similar to that of a shave factor = 1.0, in some cases such as that of the fast-food restaurant with a shave factor value of 0.62 (8.5% more CO_2 emissions than *SF*=1).

If total costs and CO_2 emissions are equally important, sizing the system based on the optimal shave factor may result in higher CO_2 emissions than desired, whereas sizing the system to a shave factor of 1.0 might result in high upfront costs than desired. An example would be the high-rise (II) building with an optimal shave factor of 0.23 in which sizing the system to a shave factor of 0.6 would reduce CO_2 emissions comparable to that of *SF*=1. The methods of analysis presented in this chapter 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 CO_2 emissions for project life greater than 20 years (long term) are similar to those of 20 years operation.

The project life 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 (project life) increases. However, the economic benefits of increasing a hybrid GSHP's assumed project life (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. The same conclusions are also observed for CO_2 emissions. For the case of the fast-food restaurant, when the project life exceeds the break-even point (13 years), the reduction in CO_2 emissions per operating year is greatest at the project life of 30 years and asymptotes thereafter.

Chapter 5
Study #3: Retrofit Analysis

5.1 Methodology

In Canada, it is estimated that 27% of all buildings use electric baseboards as the main source of heating. By province, 66% of buildings in Quebec (highest percentage) rely on baseboard heating (7% for Ontario) [84]. With the rising costs of electricity, and high heating demands for buildings situated in Ontario, a retrofit analysis was performed to determine the economic feasibility of a hybrid GSHP system. In this analysis, the buildings are assumed to be heated and cooled by electric baseboard heaters and window air conditioner units (or by a cooling tower) respectively (base case). Energy loss from outdoor air infiltration can offset the actual overall performance of window air conditioner units. Furthermore, window air conditioners have a shorter life cycle compared to that of heat pumps, 10 years compared to 20 years respectively [5, 86].

In this analysis two scenarios are considered. In the first scenario, the buildings are heated by electric baseboard heaters and cooled by window air conditioner units as the base case. Similarly, for the second scenario, cooling towers are used during the cooling mode instead of window air conditioners. As outlined in Table 5.1, the COP values for window unit GSHP systems in cooling mode are 3.4 [85] and 3.8 (CleanEnergy Developments/PC0018) respectively. In the heating mode, the electric baseboard heater and heat pump are assumed to operate with a COP of 1.0 and 3.1, respectively.

The retrofit analysis was performed using the methodology outlined in Alavy *et al*. [15], for which the algorithm was modified to consider the total costs of the electric baseboard heating, building envelope retrofit costs, ductwork costs, and other retrofit costs. The total costs (in net present value) corresponding to each shave factor, as outlined in Figure 5.1, are based on the initial cost, operating costs, and other retrofit costs.

Table 5.1: Retrofit - heating and cooling COP of equipment

Heating/Cooling Equipment	Assumed COP
Electric baseboard heater	1.0
Cooling tower	2.0
Window air conditioner unit	3.4
Heat pump: heating mode	3.1
Heat pump: cooling mode	3.8
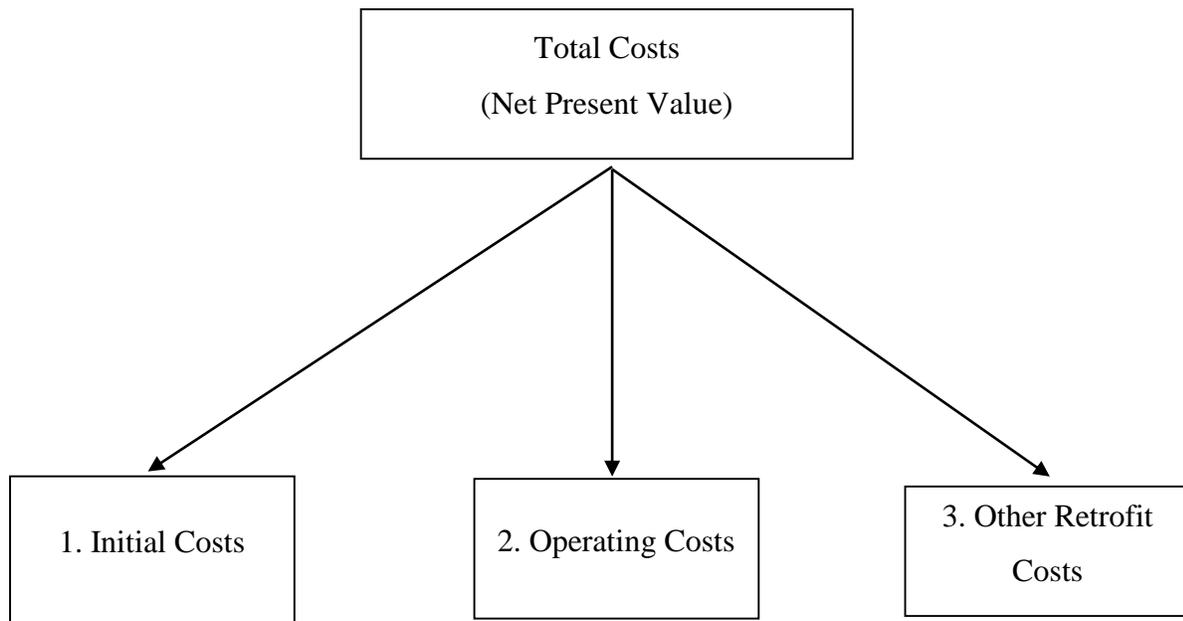
Figure 5.1: Retrofit analysis - calculation of total costs (in net present value)

The initial costs, for each shave factor value ranging from 0 to 1 with a step size of 0.01, consists of:

- Upfront electric baseboard heater cost (conventional heating), major overhaul cost.
- Upfront window air conditioner or cooling tower cost, replaced every 10 and 20 years, respectively (conventional cooling).
- Upfront GSHP system costs.

For example, a shave factor of 0.2 (for a heating dominant building) indicates that 20% of the building's peak heating demands are met by the GSHP and the remainder by the conventional system. For a shave factor of 0.2, if the peak heating demand is 100 kW, then the GSHP and

baseboard heater (major overhaul costs) will be sized to meet 20 kW and 80 kW respectively. This calculation outlined in Alavy *et al.* [15] was used to determine the initial costs for all shave factor values (from 0 to 1).

The initial costs for the hybrid GSHP system can be calculated using the parameters outlined in Table 5.2. A 1.2-kW baseboard heater unit costs $400 ($200 per unit and $200 for installation cost) [87-88]. The cost of a 12,000 Btu/h (3.5 kW) air conditioner unit was assumed to cost $500 after taxes [89-91]. Upon consulting with several contractors in the GTA (Greater Toronto Area) (personal communication with [92-94], February 10, 2014), the retrofit costs for ductwork are commonly between $6,000 and $10,000 for a 3,000 ft^2 house (total costs for materials and labour). Furthermore, the costs of adding additional insulation to bring a residential house up to code costs $1-$3 per ft^2 (total costs of materials and labour for wall or ceiling) ([95] and personal communication with [93-94], February 10, 2014). For the analysis of two residential houses, in the subsequent section, the ductwork retrofit (assuming no major wall or subfloor modifications) and insulation costs per ft^2 (R-value up to code for walls and attic floor) was assumed to be $3.3 and $1.5, respectively.

The operating costs are based on electricity consumption using a fixed rate of $0.17/kWh. Other retrofit costs (depending on the building being studied) are costs that were not accounted for such as environmental/waste disposal fees, or additional insulation/ductwork costs if the values used in the present study were underestimated.

Table 5.2: Retrofit design parameters and costs

Parameters	Value
Electric Baseboard Heater (RCC12012C – 1200W) [88]	$400/1.2 kW
Window Air Conditioner Unit [89-91]	$500/3.5 kW ($42 per kBtu/h)
Cooling Design Entering Fluid Temperature to HP*	29.4°C
Heating Design Entering Fluid Temperature to HP*	1.7°C
Ductwork (retrofit) costs for residential houses	$3.3/ft^2 (floor area)
Wall insulation upgrade costs for residential houses	$1.5/ft^2 (walls and attic floor)
Vertical borehole 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
Soil Thermal Diffusivity*	0.072 m^2/day
Soil Thermal Conductivity	2.94 W/m·K
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
Electricity rate	$0.17/kWh
Inflation Rate*	4%
Interest Rate*	8%

*data courtesy of CleanEnergy^{TM}

5.2 Retrofitting Residential Houses

Two detached residential houses, a 2,000 ft^2 bungalow (House A) and a 5,000 ft^2 2-storey residential house (House B), were modelled in eQuest using Toronto's weather patterns [55]. The two houses were modelled in accordance with 1986 OBC (Ontario Building Code) minimum insulation requirements for the building exterior [96]. Insulation for the ceiling below roof space was R30 (R50 for 2012 new building code) and exterior wall was R13 (R29 for 2012 new building code). The buildings were heated by electric baseboard heaters and the thermostat set points were set to 71°F and 75°F (~22°C and 24°C) for the heating and cooling modes respectively. Table 5.3 outlines House A's and B's annual heating and cooling loads and operating costs (based on $0.17/kWh). As presented in Table 5.3, simply upgrading the building's insulation showed a substantial reduction in energy consumption. For House A, the heating and cooling loads reduced by 24.3% and 1.6% respectively. A $5,400 investment to upgrade House A's insulation results in an annual savings of $566, a payback period of 9.5 years. For House B, upon upgrading the insulation ($10,500) the heating and cooling loads reduced by 33.8% and 1.2% respectively ($1,168 annual savings). Further savings can be achieved if better HVAC systems were implemented for these vintage 1986 buildings.

Table 5.3: Houses A and B annual energy consumption and conventional operating costs

	Annual Cooling Load (kWh)	Annual Baseboard Heating Load (kWh)	Annual Cooling Costs (Window Unit) ($)	Annual Baseboard Heating Costs ($)	Insulation Cost ($1.5/ft^2)
House A 1986 OBC	2,135	13,600	363	2,312	—
House A New Insulation	2,100	10,300	357	1,751	5,400
House B 1986 OBC	5,775	20,100	982	3,417	—
House B New Insulation	5,700	13,300	970	2,261	$10,500

A total of three tests were performed for retrofitting House A and B. In the first test, only the initial cost of the GSHP system was considered for each corresponding shave factor value from 0 to 1. The insulation upgrade (no insulation costs), ductwork costs, and major overhaul costs for the conventional system were all not considered for the analysis (Test #1). The objective of the first test, which is a highly idealized scenario, was to provide an overview on the feasibility of a hybrid GSHP system and potential savings before applying other retrofit costs. In the second test the retrofit costs considered in the analysis include ductwork costs and major overhaul costs for the window air conditioner units ($42 per kBtu/h) and electric baseboard heaters (~$333/kW). In the third test, the insulation upgrade costs were considered.

5.2.1 Test #1: only GSHP initial cost considered

Applying the aforementioned retrofit approach, the optimal shave factor for installation of a hybrid GSHP system for House A and B are 0.6 and 0.37 respectively. The total costs in net present value for House A are presented in Figure 5.2, in which the total costs for each corresponding shave factor value from 0 to 1 are presented by the blue curve. Based on an optimal shave factor value of 0.6 for House A (Table 5.4), the GSHP is still capable of providing 96% of the house's energy demands based on a ground loop length of 93 m. The total costs for house A after 20 years of operation is $21,370. This optimal hybrid design results in a total savings of $13,925 when compared with the base case in which all building energy demands are met by electric baseboard heaters and window air conditioners (shave factor value of 0). The initial costs of the GSHP, based on the assumed average cost of $65.6/m of vertical borehole length (which is more applicable for large buildings), is too low for residential houses due to the rental and/or transportation costs of drilling equipment. However, the study will continue to use the average cost of $65.6/m as a framework for the present work.
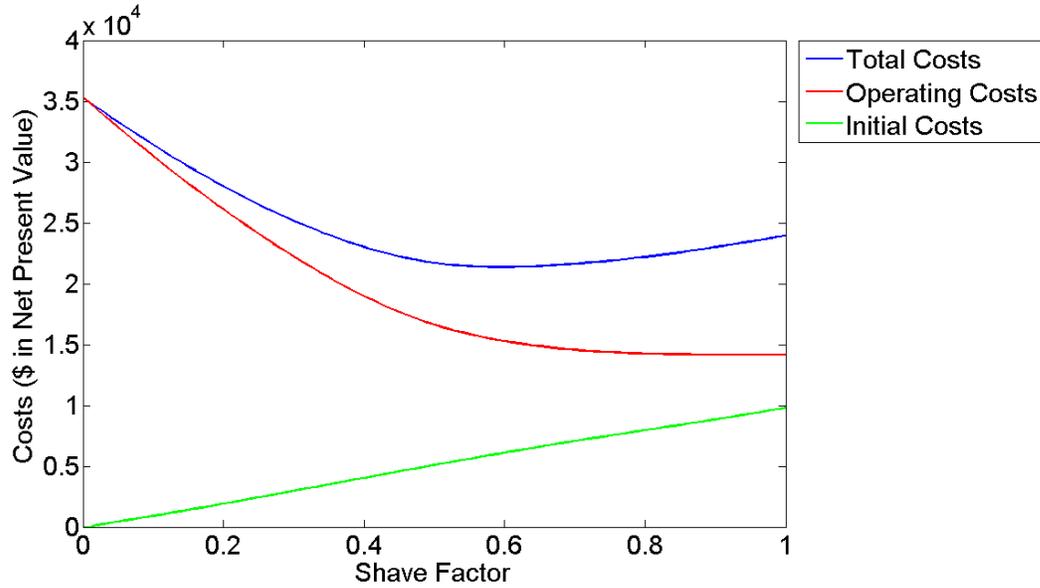
Figure 5.2: Shave factor vs. total costs (Test #1) – Retrofit analysis for House A. This analysis only considers the cost of the GSHP system.

Table 5.4: House A results (Test #1)

Shave Factor	Ground Loop Length (m)	Average TEDM (%)	Total Costs (Net Present Value) ($)	Initial Costs ($)	Payback period (years)
0*	0	0	35,295	0	—
0.6**	**93**	**96.3**	**21,370**	**6,099**	**6.1**
0.7	108	98.7	21,623	7,063	6.8
1	149	100	23,942	9,788	9.3

*Base case (no retrofit) **Optimal shave factor   Total energy demands met by GSHP (TEDM)*

Figure 5.3 presents the payback periods for the hybrid GSHP for any additional retrofit costs not considered during the analysis. These additional retrofit costs for this scenario are costs for the GSHP system that are not accounted for or were underestimated (*i.e.*, maintenance/repair costs, waste disposal). The linear curves range from $0 to the maximum savings of $13,925, $13,672, and $11,353 (compared to base case) for the optimal shave factor, a shave factor of 0.7, and 1, respectively. The payback periods reach 20 years for the three shave factors plotted in Figure 5.3 when the total savings compared to the base case approaches $0. The curves for all "other retrofit

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costs" figures are plotted based on 1% increments of the total savings (compared to the base case). For example, the total savings for the optimal design compared to the base case was $13,925, and based on 1% increments, the "other retrofit costs" are incremented based on a step-size of $139.25. Similarly, the "other retrofit costs" for the shave factor of 0.7 and 1.0 curves are incremented by $136.72 and $113.53, respectively. If other retrofit costs (in addition to the GSHP initial costs) are less than the total savings, the retrofit costs are considered to be economically justifiable. Otherwise, the retrofit costs exceed the total savings and will require more than 20 years to payback (longer than the assumed duration of operation).
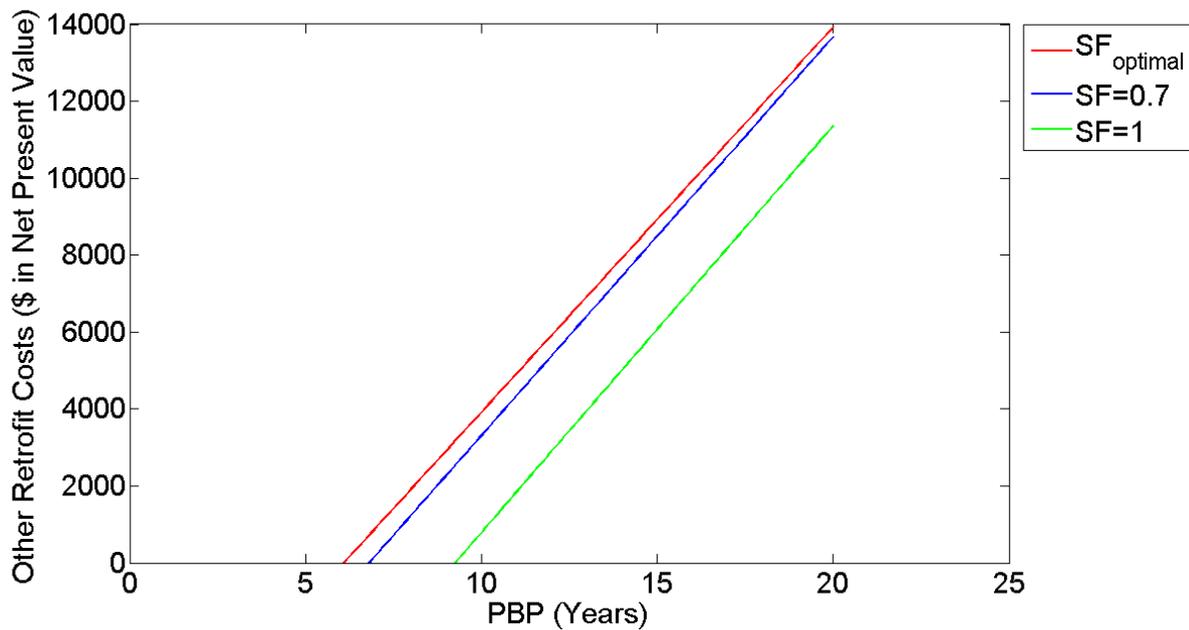
Figure 5.3: PBP vs. other retrofit costs (Test #1) – Retrofit analysis for House A. The ordinate corresponds to "other retrofit costs". For the case of $0 for "other retrofit costs", the payback period corresponds to only the cost of the GSHP system.

Similar results can be observed for House B as shown in Table 5.5 and Figure 5.4. The optimal shave factor is 0.37, meeting 83.8% of the building's total energy demands and a savings of $20,821 compared of shave factor of 0. Total savings of $15,932 and $10,328 can be found for the shave factors of 0.7 and 1.0, respectively.

Table 5.5: House B results (Test #1)

Shave Factor	Ground Loop Length (m)	Average TEDM (%)	Total Costs (Net Present Value) ($)	Initial Costs ($)	Payback period (years)
0*	0	0	58,197	0	—
0.37**	**138**	**83.8**	**37,376**	**9,063**	**6.1**
0.7	243	99.1	42,265	15,967	10
1	329	100	47,869	21,594	13.5

*Base case (no retrofit)   **Optimal shave factor*
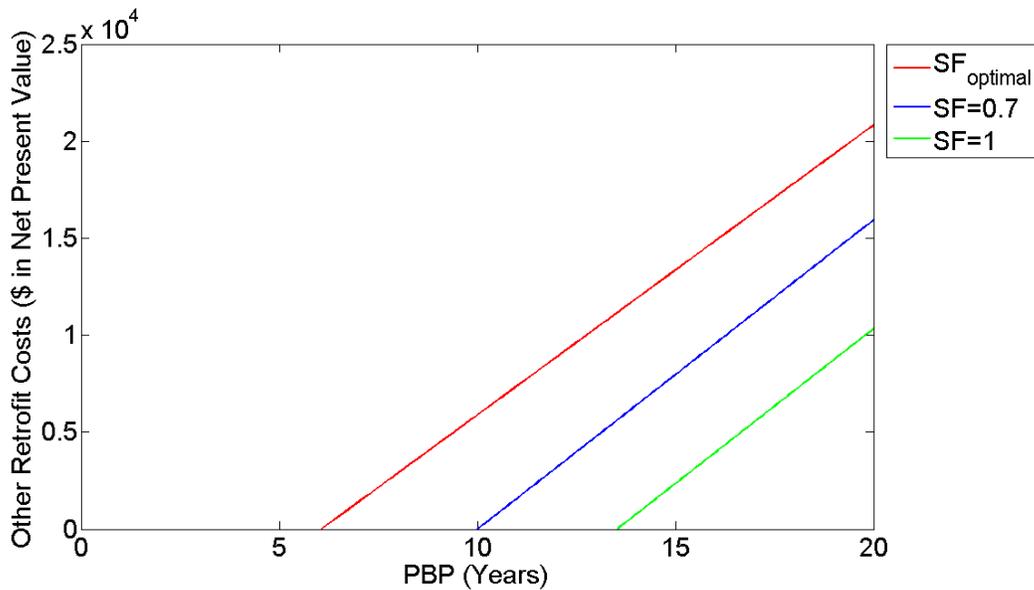
Figure 5.4: PBP vs. other retrofit costs (Test #1) – Retrofit analysis for House B. The ordinate corresponds to "other retrofit costs". For the case of $0 for "other retrofit costs", the payback period corresponds to only the cost of the GSHP system.

For Test #1, comparing between Houses A and B, it can be seen that the potential savings ($20,821 vs. $13,925) for House B is higher than for House A at their respective optimal shave factors. In addition, the payback periods are the same (6.1 years), despite higher hybrid GSHP initial costs for House B. This data indicates that a hybrid GSHP system is more economically viable for retrofitting bigger houses with higher electric baseboard heaters and window air conditioners (House B vs. House A).

5.2.2 Test #2: ductwork and major overhaul costs

In this analysis a framework is provided for determining acceptable ductwork and retrofit costs. The ductwork costs and major overhaul costs for the window air conditioner units ($42 per kBtu/h) and electric baseboard heaters (~$333/kW) are considered. The major overhaul costs of window air conditioners and baseboard heaters are only for their capacities in excess of the GSHP's capacity to cover the peak cooling and heating loads. The ductwork costs for Houses A and B are $6,600 and $16,500 respectively. Using 1986 building insulation standards, the optimal shave factor for House A is 0.7 (TEDM of 98% and payback period of 13.9 years) in which a total savings of $17,000 can be achieved compared to the base case. Similar to Test #1, Figure 5.5 illustrates the effects that additional retrofit costs have on the payback period of the hybrid GSHP system. Additional cost of $6,280 and $4,800 can be added to shave factors of 0.7 (optimal) and 1.0, respectively, before payback periods exceed 20 years.
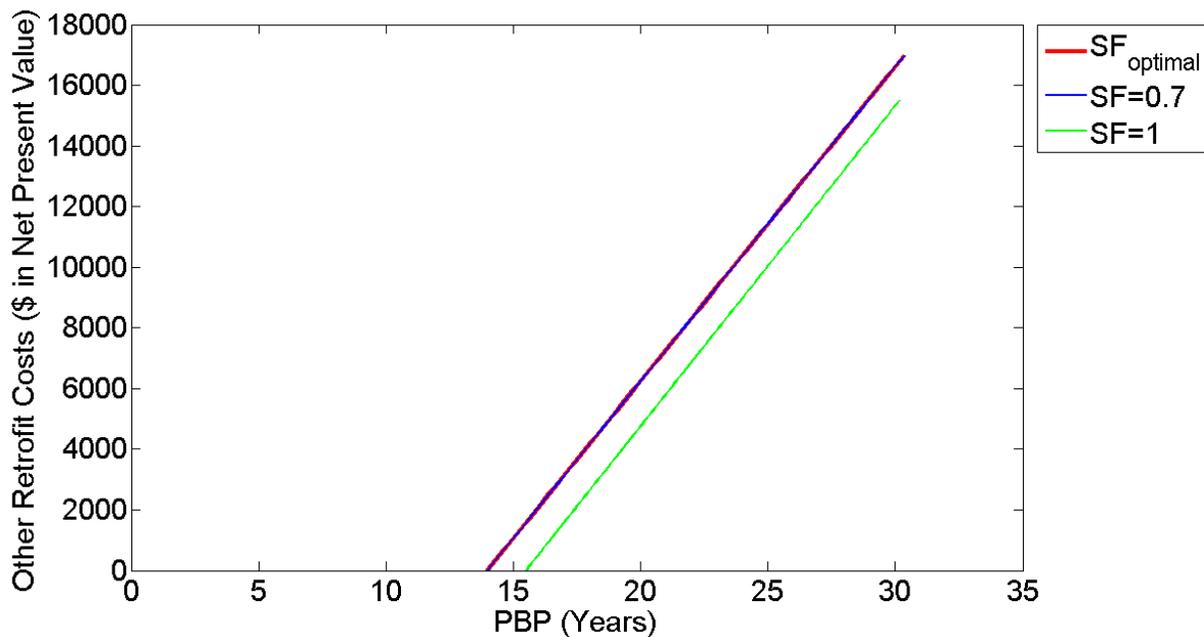

Figure 5.5: PBP vs. other retrofit costs (Test #2) – Retrofit analysis for House A. The ordinate corresponds to "other retrofit costs". For the case of $0 for "other retrofit costs", the payback period corresponds to the costs of the GSHP system, overhaul costs, and ductwork costs.

For House B, the addition of the ductwork costs of $16,500 and major overhaul costs of the conventional system make hybrid GSHPs an uneconomical solution even for the optimal shave factor of 0.45 and TEDM of 90%, because the payback periods exceed twenty years as presented in Figure 5.6. However, if the ductwork costs were $10,000, then the optimal shave factor of 0.45 for House B produces a payback period of 15.9 years (less than twenty years of operation) as presented in Figure 5.7.
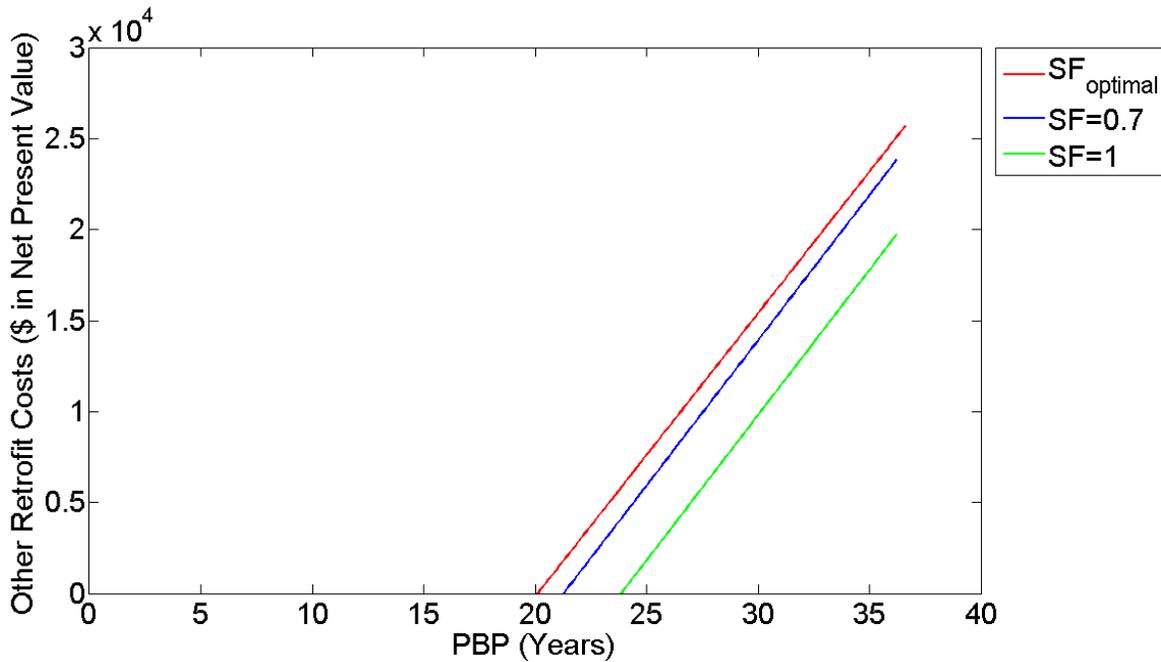
Figure 5.6: PBP vs. other retrofit costs (Test #2) – Retrofit analysis for House B. The ordinate corresponds to "other retrofit costs". For the case of $0 for "other retrofit costs", the payback period corresponds to the costs of the GSHP system, overhaul costs, and ductwork costs ($16,500).
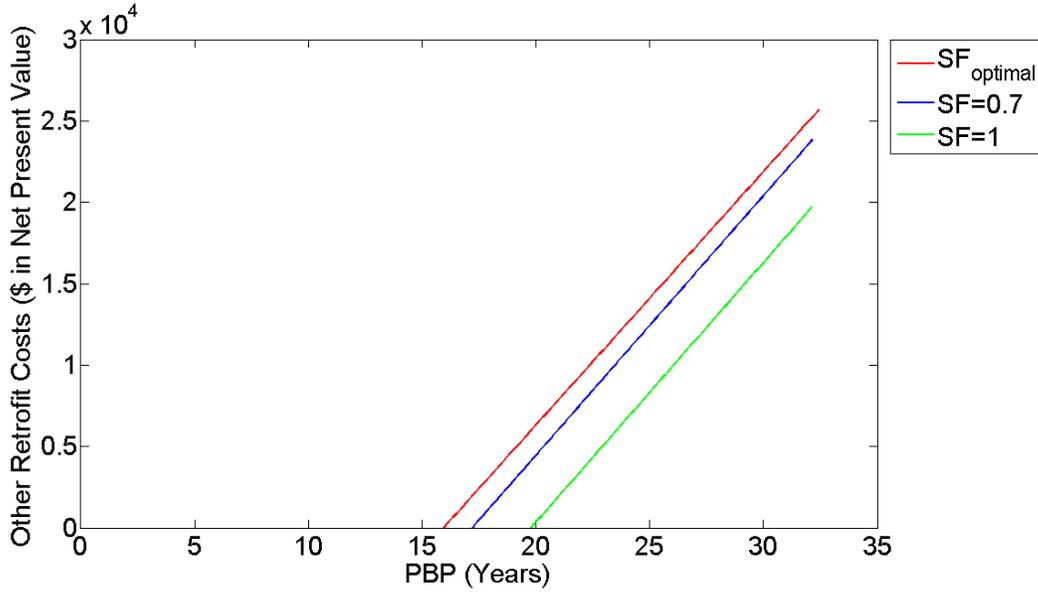
Figure 5.7: PBP vs. other retrofit costs (Test #2) – Retrofit analysis for House B. The ordinate corresponds to "other retrofit costs". For the case of $0 for "other retrofit costs", the payback period corresponds to the costs of the GSHP system, overhaul costs, and ductwork costs ($10,000).

For Test #2, because of higher retrofit costs for ductwork ($16,500 vs. $6,600) and for the major conventional system overhaul ($4,100 vs. $1,100) compared to House A, there is no savings within the twenty years of operation for House B even for the optimal shave factor of 0.45 and TEDM of 90%. Comparing Tests #1 and #2, it can be seen that the additional retrofit costs of ductwork and overhauling can change the optimal shave factor (0.37 vs. 0.45) for House B, as well as resulting in longer payback periods (6.1 years vs. 20.1 years). However, the additional retrofit costs have also changed the optimal shave factor (0.6 vs. 0.7) for House A, as well as resulting longer payback period (6.1 years vs. 13.9 years); but the hybrid GSHP system for House A is still economically viable due to lower retrofit costs.

5.2.3 Test #3: insulation costs

In addition to the costs considered in Test #2, the insulation of the two houses are upgraded, from R13 to R29 and R30 to R50 for the exterior walls and ceiling respectively. The insulation upgrade costs are incorporated into the analysis. Using $1.5 per ft^2 of insulation, the insulation costs for Houses A and B are $5,400 and $10,600 as previously mentioned in Table 5.3. As expected, from

Test #1 and Test #2, although upgrading the insulation reduces the total building's energy demands, the high upfront costs of retrofitting a hybrid GSHP system makes it an uneconomical solution compared to a conventional system for Houses A and B. The payback period exceeds 20 years when the cost of insulation costs, ductwork costs, and major overhaul costs are considered. Although the optimal hybrid GSHP designs for Houses A and B produce respectively a total savings of about $13,000 and $17,000, the payback period (optimal design) for Houses A and B are 23 and 37.3 years (Table 5.6), respectively. Again, the additional retrofit costs of insulation can effect a different optimal shave factor for the hybrid GSHP design. For House A, the optimal shave factors are 0.6, 0.7 and 0.64 for Tests #1, #2 and #3, respectively. Whereas, for House B, the optimal shave factors are 0.37, 0.45 and 0.28 for Tests #1, #2 and #3, respectively. Furthermore, it is clear that, as the retrofit costs increase from Test #1 to Test #3, the optimal shave factor may not monotonically increase or decrease. Therefore, it is beneficial to perform this kind of optimization study for each considered case.

Table 5.6: Houses A and B results (Test #3)

Building	Shave Factor	Ground Loop Length (m)	Average TEDM (%)	Total Costs (Net Present Value) ($)	Initial Costs ($)	Payback period (years)
House A	0*	0	0	43,594	15,654	—
	0.64**	**85**	**97.7**	**30,377**	**18,360**	**23**
	0.7	117	98.9	30,422	18,559	23.1
	1	79	100	31,379	19,646	24.3
House B	0*	0	0	77,707	34,984	—
	0.28**	**110**	**75.7**	**60,516**	**38,406**	**37.3**
	0.7	242	99	65,286	44,070	41
	1	323	100	69,158	47,964	44.6

*Base case   ** Optimal shave factor;   Total energy demands met by GSHP (TEDM)

5.3 Retrofit Analysis for Other Buildings

In this section, a retrofit analysis was performed by using the building loads of a school, two high-rise multi-residential buildings (HR A and HR B), a mid-rise multi-residential building, and an office in order to determine whether a hybrid GSHP system retrofit would be economical. The loads of the five buildings were obtained using Toronto's weather patterns, and are courtesy of CleanEnergy Developments Corporation.

Two tests were carried out for the three buildings (School, HR A and the Office). In the first test, the major overhaul costs for the electric baseboard heaters and window air conditioners were considered. Since no rough rules-of-thumb exists for approximating ductwork costs for these four buildings (personal communication with [92-94], February 10, 2014), the ductwork costs were incorporated as part of "other retrofit costs". In the second test the analysis remains the same as that of the first test, however, cooling towers ($40 per kBtu/h, overall COP = 2) were used instead of window air conditioner units for the retrofit analysis.

5.3.1 Test #1: baseboard heaters and window air conditioners

As mentioned, a COP value of 1.0 and 3.4 were used to determine the operating costs of the electric baseboard heaters and window air conditioner units respectively. The optimal designs for the buildings were determined and the results are presented in Table 5.7.

There are several factors contributing to the result of no optimal hybrid GSHP design (uneconomical) for the high-rise B and mid-rise buildings. In this analysis, the window air conditioner units were assumed to have COP values similar to that of a GSHP's while in the cooling mode (3.4 compared to 3.8). The high-rise B building requires a cooling-heating load ratio of 4:1. As a result, the high upfront costs for the GSHP system, and window air conditioner units (replaced every 10 years), for each corresponding shave factor value makes these buildings less economical to operate with a GSHP than by a pure conventional system. However, for example, if the COP of the window air conditioner units were 2.0 (not a reasonable assumption) instead of 3.4, the high-rise B building would have an optimal design ($SF = 0.34$). A shave factor value of

0.34 would provide 74% of the high-rise's total energy demands, resulting in a payback period of 12 years, and a total savings of $553,000.

Table 5.7: Large buildings retrofit results (Test #1)

Building	Heating Dominant/ Cooling Dominant (HD/CD)	Shave Factor	Average TEDM (%)	Total Costs (Net Present Value) ($)	Initial Costs ($)	Payback period (years)
School	CD	0	0	677,928	92,094	—
		0.41*	**91**	**420,001**	**142,061**	**9**
		0.7	99	441,863	171,237	11
		1	100	482,334	211,950	13
High-Rise A	CD	0	0	776,385	131,868	—
		0.1*	**43**	**541,595**	**127,868**	**11.1**
		0.7	99	724,682	334,073	26.3
		1	100	790,871	400,642	31.5
Office	HD	0	0	6,208,644	626,649	—
		0.47*	**95.4**	**3,794,023**	**1,700,017**	**9.7**
		0.7	99.8	4,042,560	2,127,770	11.6
		1	100	4,545,759	2,638,445	14.4

Optimal hybrid GSHP design

The optimal shave factor for the school is 0.41, meeting 91% of the building's total energy demands. By sizing the hybrid GSHP system according to the optimal shave factor, the payback period is 9 years and a total savings of $257,900 can be achieved. However, this analysis does not consider the ductwork costs. As presented in Figure 5.8, as the ductwork costs increases, so too does the payback period. The payback period would be twenty years if additional retrofit costs for the ductwork were $167,600 (for the optimal design).
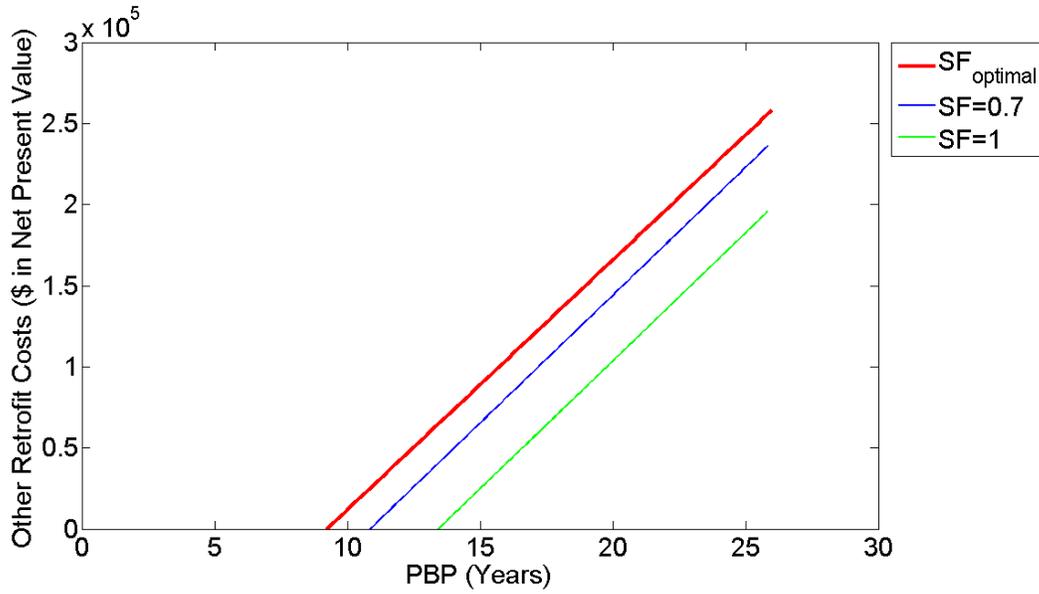
Figure 5.8: PBP vs. other retrofit costs (Test #1) – Retrofit analysis for a school located in Toronto, Ontario. The ordinate corresponds to "other retrofit costs". For the case of $0 for "other retrofit costs (ductwork costs)", the payback period corresponds to the costs of the GSHP system and overhaul costs (baseboard heaters and window air conditioner units).

The optimal shave factor for the high-rise A building is 0.1, meeting 43% of the building's total energy demands. By sizing the hybrid GSHP system according to the optimal shave factor the payback period is 11.1 years and a total savings of $234,800 can be achieved. However, when additional ductwork costs are considered, as presented in Figure 5.9, the payback period increases. The payback period would be twenty years if additional retrofit costs for the ductwork were $103,300 (for the optimal design).
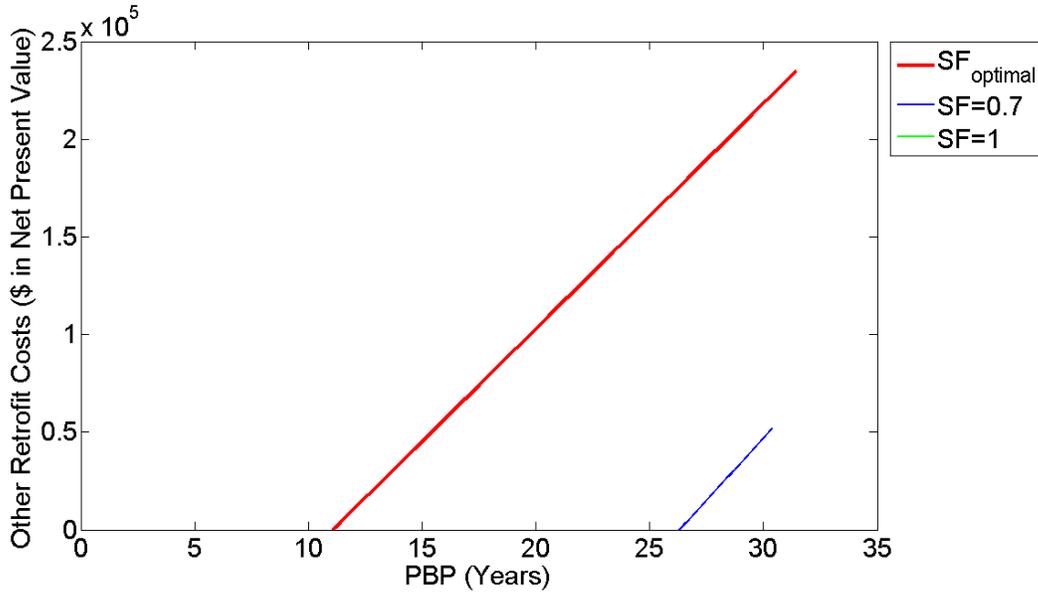
Figure 5.9: PBP vs. other retrofit costs (Test #1) – Retrofit analysis for High-rise A located in Toronto, Ontario. The ordinate corresponds to "other retrofit costs". For the case of $0 for "other retrofit costs (ductwork costs)", the payback period corresponds to the costs of the GSHP system and overhaul costs (baseboard heaters and window air conditioner units).

The optimal shave factor for the office building is 0.47, meeting 95% of the building's total energy demands. By sizing the hybrid GSHP system according to the optimal shave factor the payback period is 9.7 years and a total savings of $2,415,000 can be achieved. However, when additional ductwork costs is considered, as presented in Figure 5.10, as the ductwork costs increase, so too does the payback period. The payback period would be twenty years if additional retrofit costs were $1,787,000 (for the optimal design). The large savings are due to the building being extremely heating dominant (more economical to provide heating by a GSHP) from an all-glass (wall) building envelope.
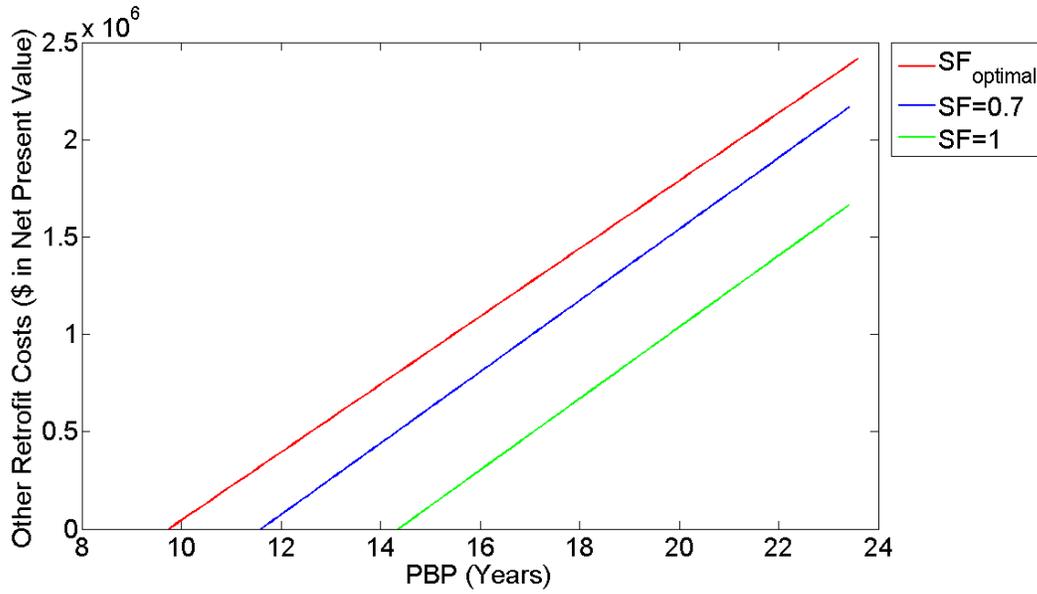
Figure 5.10: PBP vs. other retrofit costs (Test #1) – Retrofit analysis for an office located in Toronto, Ontario. The ordinate corresponds to "other retrofit costs". For the case of $0 for "other retrofit costs (ductwork costs)", the payback period corresponds to the costs of the GSHP system and overhaul costs (baseboard heaters and window air conditioner units).

5.3.2 Test #2: baseboard heaters and cooling towers

The analysis remains the same as that of the first test, however, cooling towers ($40 per kBtu/h, overall COP = 2.0) were used instead of window air conditioner units for the retrofit analysis. This analysis would be more appropriate for commercial buildings where window air conditioner units are rare. The optimal designs for the buildings were determined and the results are presented in Table 5.8.

The optimal shave factor for the high-rise A building is 0.21, meeting 64.3% of the building's total energy demands. The payback period is 8.1 years and a total savings of $302,900 can be achieved. However, when additional ductwork costs are considered, as presented in Figure 5.11, the optimal shave factor curve exceeds a payback period of twenty years when other retrofit costs (such as ductwork costs) are greater than $213,000. For the shave factors 0.7 and 1.0 (blue and green curves), payback period exceeds twenty years when other retrofit costs are greater than $150,000 and $75,000 respectively.
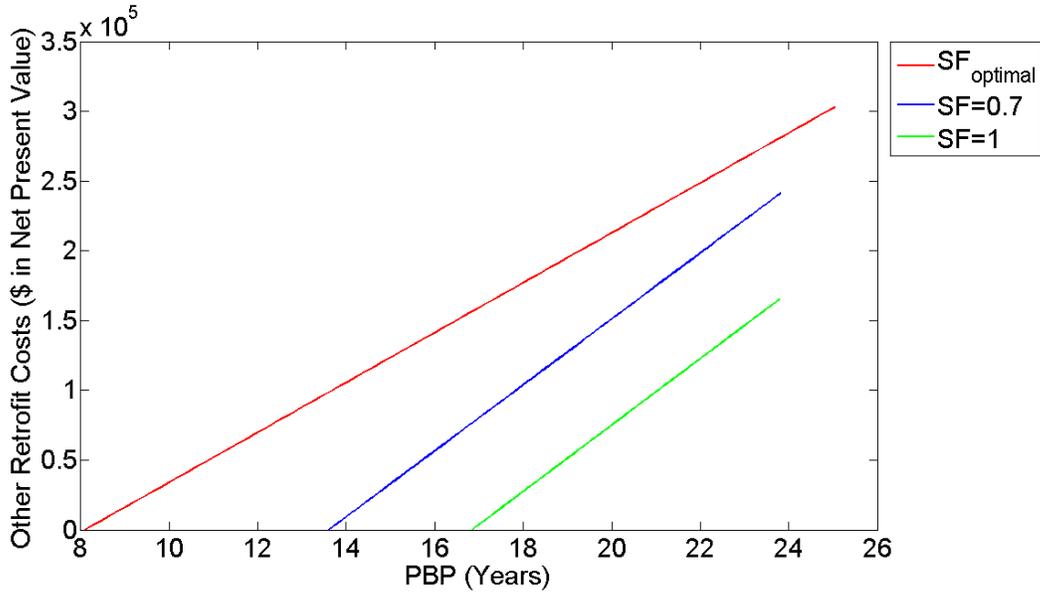
Figure 5.11: PBP vs. other retrofit costs (Test #2) – Retrofit analysis for High-rise A located in Toronto, Ontario. The ordinate corresponds to "other retrofit costs". For the case of $0 for "other retrofit costs (ductwork costs)", the payback period corresponds to the costs of the GSHP system and overhaul costs (baseboard heaters and cooling tower).

Table 5.8: Large buildings retrofit results (Test #2)

Building	Heating Dominant/ Cooling Dominant (HD/CD)	Shave Factor	Average TEDM (%)	Total Costs (Net Present Value) ($)	Initial Costs ($)	Payback period (years)
High-Rise A	CD	0	0	955,881	90,066	—
		0.21*	**64.3**	**652,979**	**144,715**	**8.1**
		0.7	99.1	714,787	321,532	13.6
		1	100.0	790,871	400,642	16.9
High-Rise B	CD	0	0	1,988,168	173,516	—
		0.23*	**60.9**	**1,459,675**	**325,895**	**9.6**
		0.7	98.0	1,561,148	697,086	14.7
		1	100	1,714,959	865,817	17.9
School	CD	0	0	751,477	66,833	—
		0.46*	**93.4**	**419,334**	**133,237**	**6.7**
		0.7	99.1	435,964	163,658	7.9
		1	100	482,334	211,950	10.2
Office	HD	0	0	6,263,760	552,289	—
		0.47*	**95.4**	**3,794,023**	**1,700,017**	**9.4**
		0.7	99.8	4,042,560	2,127,770	11.2
		1	100	4,545,759	2,638,445	13.9
Mid-rise	CD	0	0	1,067,332	87,111	—
		0.34*	**74**	**867,559**	**263,339**	**14**
		0.7	98.3	929,000	429,898	17.9
		1	100	1,021,723	529,753	21.7

Optimal hybrid GSHP design (optimal shave factor)

Previously, based on window air conditioner units and high-rise B's large cooling demands, it was uneconomical to install a GSHP system. For this analysis, using cooling towers (as the conventional cooling system), the optimal shave factor for high-rise B is 0.23. Based on this optimal design, 60.9% of the building's total energy demands are met. The payback period is 9.6 years and a total savings of $528,500 can be achieved. However, when additional ductwork costs is considered, as presented in Figure 5.12, the optimal shave factor curve exceeds a twenty year payback period when other retrofit costs are greater than $355,000. For the shave factors 0.7 and 1.0 (blue and green curves), payback period exceeds twenty years when other retrofit costs are greater than $253,000 and $99,000 respectively.
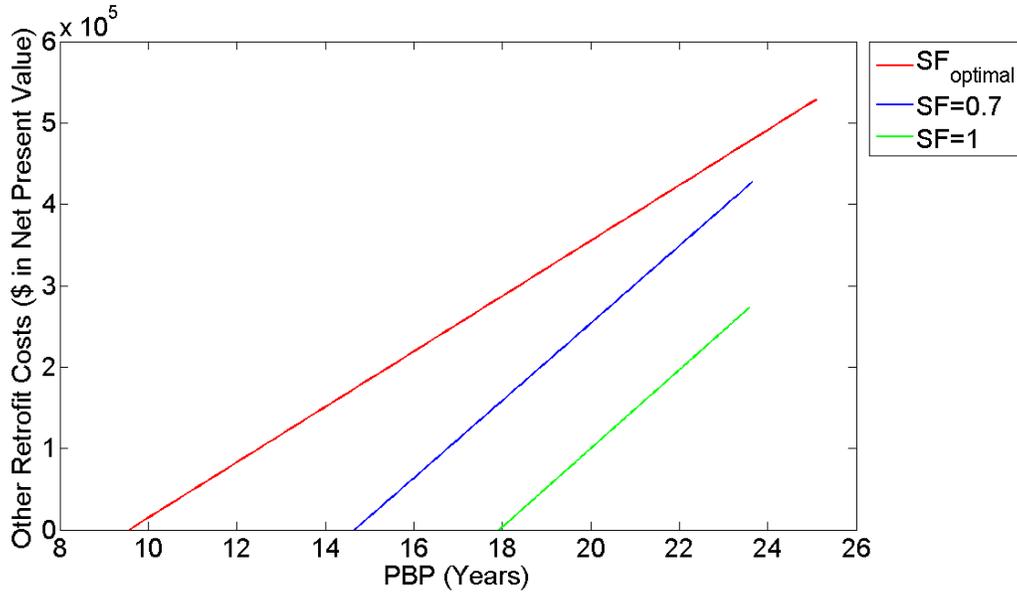
Figure 5.12: PBP vs. other retrofit costs (Test #2) – Retrofit analysis for High-rise B located in Toronto, Ontario. The ordinate corresponds to "other retrofit costs". For the case of $0 for "other retrofit costs (ductwork costs)", the payback period corresponds to the costs of the GSHP system and overhaul costs (baseboard heaters and window air conditioner units).

The optimal shave factor for the school is 0.46, meeting 93.4% of the building's total energy demands. The payback period is 6.7 years and a total savings of $332,000 can be achieved. However, when additional ductwork costs are considered, as presented in Figure 5.13, the optimal shave factor curve exceeds the twenty years payback period when other retrofit costs are greater than $264,000. The curves for shave factors of 0.7 and 1.0 exceed the twenty-year payback period when other retrofit costs are greater than $248,000 and $202,000 respectively.
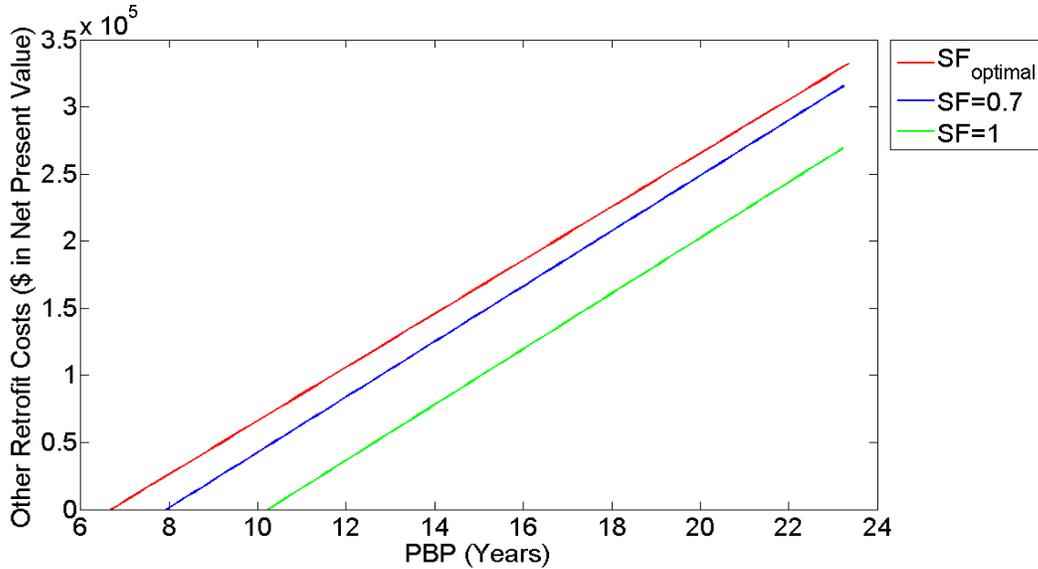
Figure 5.13: PBP vs. other retrofit costs (Test #2) – Retrofit analysis for a school located in Toronto, Ontario. The ordinate corresponds to "other retrofit costs". For the case of $0 for "other retrofit costs (ductwork costs)", the payback period corresponds to the costs of the GSHP system and overhaul costs (baseboard heaters and window air conditioner units).

Based on the five buildings analyzed, it was most economical (in terms of total savings) for the office building to install a hybrid GSHP system. The optimal shave factor for the office building is 0.47, meeting 95.4% of the building's total energy demands, a payback period of 9.4 years, and a total savings of $2,470,000. As presented in Figure 5.14, the curves for the optimal design, shave factors of 0.7 and 1.0 exceed twenty-year payback period when additional retrofit costs (such as ductwork costs) are more than $191,000, $167,000 and $116,000 respectively.
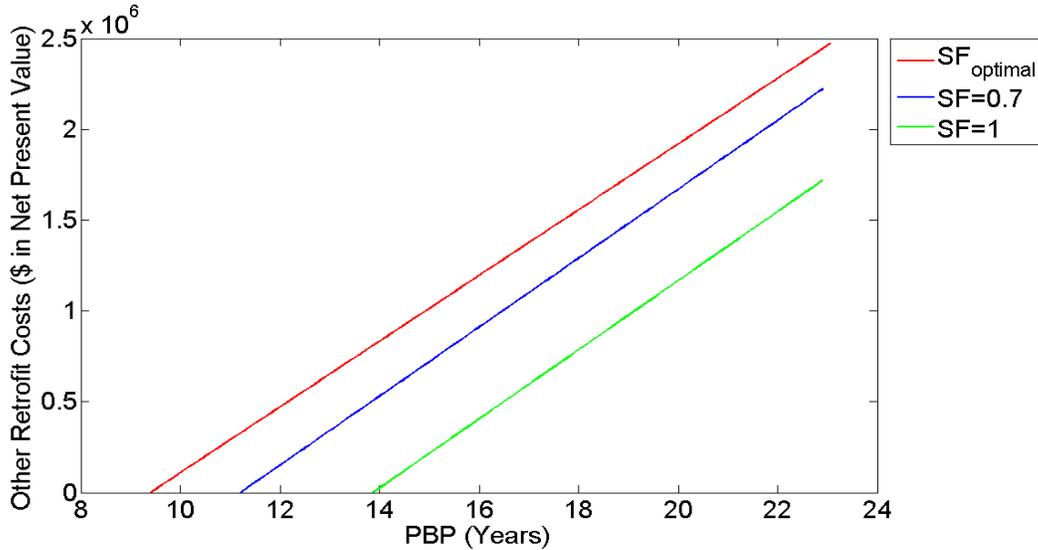
Figure 5.14: Office – PBP vs. other retrofit costs (Test #2) – Retrofit analysis for an office located in Toronto, Ontario. The ordinate corresponds to "other retrofit costs". For the case of $0 for "other retrofit costs (ductwork costs)", the payback period corresponds to the costs of the GSHP system and overhaul costs (baseboard heaters and window air conditioner units).

Lastly, the optimal shave factor for the mid-rise multi-residential building is 0.34. Based on the optimal design, 74% of the buildings total energy demands are met, a total savings of $199,800 (compared to the base case, *SF*=0) and a payback period of 14 years. As presented in Figure 5.15, the curves for the optimal design and shave factor of 0.7 exceed the twenty-year payback period when additional retrofit costs (such as ductwork costs) are more than $112,000 and $51,500 respectively.
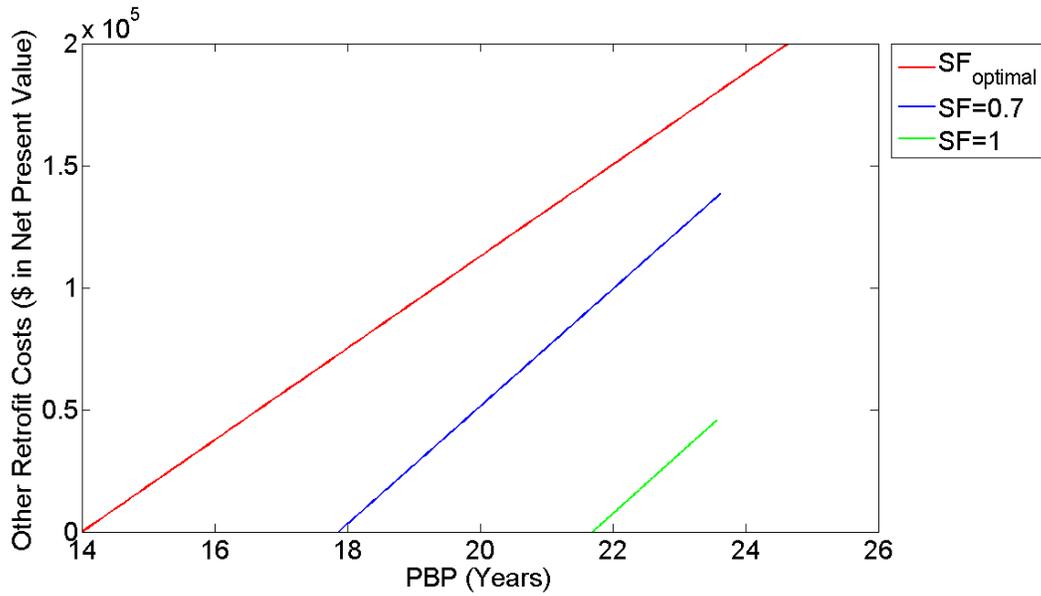
Figure 5.15: PBP vs. other retrofit costs (Test #2) – Retrofit analysis for a mid-rise multi-residential building located in Toronto, Ontario. The ordinate corresponds to "other retrofit costs". For the case of $0 for "other retrofit costs (ductwork costs)", the payback period corresponds to the costs of the GSHP system and overhaul costs (baseboard heaters and window air conditioner units).

5.4 Chapter Summary

For the two residential houses, Houses A and B, the results in Test #1 (only costs of GSHP system considered) shows that the potential savings ($20,821 vs. $13,925) for House B is higher than for House A at their respective optimal shave factors; in addition, the payback periods are the same (6.1 years), despite higher hybrid GSHP initial costs for House B.

In Test #2, retrofit ductwork costs, major overhaul costs of window air conditioners, and baseboard heaters are considered. The high costs of the ductwork resulted in longer payback periods for Houses A and B; 13.9 years and 20.1 years respectively. The ductwork costs for House B needs to be less than $16,500 for the payback period to be less than twenty years. Due to reduced energy demands from upgrading the building envelope, there is lesser savings for hybrid GSHP systems compared to the conventional heating and cooling systems. As a result, in Test #3, the addition of insulation costs resulted in longer payback periods for both houses. It is clear that, as the retrofit costs increase from Test #1 to Test #3, the optimal shave factor may not exhibit monotonic behavior.

For the other buildings analyzed (commercial and residential), hybrid-GSHP systems are not as economical for cooling dominant buildings with a high cooling to heating ratio. The economic viability for these particular buildings depend on the COP of the conventional system being less than that of the GSHP system. However, in Test #1, the air conditioner and heat pump have similar cooling COPs (3.4 vs. 3.8), resulting in no economical designs (*i.e.*, for the case of High-rise B). The results indicate that larger buildings generally benefit more from a hybrid GSHP retrofit — larger energy savings tend to compensate for the high upfront costs of the system, especially for large buildings with a compatible distribution system (low ductwork costs).

Chapter 6

6.1 Conclusions

The three studies performed gave an overview of how complex sizing of a hybrid GSHP system can be. However, as suggested by the literature [46 – 48], the use of sensitivity analysis has allowed for a better determination of the impact that variations in input parameters such as pricing, operating hours, inflation and ground temperatures have on the design and performance of hybrid GSHPs. The approach taken in these sensitivity analyses is consistent with that undertaken in recent modelling of GSHP energy systems [51, 53, 63]. The findings of the sensitivity analyses have implications for GSHP technology developers, energy utilities, energy regulators and operators of multi-residential and commercial building complexes who may be contemplating installation of a GSHP energy system. Based on the studies performed, a framework has been established and the algorithms and results can be used as tools and guides to complement existing ground loop design tools and aid the engineer during the design process.

The economic viability and optimal design of hybrid GSHPs is dependent on weather, operating costs (fixed or time-of-use rates), inflation rates, project life, heat pump EFT, carbon taxation, and the control strategies used. The conclusions from the three studies are:

Weather sensitivity:
- Extremely cooling dominant buildings had longer payback periods in warmer weather. The average change in payback periods (excluding the school) ranges between +1.2 (Charles, IA) and -3.1 (Austin, TX); a negative value indicates a longer payback period.
- It is more economical for extremely cooling dominant buildings to install GSHP systems in colder weather due to lower ground temperatures (better heat pump performance).
- In warmer weather where ground temperatures were higher, it was most economical to downsize the ground loop length and expand the cooling tower. The change in shave factor are between +0.07 (Kearney, NE) and -0.44 (Fresno, CA) using Toronto's rates.

- Buildings situated in colder weather have larger heating demands. For heating dominant buildings, it is more economical to install conventional heating systems — the cost of natural gas per kWh heating is cheaper than electricity.

Natural gas, electricity and inflation rates:
- For buildings with long operating hours during off-peak periods (time-of-use rates), the GSHP system was downsized (shave factor) by 1% and 3% for the restaurant and fast-food restaurant respectively, reducing initial costs. However, downsizing of the GSHP system resulted in longer payback periods due to lower savings on operating cost.
- The widely varying electricity rates in North America significantly affect the shave factor values — in some cases generating much more economically viable designs in regions with higher rates.
- Inflation for natural gas or electricity rates can benefit or adversely affect the hybrid GSHP system's economic viability depending on the building and weather patterns.
- For cooling dominant buildings, hybrid GSHP systems become more favorable when electricity rates or inflation is increased.
- The economics for buildings with GSHPs that provided heating were worsened when electrical prices increased but were improved when natural gas price increases.
- For heating dominant buildings, the low rates for natural gas found in many parts of North America make it uneconomical to install a GSHP system.

Seasonality control:
- In the winter months, all cooling demands were set to zero (free cooling from cold outdoor air) and in the summer months, all heating demands were also set to zero (free heating from hot outdoor air). Under these conditions a hybrid GSHP system was only economical for the multifamily residential buildings that were considered. For all non-residential buildings considered, although some are cooling dominant, a conventional system was less expensive to install and to operate for twenty years compared to a hybrid-GSHP system when a seasonal control strategy is being implemented.

Heat pump EFT:

- Although heat-pump EFT plays a crucial role in determining the efficiency of the system, the effects of varying the EFT pairs (for heating and cooling operations) 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 requires a larger ground loop which results in higher upfront costs (*vice versa* for reducing upfront costs).

- The largest savings achieved from the ten real buildings analyzed, compared to the base case (optimal EFT pair vs. fixed EFT pair) was only 3.6% for a school located in Toronto, Canada.

CO_2 emissions:

- In a scenario in which both total costs and CO_2 emissions are important, sizing the system based on the optimal shave factor may result in higher CO_2 emissions than desired, whereas sizing the system to a shave factor of 1.0 (for the least CO_2 emissions) might result in high upfront costs than desired. An example would be the high-rise (II) building with an optimal shave factor of 0.23 in which sizing the system to a shave factor of 0.6 would reduce CO_2 emissions, comparable to that of shave factor = 1 (without the high upfront costs for shave factor = 0.6).

- The methods of analysis presented 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 CO_2 emissions for project life greater than twenty years (long term) are similar to those of twenty years operation. For twenty years operation, CO_2 reductions are between 21% and 44% (average reduction of 20,000 kg CO_2 per year).

Carbon taxation:

- Based on a carbon tax of $30 per tonne of CO_2 emitted, a carbon tax increases the operating costs of a hybrid GSHP system. To accommodate the increase in operating costs, for all of

the buildings analyzed the optimal shave factor increased between 0.01 and 0.02, contributing to some reductions in CO_2 emissions and payback periods (especially for the case of a shave factor of 0.0).

- Buildings that are best suited for a hybrid GSHP system from an economics perspective with high TEDM benefit the most from a carbon tax.

- In the analysis in which a carbon tax was not applied, using the optimization methodology outlined in *Alavy et al.* [15] yields CO_2 emission levels similar to that of a *SF* = 1.0. For example, the fast-food restaurant with a shave factor value of 0.62 produces only 8.5% more CO_2 emissions than the minimum possible amount.

Project Life:

- The project life analysis was performed to determine its economic and environmental effects on sizing hybrid GSHP systems. Using the "NPV/operating duration" (NPV per operating year) parameter, to determine the amortized system cost per year, reductions in annual amortized system costs are achieved as the assumed project life increases.

- The economic benefits of increasing a hybrid GSHP's assumed project life (exceeding the break-even point), on average, begins to asymptote at year 50 (and no changes occur at around year 100 or more). This analysis may be of particular interest when government owned buildings or schools are considered, as such buildings infrequently change ownership.

- The same conclusions are also observed for CO_2 emissions. For example, for the case of the fast-food restaurant, when the project life exceeds the break-even point (13 years), the reduction in CO_2 emissions per operating year is the greatest at the operation duration of 30 years (41% or 18,000 kg of CO_2) and begins to level-off thereafter. All buildings analyzed emit no more than 10% CO_2 for project life between twenty and twenty-five years compared to a project life of 100 years.

Building Retrofit:

- For single detached houses, a full GSHP installation meeting all of the building's energy demands can cost $20,000 or more. However, using the methodology outlined in Alavy *et al.* [15], a GSHP sized to meet 37% of House B's (a large 5000 ft^2 house) peak energy

demands can still provide 83.8% TEDM without other retrofit costs. However when the house requires major retrofit costs, including ductwork and major overhaul costs of electric baseboard heaters and window air conditioners, a larger GSHP sized to meet 45% and 90% of House B's peak energy demands and TEDM, respectively, would be required with an extra 14 years of payback period.

- Due to retrofit costs such as ductwork, for building owners with low capital, it may be more economical to use the building's existing systems and improve the building's insulation. Heating demands for House A (a smaller house with 2000 ft^2) and House B were reduced by 24.3% and 33.8%, respectively, when building insulation was improved from 1986 OBC insulation standards of R30 (ceiling) and R13 (wall) to the new OBC standards of R50 and R29, respectively.

- Applying the rough rule-of-thumb ductwork costs for Houses A and B, hybrid GSHP systems remain more economical than the conventional systems (based on a project life of twenty years). However, if insulation costs are considered, hybrid GSHP systems will remain more economical but payback period will exceed twenty years.

- Large buildings such as the school, high-rise A, and office, a hybrid GSHP system is more economical than a conventional system after twenty years of operation. However, the overall benefit depends on the ductwork retrofit costs.

Table 6.1 provides a summary of all the parameters studied giving their effects on the design, payback period and/or feasibility of a hybrid GSHP system.

Table 6.1: Summary of trends based on sensitivity variations

Parameter	Sensitivity Variation	Trend
Discount rate	Increase	• The dollar value for annual savings in subsequent years reduces. As a result, payback period increases. • The payback period was increased by at least 2.3 years due to an increase in discount rate from 4% to 8% (chapter 3.6).
Electricity inflation	Increase	• For cooling dominant buildings, hybrid GSHP systems become more favorable when electricity rates or inflation is increased. • For heating dominant buildings, the low rates for natural gas found in many parts of North America make it uneconomical to install a GSHP system. As electricity rates or inflation is increased, boilers become more favorable than GSHPs.
Natural gas inflation	Increase	• Inflation for natural gas adversely affect the economic viability of boilers (hybrid GSHP systems become a more favorable).
Weather patterns	Warmer	• In warmer weather, cooling demands increases and heating demand decreases. • Due to higher ground temperatures and cooling demands (reduced ground loop efficiency for the cooling mode) substantially larger ground loops are required. • To reduce high upfront costs, the ground loop is downsized and the cooling tower is expanded. • Payback period increases.
Project life	Increase	• Shave factor increases. • Total annual CO_2 emission reduces. • Annual operating cost savings increases.
Carbon tax	Increase	• Payback period for conventional system increases. • Payback period for hybrid GSHP system decreases. • Shave factor increases. • Economical designs with high TEDM benefit more from a carbon tax.
Building insulation (R-value)	Increase	• Building energy demands decreases. • Upfront costs increases and shave factor decreases. • Cost reduction by shave factor parameter reduces.
Conventional system efficiency	Increases	• Economic viability of GSHP system decreases.

6.2 Recommendations

Based on the findings from the analyses performed in this thesis (and in Alavy *et al*. [15, 97]), a general knowledge base of automatically sizing GSHPs as a component of a hybrid system has been achieved. However, the findings are based on vertical hybrid-GSHP systems. As such, there are several questions that have now become subjects of further inquiry:

- To continue expanding the knowledge base of automatically sizing hybrid GSHP systems, similar studies performed thus far should be carried out for other commonly used ground loop configurations such as the horizontal configuration.

- It would also be interesting to investigate the feasibility of combining multiple residential buildings into one district system/common ground loop (*i.e.*, a utility model).

- An investigation on the efficiency of a common water loop system should be investigated.

- Supply mix for power generation varies throughout the day, as such, it is of interest to investigate the effects of time-of-use electricity rates and the variation in the supply mix on CO_2 emissions. The analysis can be further expanded by providing how much CO_2 is produced from each supply mix for each component of a hybrid GSHP system.

- Discount rate and inflation rate are not 1:1 relationship. As such, it is of interest to further test the sensitivity of these parameters.

- The COPs of the cooling tower, heat pump, boiler, soil thermal properties, and local material and installation costs used in this thesis (data courtesy of CleanEnergy^{TM}) can be better quantified for Toronto and other geographical locations.

- The assumed cost of $65/m vertical borehole length is more applicable for large buildings. For smaller buildings, the fixed costs (such as, rental and/or transportation of drilling equipment) of a GSHP installation may result in higher cost and should be better quantified.

- The COP of a heat pump will likely to vary from high to low over a heating or cooling season due to changes in heat pump entering fluid temperature. As such, the heat pump entering fluid temperature analysis can be improved to consider such variations over a season.

- The CO_2 analysis can also be furthered improved by implementing a module for the algorithm to take into account long-term supply mix profiles; in an ideal case, all power generation will be green electricity in the next twenty years.

- Lastly, the findings can be used towards studying the long-term system performance of (and improvement to) the GSHP system at the TRCA house.

6.3 Author's Contributions

The author's contribution can be summarized as follows:

- Studied and explained in detail GSHP technology and the procedure in sizing hybrid GSHP systems
- Assisted in the development of a rigorous computer program in minimizing the net present value of total costs of GSHPs as a component of a hybrid system.
- Co-developed an algorithm, for Chapter 4 of this thesis, capable of determining the optimal entering fluid temperatures of a heat pump (varying inlet temperature). The algorithm can be used as a tool to complement existing ground loop design tools and aid the engineer during the design process.
- Co-developed an algorithm, for the CO_2 analysis in Chapter 4 of this thesis, capable of determining the CO_2 emissions for the hybrid GSHP system. The algorithm can be used as a tool to complement existing ground loop design tools and aid the engineer during the design process.
- An algorithm was developed, for the retrofit analysis in Chapter 5, to consider the total costs of the electric baseboard heating, building envelope retrofit costs, ductwork costs, and other retrofit costs. The algorithm can be used as a tool to complement existing ground loop design tools and aid the engineer during the design process.
- Three studies were performed, a framework was established, as a way of increasing the knowledge base of automatically sizing GSHPs as a component of a hybrid system. The three studies are as follows:
  - A sensitivity analysis (Study #1) was performed to determine the effects of operating costs, inflation, geographical location within North America, and a seasonality control strategy on sizing hybrid GSHP systems.
  - The effects of EFT for heat pump, CO_2 emissions and carbon taxation on a hybrid GSHP system were studied for a variety of commercial installations (Study #2).

o A retrofit analysis (Study #3) was performed to determine the economic viability of retrofitting a hybrid GSHP system for electrically heated (baseboards) and cooled (air-conditioners/cooling towers) residential and commercial buildings.

# Appendix A
Building Loads
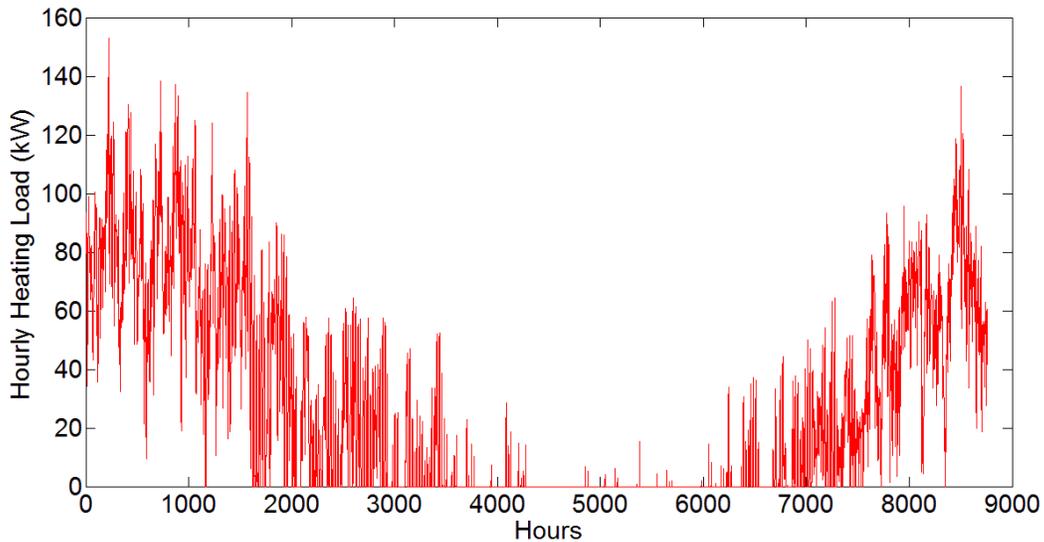
Figure A.1: Hourly heating loads for a hospital located in Toronto, Ontario. The hours in a year (8760 hours in a year) are along the abscissa. The peak and total heating loads are 153 kW and 243,000 kWh respectively.
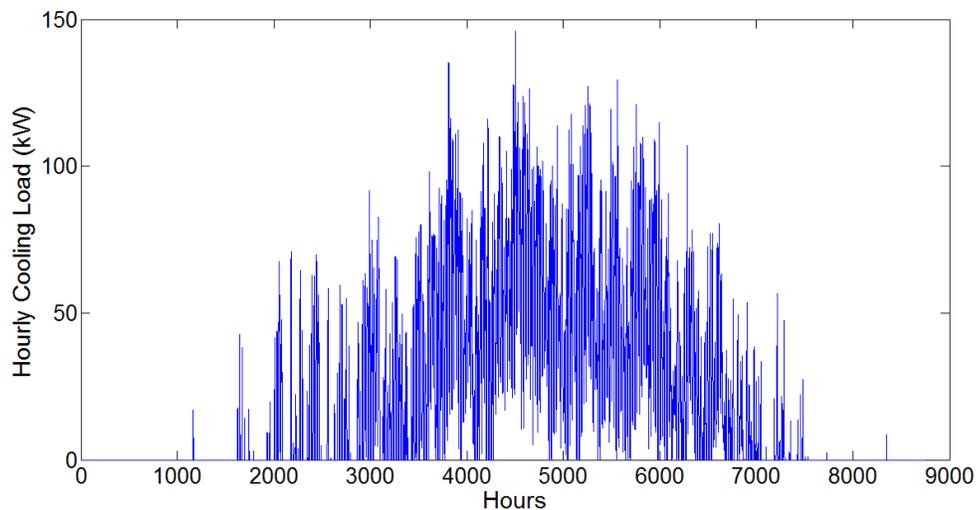

Figure A.2: Hourly cooling loads for a hospital located in Toronto, Ontario. The hours in a year (8760 hours in a year) are along the abscissa. The peak and total cooling loads are 146 kW and 175,000 kWh respectively.
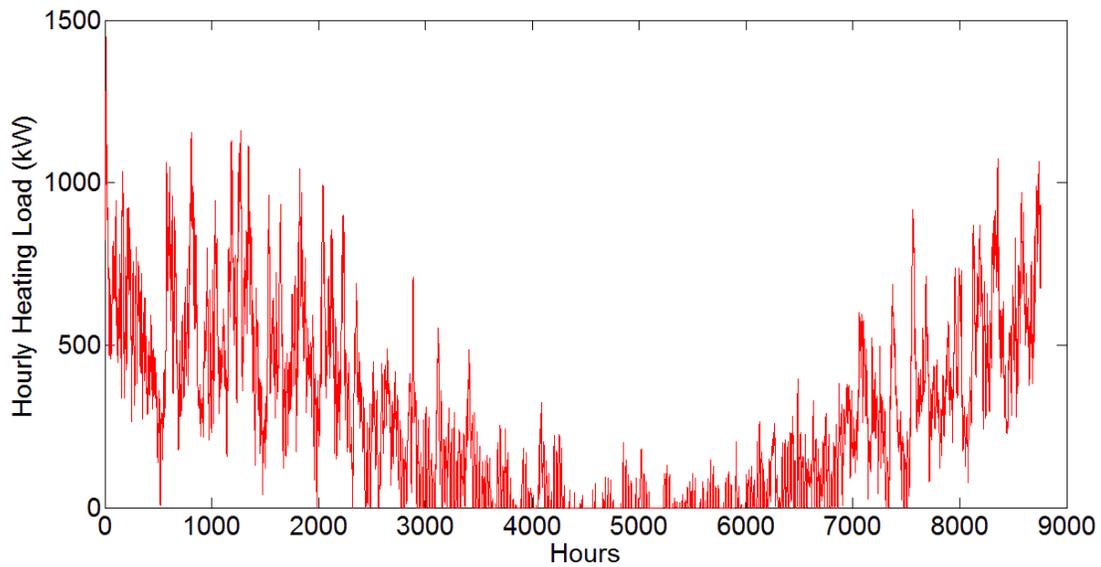
Figure A.3: Hourly heating loads for an office building located in Toronto, Ontario. The hours in a year (8760 hours in a year) are along the abscissa. The peak and total heating loads are 1,449-kW and 2,396,500 kWh respectively.
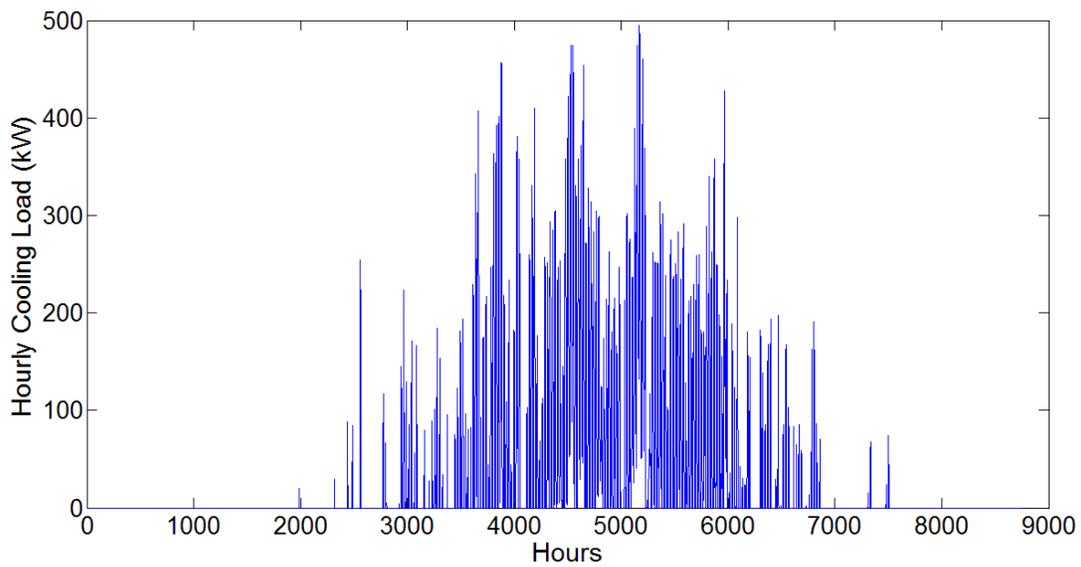

Figure A.4: Hourly cooling loads for an office building located in Toronto, Ontario. The hours in a year (8760 hours in a year) are along the abscissa. The peak and total cooling loads are 495 kW and 279,200 kWh respectively.
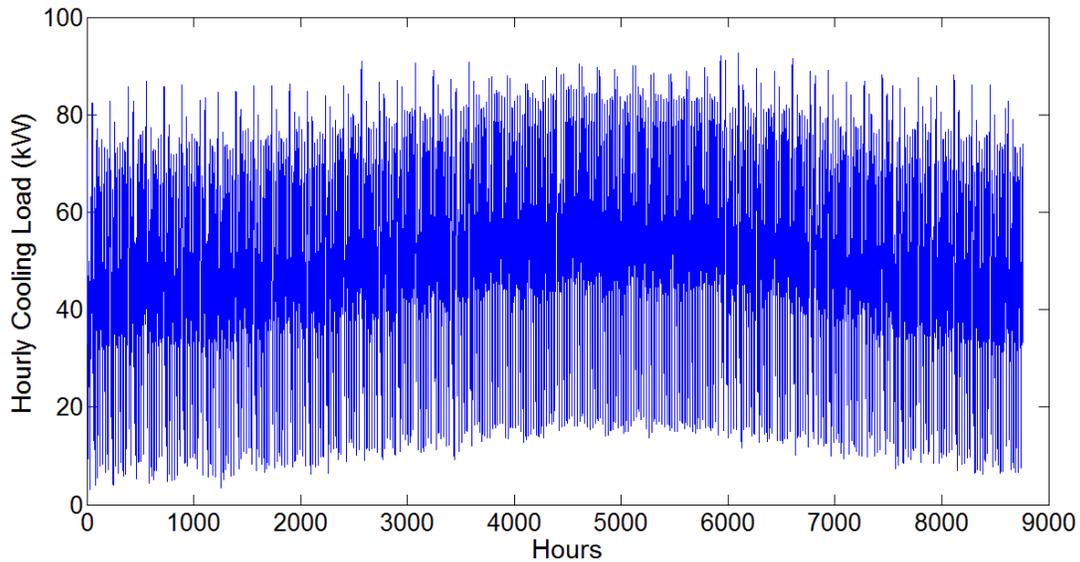
Figure A.5: Hourly cooling loads for a restaurant located in Toronto, Ontario. The hours in a year (8760 hours in a year) are along the abscissa. The peak and total cooling loads are 93 kW and 430,950 kWh respectively (No hourly heating loads).
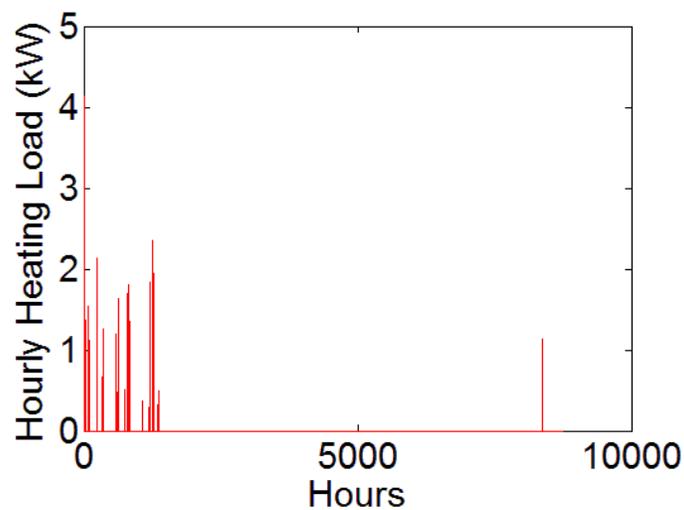

Figure A.6: Hourly heating loads for a fast-food restaurant located in Toronto, Ontario. The hours in a year (8760 hours in a year) are along the abscissa. The peak and total heating loads are 4 kW and 40 kWh respectively.
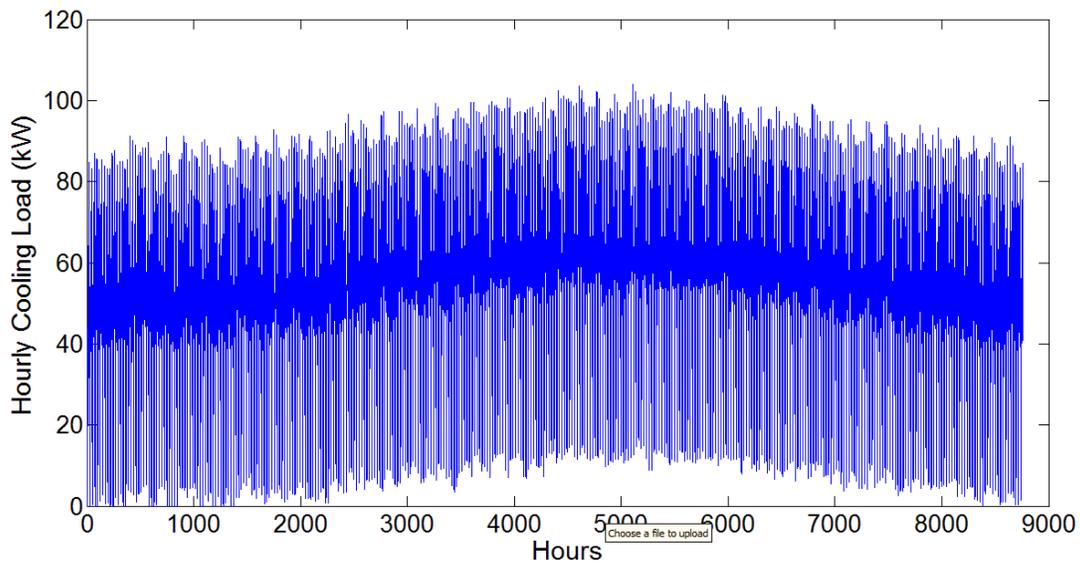
Figure A.7: Hourly cooling loads for a fast-food restaurant located in Toronto, Ontario. The hours in a year (8760 hours in a year) are along the abscissa. The peak and total cooling loads are 104 kW and 475,150 kWh respectively.
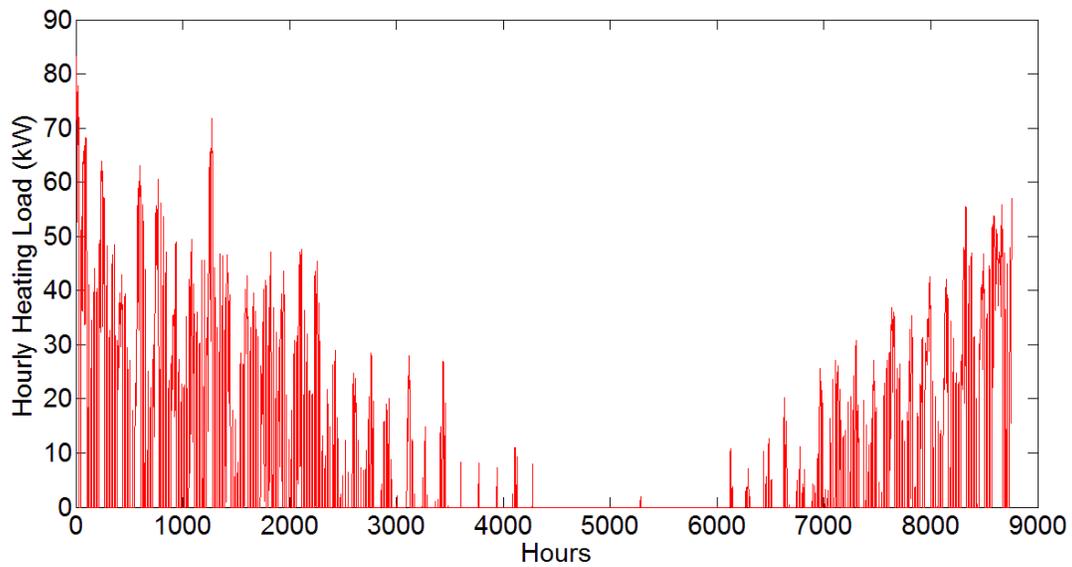

Figure A.8: Hourly heating loads for a transit facility located in Toronto, Ontario. The hours in a year (8760 hours in a year) are along the abscissa. The peak and total heating loads are 83 kW and 66,460 kWh respectively.

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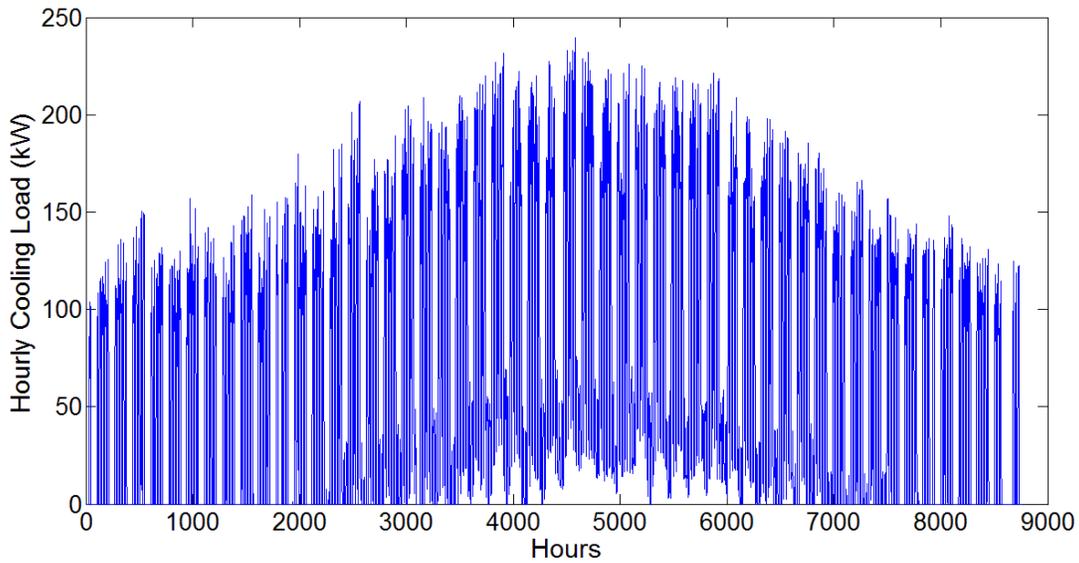
Figure A.9: Hourly cooling loads for a transit facility located in Toronto, Ontario. The hours in a year (8760 hours in a year) are along the abscissa. The peak and total cooling loads are 239 kW and 606,220 kWh respectively.
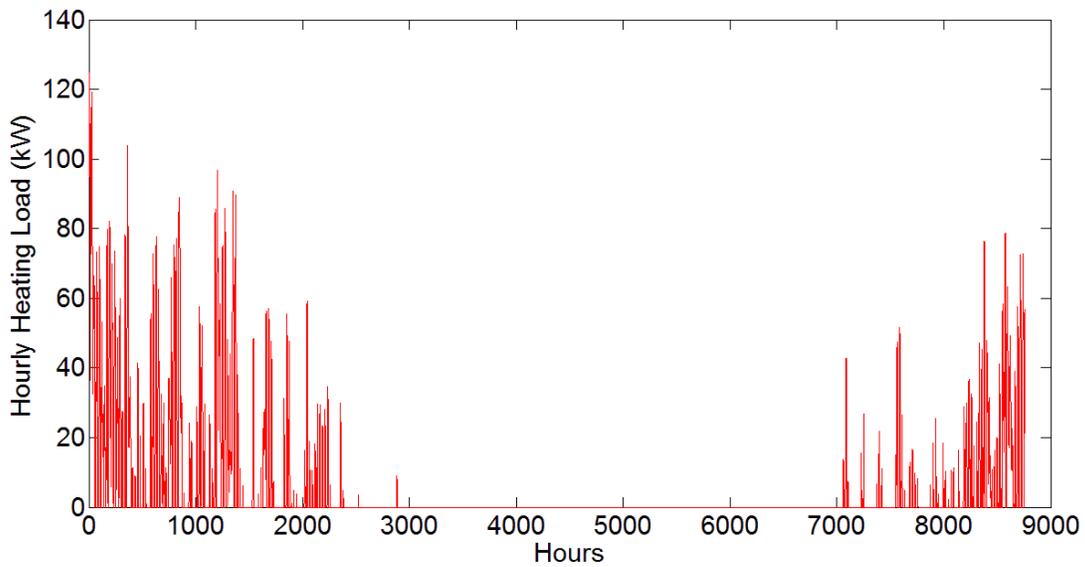

Figure A.10: Hourly heating loads for a mid-rise multi-residential building located in Toronto, Ontario. The hours in a year (8760 hours in a year) are along the abscissa. The peak and total heating loads are 125 kW and 50,290 kWh respectively.
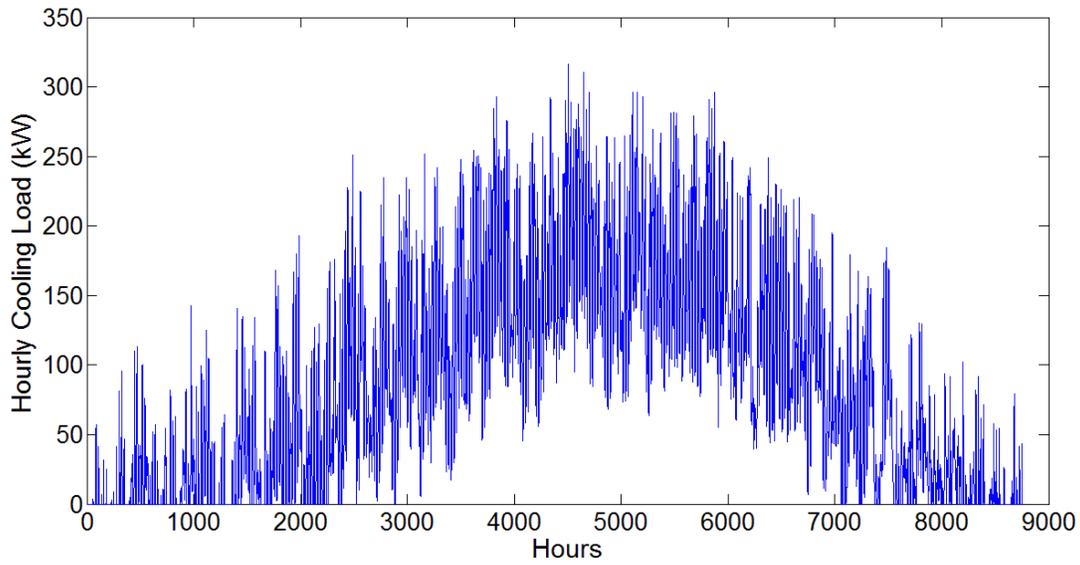
Figure A.11: Hourly cooling loads for a mid-rise multi-residential building located in Toronto, Ontario. The hours in a year (8760 hours in a year) are along the abscissa. The peak and total cooling loads are 316 kW and 765,510 kWh respectively.
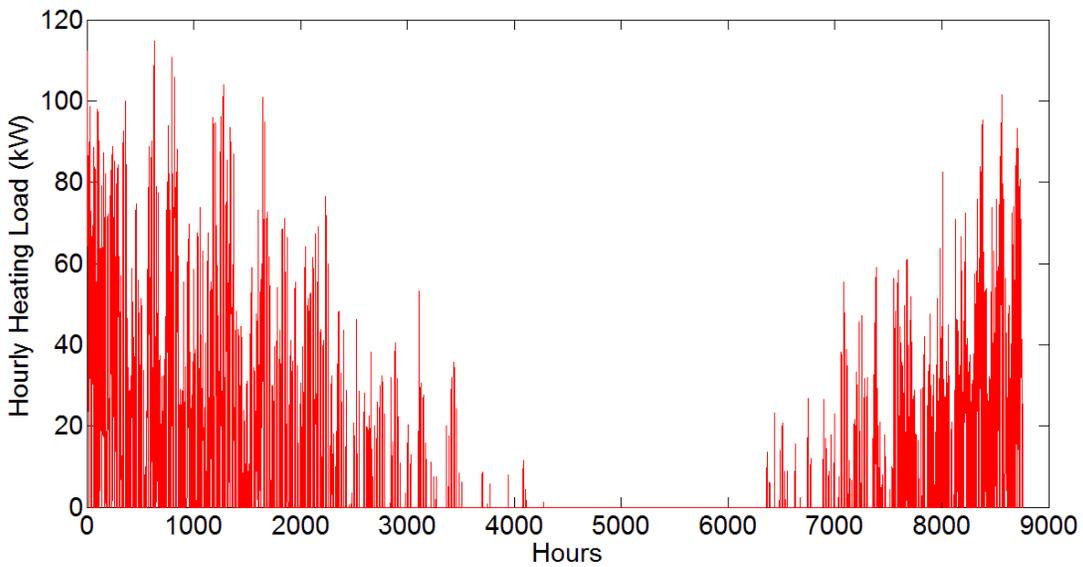
Figure A.12: Hourly heating loads for High-rise A (multi-residential building) located in Toronto, Ontario. The hours in a year (8760 hours in a year) are along the abscissa. The peak and total heating loads are 114 kW and 8,700,000 kWh respectively.

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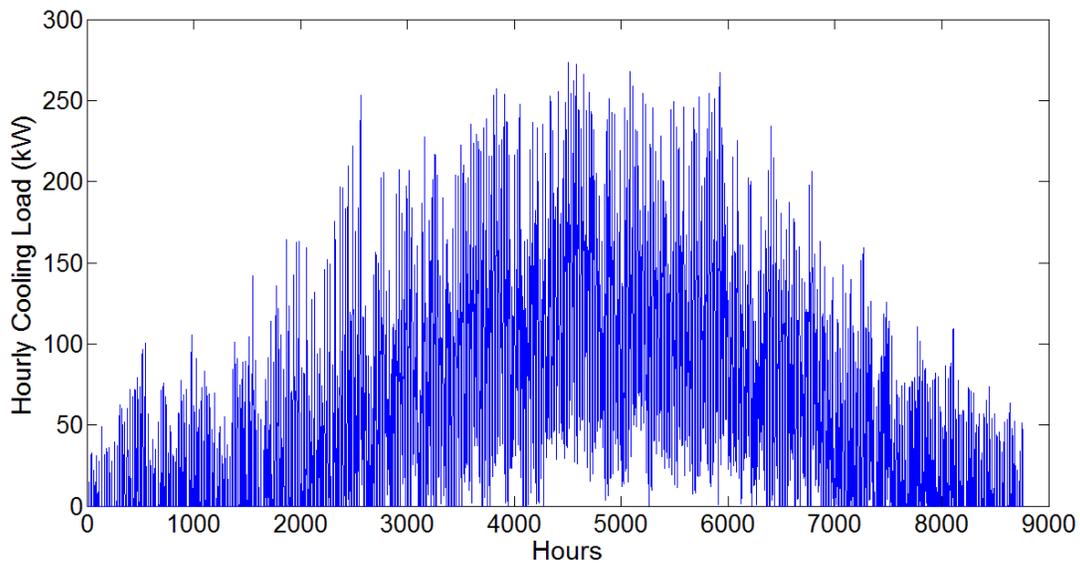
Figure A.13: Hourly cooling loads for High-rise A (multi-residential building) located in Toronto, Ontario. The hours in a year (8760 hours in a year) are along the abscissa. The peak and total cooling loads are 273 kW and 518,000 kWh respectively.
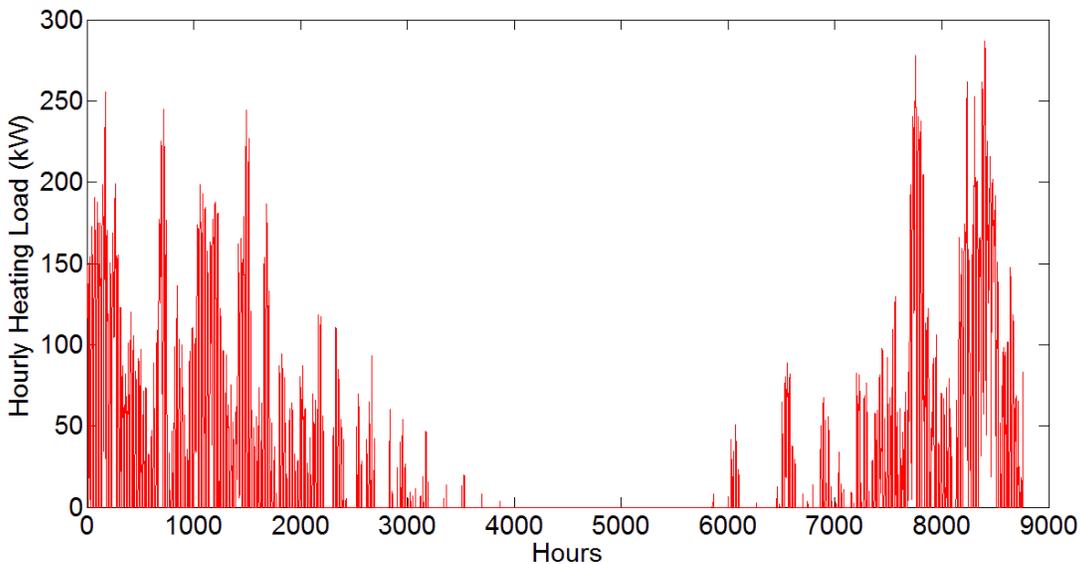
Figure A.14: Hourly heating loads for High-rise B (multi-residential building) located in Toronto, Ontario. The hours in a year (8760 hours in a year) are along the abscissa. The peak and total heating loads are 287 kW and 240,000 kWh respectively.
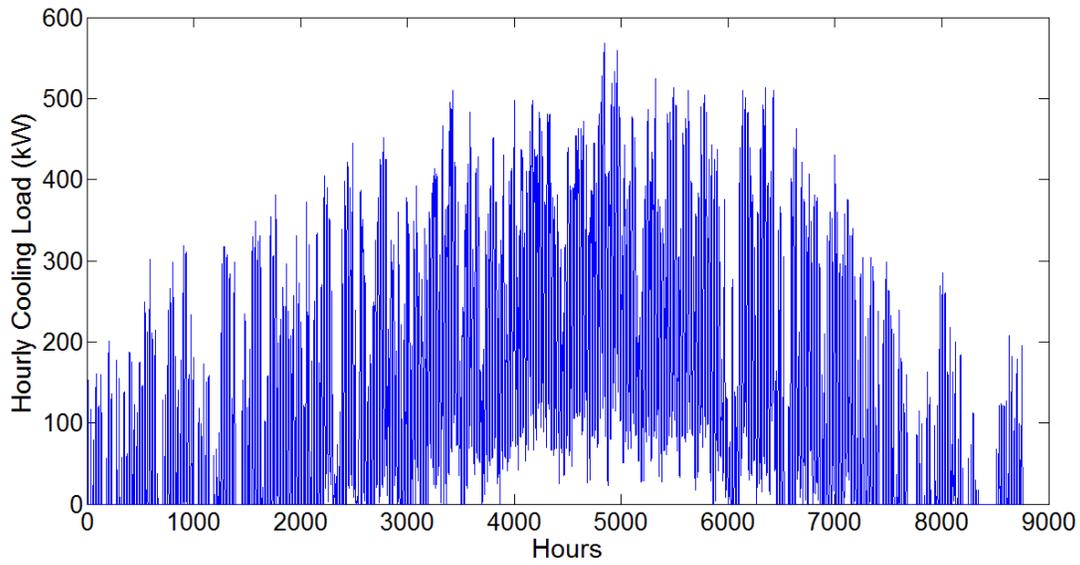
Figure A.15: Hourly cooling loads for High-rise B (multi-residential building) located in Toronto, Ontario. The hours in a year (8760 hours in a year) are along the abscissa. The peak and total cooling loads are 568 kW and 1,140,000 kWh respectively.
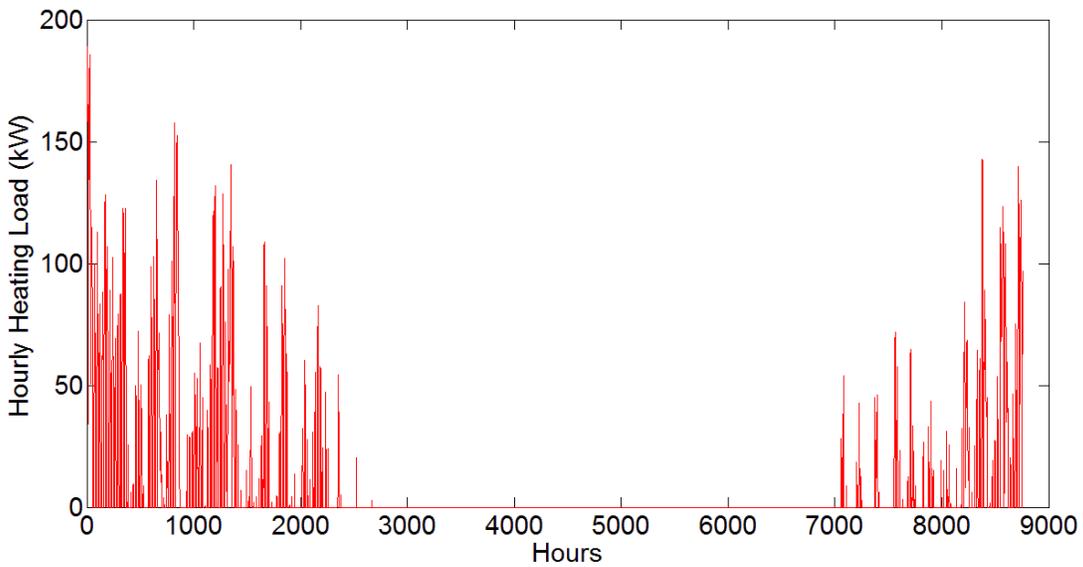
Figure A.16: Hourly heating loads for High-rise C (multi-residential building) located in Toronto, Ontario. The hours in a year (8760 hours in a year) are along the abscissa. The peak and total heating loads are 189 kW and 80,000 kWh respectively.
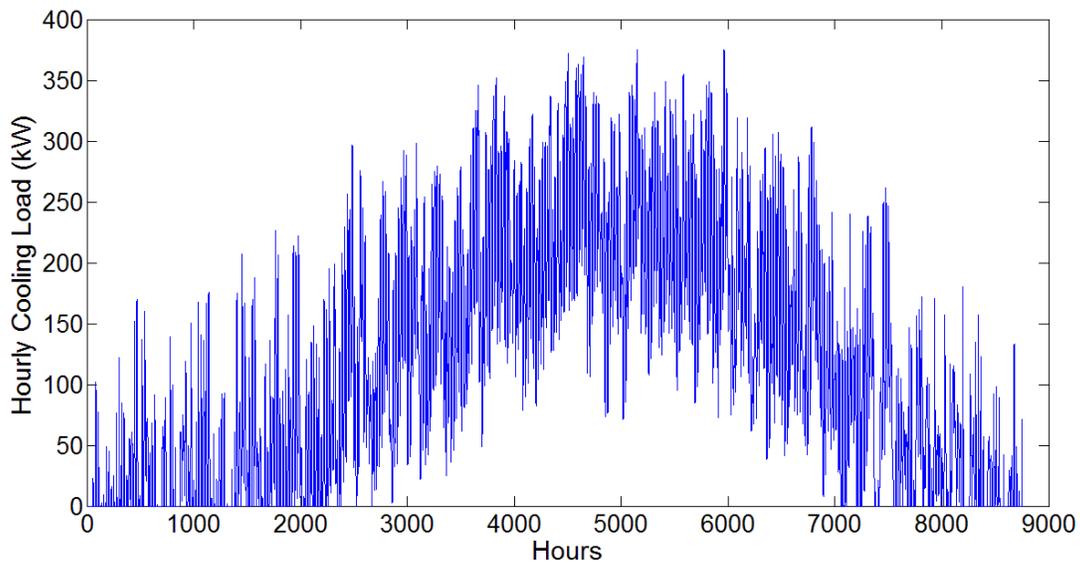
Figure A.17: Hourly cooling loads for High-rise C (multi-residential building) located in Toronto, Ontario. The hours in a year (8760 hours in a year) are along the abscissa. The peak and total cooling loads are 375 kW and 1,030,000 kWh respectively.
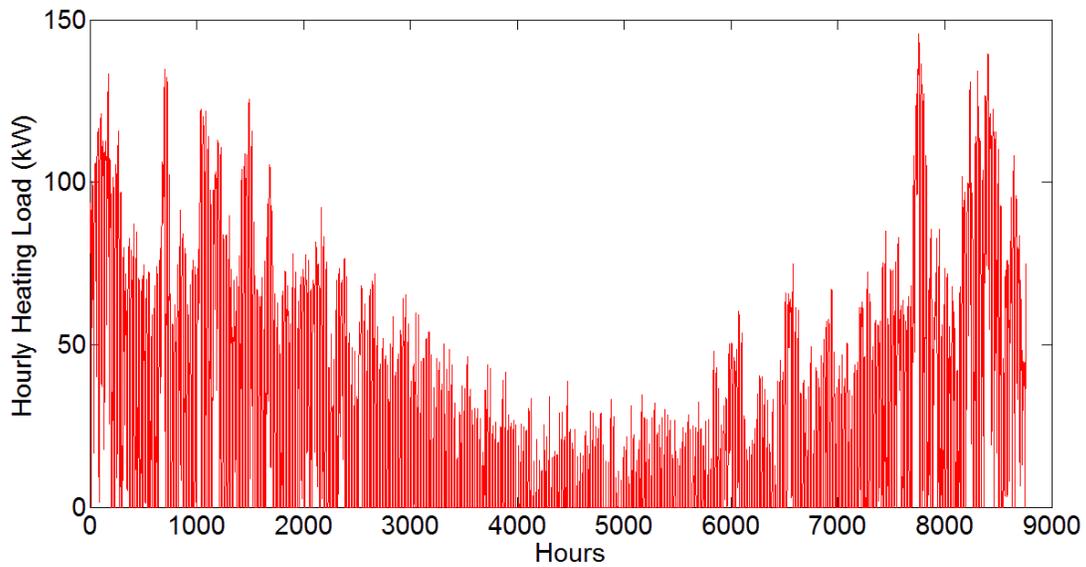
Figure A.18: Hourly heating loads for a school located in Toronto, Ontario. The hours in a year (8760 hours in a year) are along the abscissa. The peak and total heating loads are 146 kW and 247,180 kWh respectively.
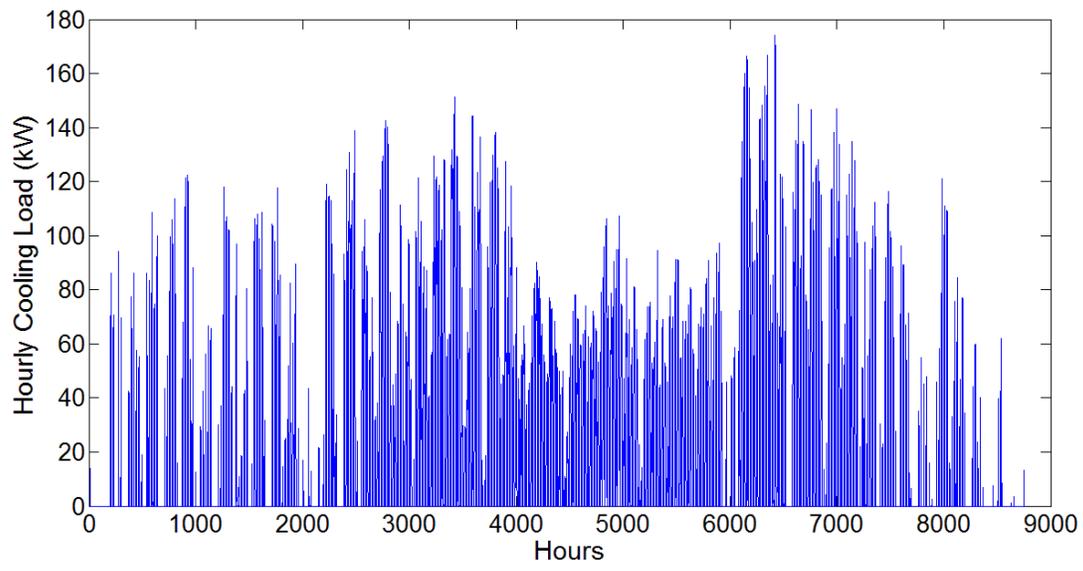
Figure A.19: Hourly cooling loads for a school located in Toronto, Ontario. The hours in a year (8760 hours in a year) are along the abscissa. The peak and total cooling loads are 174 kW and 203,350 kWh respectively.

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