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Optimization of Hybrid Ground Source Heat Pump System Design

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OPTIMIZATION OF HYBRID GROUND SOURCE HEAT PUMP SYSTEM DESIGN

By
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ABSTRACT

OPTIMIZATION OF HYBRID GROUND SOURCE HEAT PUMP SYSTEM DESIGN

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The lack of a computerized approach to optimally size hybrid Ground Source Heat Pump (GSHP) systems leaves a glaring gap in our knowledge of their benefits when utilized in an urban environment. To address this issue, this study introduces two new, robust methodologies, one for determining optimal GSHP size as part of a hybrid system for an individual building and one for assessing the appropriateness of combining multiple buildings onto a single hybrid GSHP system. Both methodologies simultaneously consider heating and cooling and are applicable to residential, commercial and industrial buildings that are either heating or cooling dominant. Using these methodologies can result in significant reductions in initial costs of installation, payback period, and operation costs, when compared to following rules of thumb or using non-hybrid systems. In most cases, when optimization is performed, the GSHP meets very large portions of the total annual heating and cooling demand of buildings.

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NOMENCLATURE

English Letter Symbols

CD	Cooling Dominant
C_{fc} and C_{fh}	Correction factors that account for the amount of heat rejected or absorbed by the heat pumps. The values depend on the respective EER and COP of the units and are provided in the design manual.
CF	Cash Flow
COP	Coefficient of Performance of a heat pump
EER	Energy Efficiency Ratio
$\mathrm{EFLH_c}$ and $\mathrm{EFLH_h}$	Annual equivalent full-load cooling and heating hours (Hours)
$\mathrm{F_{sc}}$	Short-circuit heat loss factor, which accounts for heat loss due to heat transfer between the two different legs of the U-tube in the borehole.
GSHP	Ground Source Heat Pump
HD	Heating Dominant
HVAC	Heating, Ventilation, and Air Conditioning
IR	Interest Rate
L	Ground loop length
L_c	Required ground-loop length to meet the shaved cooling demand (m)
L_h	Required ground-loop length to meet the shaved heating demand (m)
n	Number of years
NPV	Net Present Value of total costs
PBP	Payback Period
PLF_m	Part-load factor during design month, which represents the ratio of equivalent full load hours during the design month to the total number of hours in that month $PLF_m = \frac{\bar{q}}{q_{max}}$, where $\bar{q}$ and q_{max} are the average demand and peak demand for the design month, respectively.
q_a	Net annual average heat transfer to the ground (Watts)
q_{lc}	Building peak cooling demand (Watts)
q_{lh}	Building peak heating demand (Watts)

R_{ga}	Effective thermal resistance of the ground; annual pulse, which accounts for transient heat transfer from the borehole wall to the undisturbed ground temperature corresponding to annual ground loads (for calculation details the reader is referred to [21]) (m·K/W)
R_{gd}	Effective thermal resistance of the ground; daily pulse, which accounts for transient heat transfer from the borehole wall to the undisturbed ground temperature corresponding to daily ground loads (for calculation details the reader is referred to [21]) (m·K/W)
R_{gm}	Effective thermal resistance of the ground; monthly pulse, which accounts for transient heat transfer from the borehole wall to the undisturbed ground temperature corresponding to monthly ground loads (for calculation details the reader is referred to [21]) (m·K/W)
R_b	Thermal resistance of the borehole; including the convective resistance inside each tube, the conduction resistance for each tube, and the grout resistance. (For calculation details the reader is referred to [21]) (m·K/W)
t_g	Undisturbed ground temperature (°C)
t_p	Temperature penalty (change in ground temperature over a long period due to the thermal interference between adjacent boreholes), (For calculation details the reader is referred to [21]) (°C)
t_{wi}	Water temperature at heat pump inlet (°C)
t_{wo}	Water temperature at heat pump outlet (°C)
t	time
TDM	Total Demand Met by the GSHP.

Greek Letter Symbols

α	Portion of the peak cooling demand met by the GSHP.
β	Portion of the peak heating demand met by the GSHP.
γ	Ratio of the sum of the NPVs of the individual buildings to the NPV of a combined building, comprising those same individual buildings.
γ_{cutoff}	Minimum value of γ for statistical analysis.

CHAPTER 1

INTRODUCTION

1.1 Motivation

Global warming has been recognized as a major threat to the future, the main cause being the dependency on fossil fuels in most residential, industrial, and commercial applications [1]. Sustainable energy technologies offer potential solutions to counteract the effects of climate change. Wind, biomass, solar, hydro, and geothermal energies are common examples of sustainable energy technologies that produce little to no greenhouse gas (GHG) emissions [2].

It has been documented that the ground temperature is relatively constant below a certain depth [3]. This is because high thermal inertia of the soil diminishes the temperature fluctuations in higher depths of the ground. In addition, there exists a time lag between the temperature fluctuations at the ground surface and at a sufficient depth of the ground. Due to this time lag, the ground temperature will always be higher (lower) than the ambient temperature in winter (summer).

Taking advantage of this abundant, free energy storage in the ground, ground source heat pump (GSHP) systems are known as a relatively new alternative energy technology that can provide heating and cooling for residential, commercial, and industrial buildings. Significantly reducing energy usage, these systems have proven to be an environmentally friendly, viable alternative to conventional, separate heating and cooling systems [4]. However, longer payback periods, lesser return on investment, and higher upfront costs of GSHP systems as compared to their conventional alternatives, create economic obstacles to their further penetration into the market. The unappealing short-term economics of GSHP systems is more tangible when it comes to their installation in large residential, commercial and industrial buildings [5]. Hybrid GSHP systems offer a solution to decrease the initial costs and to make GSHP systems more economically viable. Hybrid systems employ GSHP for providing base building load needs, and conventional systems for supplementing peak demands. The capacity of a GSHP in a hybrid system is usually determined by following rough rules of thumb, and then calculations are made to test for economic viability. The literature lacks a rigorous mathematical and computational approach to optimally size hybrid GSHP systems.

1.2 Objectives

The lack of a computerized approach to optimally size hybrid GSHP systems leaves a glaring gap in our knowledge of their benefits when utilized in an urban environment. To address this issue, the first objective is to introduce a robust methodology for determining optimal GSHP size as part of a hybrid system for an individual building. The methodology simultaneously considers both heating and cooling and is applicable to residential, commercial and industrial buildings that are either heating or cooling dominant. The second objective will be to assess the potential economic benefits of combining multiple buildings onto a single GSHP system using a common water loop in a so-called "utility model" of heating and cooling, in which a utility may install a large hybrid GSHP system and then sell energy to building owners. For this purpose, a new methodology that enhances and utilizes the first methodology is introduced. The two methodologies will be used to systematically determine the viability of utilizing hybrid GSHP systems in an urban environment. They can be used to significantly reduce the initial costs of installation, payback period, and operation costs, when compared to following rules of thumb or using non-hybrid systems.

1.3 Outline of the thesis

This thesis includes data and information from one published and one submitted journal article at the time of writing, each addressing one of the main objectives described above. The following chapters are organized as follows:

Chapter 2 starts with a literature review on building energy modeling programs and an introduction to GSHP systems. The chapter ends with a literature review on hybrid GSHP systems and those systems that are coupled to a common water loop through a heat exchanger.

Chapter 3 deals with explaining the two methodologies described in the two objectives above.

In Chapter 4, detailed results of implementing and testing the methodologies are presented, and new findings are presented that are applicable to the geothermal heating and cooling industry.

Finally, the overall conclusions of the entire thesis are presented in Chapter 5.

CHAPTER 2

LITERATURE REVIEW

2.1 Building Energy Modeling Programs

Many programs have been developed in an attempt to model how much energy a building consumes. The focus of these programs may be to model certain components of a building only, such as windows or walls, or they may intend to simulate how much energy the whole building consumes. For instance, THERM [6] is a program developed at Lawrence Berkeley National Laboratory (LBNL) in the United States that can be used to model two-dimensional heat transfer effects in building components such as windows, and walls. Whereas DOE-2 [7], which is developed by James J. Hirsch & Associates (JJH), is a program that models heating, cooling, lighting, ventilation, etc. of a whole building. Here the focus will only be on the programs that simulate the whole building.

When using a building energy simulation program, the user provides a series of inputs, such as the building geometry, weather data patterns for a given locale, the occupancy patterns, thermostat settings, and the insulating materials. Using these inputs and applying sophisticated building energy use simulation techniques, such as the Heat Balance method (HB) [5] and the Radiant Time Series method (RTS) [7], the programs calculate the annual building heating and cooling demands, and can do so providing the information on an hourly basis throughout the year (*i.e.*, 8760 heating demands and 8760 cooling demands). Note that the discussion on the building energy use simulation techniques is beyond the scope of this thesis. For more information, the reader is referred to [5].

Often, short time steps, such as one-hour intervals, are used to calculate annual building heating and cooling demands. Calculating building demands with a time step of one hour will result in finding the hourly building heating and cooling demands throughout a year. Trading the expense of more computational time, using smaller time steps may lead to results that are more accurate.

Three building energy simulation programs will be discussed here, eQuest [8], TRNSYS [9], and EnergyPlus [10]. The reason why these programs have been selected is that they are commonly used in industry and academia.

2.1.1 eQuest

The United States Department of Energy funded DOE-2 [7] to provide a free building energy modeling program. eQuest [8] is one of many user interfaces built to use with the DOE-2 engine. It has been claimed in the literature that eQuest [8] is the most commonly used building energy modeling program in North America [11]. It has a series of input screens that help the user to describe the building characteristics such as geometry, occupancy pattern, insulating materials, enclosure, weather patterns, HVAC systems and plants. The output that the program provides, which is a summary of the annual building energy consumption, is easy to understand and clear. It also outputs a spreadsheet file with the hourly building heating and cooling demands in BTUs.

Although eQuest [8] is very user-friendly, it is not able to model newer system configurations such as radiant heating and cooling, or solar preheating [11]. eQuest [8], like many other DOE-2 [7] based programs, is very popular in industry since it is user-friendly and free. However, poor documentation, and limited ability to model newer systems are the disadvantages associated with using the program.

2.1.2 TRNSYS

TRNSYS [9] was developed at the University of Wisconsin – Madison in 1975. The program models a building as a series of components in a modular structure, which will allow the user to either use a library of pre-defined components or create their own components.

TRNSYS [9] has a vast library of components that includes models for many different HVAC systems. Some of the components include solar thermal collectors, photovoltaic systems, and heat recovery systems. If a model is unavailable in the library, users can create their own component models, though, they must have some programming skills. The library allows users to model far more systems than are available in eQuest [8]. For example, unlike eQuest [8], TRNSYS [9] can model various forms of radiant heating and cooling systems.

2.1.3 EnergyPlus

EnergyPlus [10] was developed in the University of Illinois in 2009. The building creation process is more complicated in EnergyPlus [10] than in eQuest [8] and TRNSYS [9]. This complexity is because of the lack of a good graphical user interface for EnergyPlus [10]. As with TRNSYS [9], EnergyPlus [10] has a modular structure so that if users wish to create a new system, they can add system modules.

There are some accurate models in EnergyPlus [10] that cannot be found in other programs. For instance, it has a slab and basement program to model heat transfer from the ground. In addition, EnergyPlus [10], like TRNSYS [9], has a good library of models for new technologies which include solar hot water systems, heat recovery, and demand controlled ventilation. The disadvantages associated with EnergyPlus [10] are that this program does not output building demands and is more difficult to use than TRNSYS [9] and DOE-2 [7] as it lacks a graphical user interface.

2.2 Ground Source Heat Pump Systems

2.2.1 Introduction

Heat pumps are devices that transfer heat from a low-temperature source to a high-temperature one using electrical or mechanical energy [12]. The objective of a heat pump is to maintain a heated environment, such as a building interior, at a higher temperature than its surroundings. This is done by absorbing heat from a low-temperature medium, such as air or water, and supplying the heat to a high-temperature environment, such as a house. A schematic representation of how a heat pump works is shown in Fig. 2.1. The performance of a heat pump is measured by its coefficient of performance (COP) which is calculated by Eq. (2.1):

$$\mathrm{COP}_{\mathrm{heat\ pump}} = \frac{\mathrm{Heat\ Supplied}}{\mathrm{Required\ Work\ Input}} \tag{2.1}$$

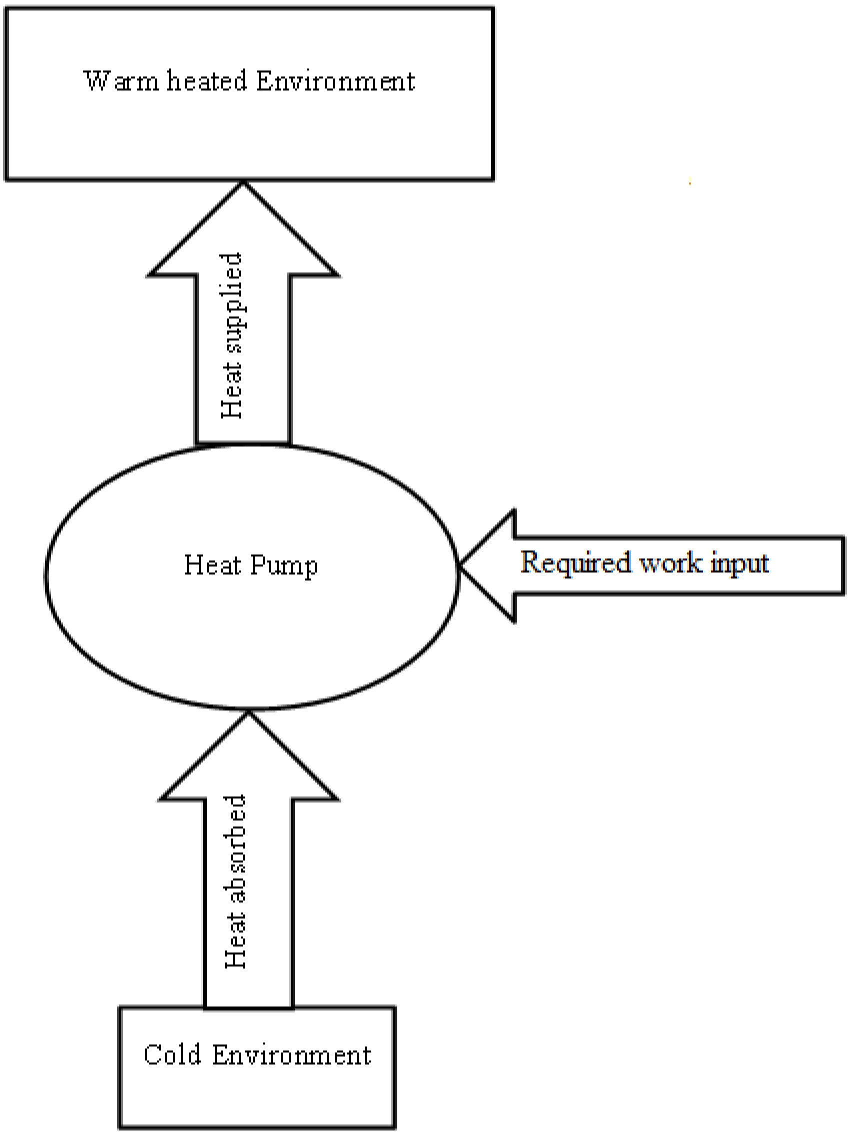

Figure 2.1: Schematic representation of the working principle of a heat pump showing types and directions of energy inputs and outputs

Heat pumps that use the cold outside air as the low-temperature source in winter are referred to as air-source heat pumps. The COP of such heat pumps is about 3.0 at design conditions [12], which means that for a unit of work input there are three units of heat supplied. Air-source heat pumps are not suitable for cold climates as their COP significantly drops when temperatures are below the freezing point. In such cases, a ground source heat pumps (GSHP) that uses the ground as the heat source can be a better option. Utilizing the ground as the heat source is advantageous because the ground temperature is relatively constant below a certain depth. The variation of ground temperature at various depths in a borehole drilled in Nicosia, Cyprus [13] is shown in Fig. 2.2. The blue line represents a typical winter day and the red line represents a typical summer day. As is evident from Fig. 2.2, the ground temperature is relatively constant below a depth of 5 m all year.

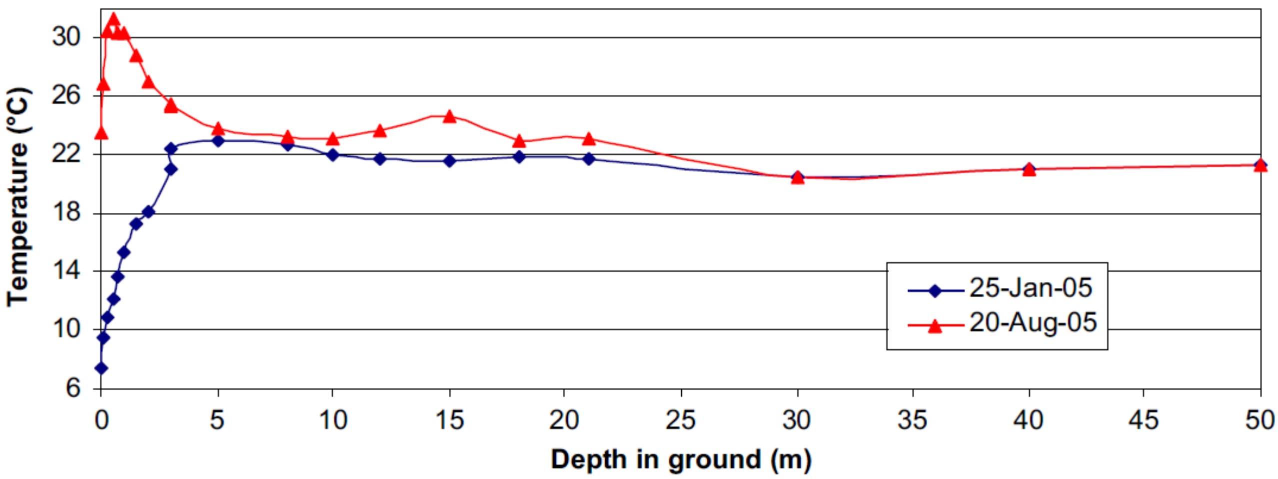

Figure 2.2: Ground temperature variations with depth for a borehole in Nicosia, Cyprus (reproduced from [13])

GSHPs are up to 45% more efficient than air source heat pumps, however, they are more expensive to install. The COP of GSHPs is about 4.0 [12]. GSHPs are used in the cold season to extract heat from the warm ground and pump it into the space considered. In the hot season, this process will be reversed and the heat pump will extract heat from the space and discharge it to the relatively cold ground [13]. The fact that a GSHP can also work in both heating and cooling modes is advantageous because it eliminates or reduces the need for utilizing separate heating and cooling systems.

GSHPs consist of three main elements, a schematic of which is shown in Fig. 2.3:

1- The ground loop
2- The heat pump
3- The heating/cooling distribution system.

A brief description of each element is presented hereafter:

A loop of pipes that is buried in the ground is called the ground loop. The pipes usually make a closed circuit. They are filled with water plus antifreeze. The mixture is pumped through the ground loop to absorb heat from or discharge heat to the ground.

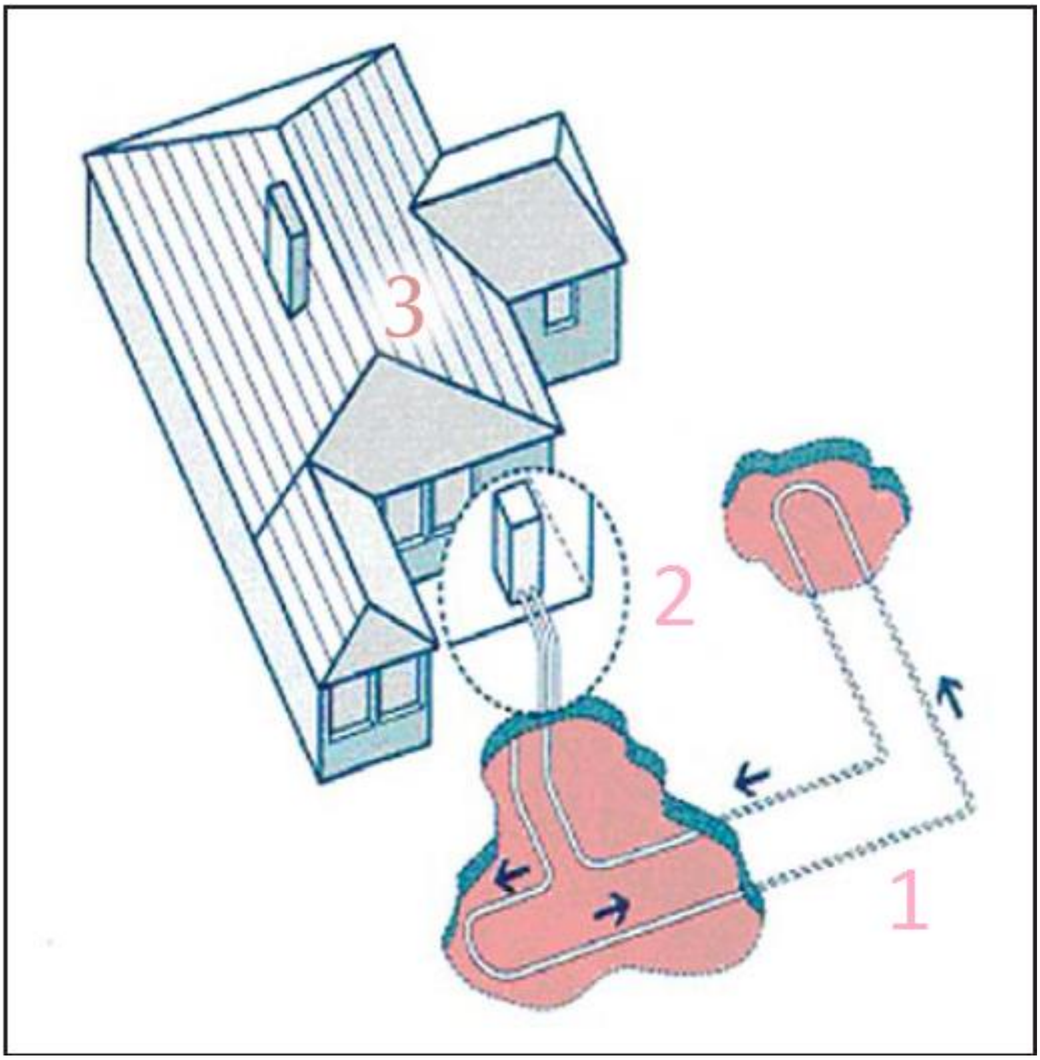

Figure 2.3: Three major parts of a GSHP system showing the locations of the ground loop (1), the heat pump (2) and the heating/cooling distribution system (3) (adopted from [14])

The heat pump has four main parts: the evaporator, the compressor, the condenser, and the expansion valve. It transfers the heat between the heating/cooling distribution system and the ground loop. It is considered as the main block of a GSHP system. Most commonly, water-to-air heat pumps are used in GSHP systems. The reason why these types of heat pumps are called “water-to-air” is because the fluid that carries heat to and from the ground loop is a mixture of water and antifreeze while the fluid that distributes the heat to the building is air. Water-to-air heat pumps range in size from 3.5 kW to 35 kW of cooling capacity [14].

The heat pump works on the same cycle as a refrigerator. The only difference between a GSHP and a refrigerator is that a GSHP can operate on both heating and cooling modes while a refrigerator only operates in cooling mode.

The heating-mode cycle of a heat pump is shown schematically in Fig. 2.4.

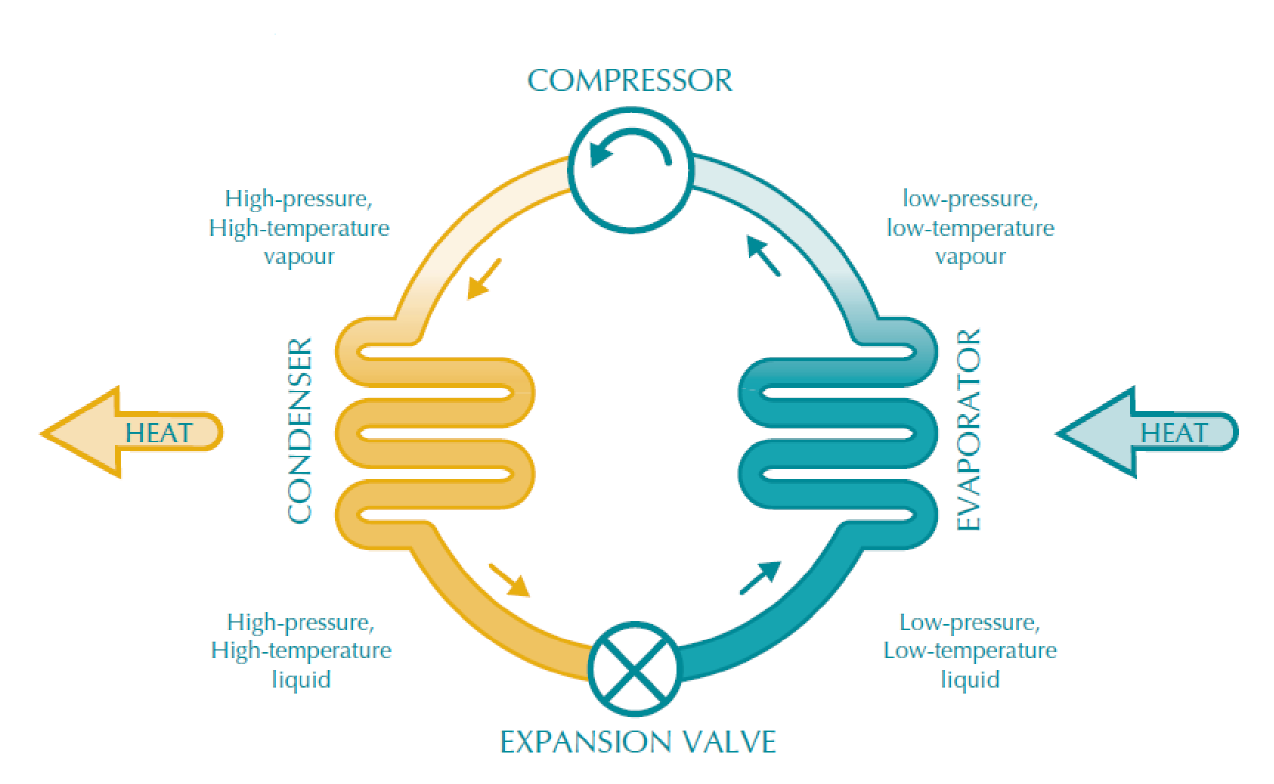

Figure 2.4: Heating-mode operation of a heat pump (adopted from [14]).

In heating mode, the heat pump or here a GSHP operates as follows: "hot" antifreeze solution coming from the ground loop passes through the first heat exchanger called the evaporator. A stream of cold liquid refrigerant that is at the other side of the evaporator cools the "hot" antifreeze solution. Gaining heat from the "hot" antifreeze solution, the cold refrigerant evaporates and turns into a gaseous, low-pressure, low-temperature fluid. The gaseous, low-pressure, low-temperature refrigerant then passes into a compressor. The compressor raises the refrigerant's pressure and thus its temperature. Now, the gaseous, high-pressure, high-temperature refrigerant passes through the second heat exchanger, namely the condenser. In water-to-air heat pumps, there exists an air-coil through which air is blown by a fan to cool down the refrigerant. Gaining heat from the refrigerant, the "hot" air will heat the building. Losing heat to the air, the gaseous, high-pressure, high-temperature refrigerant condenses and becomes a liquid with a high pressure and temperature. Then, it passes through an expansion valve and loses its high pressure and consequently its high temperature. The cycle starts over with a low-pressure, low-temperature liquid refrigerant. In cooling mode, a reversing valve inside the GSHP reverses the cycle.

Consequently, the first heat exchanger explained above will act as the condenser and the second heat exchanger will act as the evaporator.

The last component of a GSHP system is the heating/cooling distribution system. This system delivers heating or cooling from the heat pump to the building. It usually takes the form of an air duct distribution system, under floor heating and cooling or radiators.

2.2.2 Types of Ground Heat Exchangers

Two general types of GSHPs are usually discussed in the literature: open loop and closed loop [13]. Ground water, in open loop systems, is directly used to heat or cool a building. In these systems, one well is used to extract the ground water from the ground while another well is employed to inject the water back into the ground, as shown in Fig. 2.5.

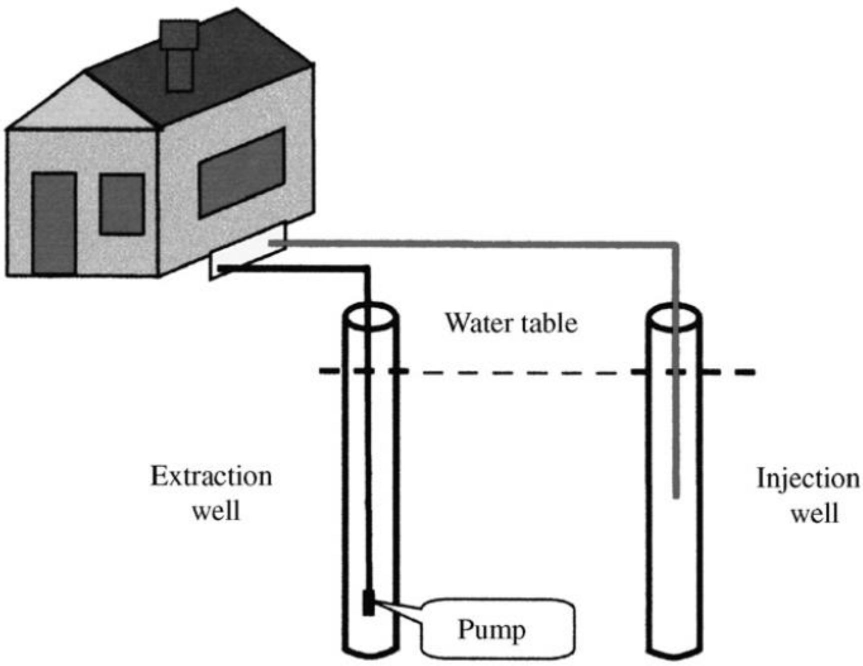

Figure 2.5: Schematic representation of an open loop GSHP system (reproduced from [13])

In closed loop GSHPs, a series of pipes is buried underground circulating the mixture of water plus antifreeze. The water and antifreeze mixture is never discharged out of the system; rather it travels back and forth between the ground and the heat pump.

Closed loop GSHP systems are further classified based upon their configuration as horizontal, vertical, and slinky. Horizontal ground heat exchangers, shown in Fig. 2.6, are used when sufficient ground space is available. In these types of systems, pipes can be connected together in series or parallel and are 35-60 m long per kW of cooling or heating [13]. Vertical ground heat exchangers or borehole heat exchangers, shown in Fig. 2.7, however, are mostly used when there is no abundant ground space available, yet substantial heating or cooling capacity is required. In general, vertical ground loops are more expensive to install than horizontal ones because vertical ground loops have higher drilling costs. In vertical GSHP systems a borehole is first drilled, which is usually 50-150 meters deep [13]. Then, U-pipes are installed in the borehole with spacing between the pipes and borehole wall usually filled with grout for its good thermal conductivity. In case there is a leak from the pipe, the grout also protects the ground water from contamination of antifreeze. Ground-loop pipes are usually made of high-density polyethylene because of its long durability.

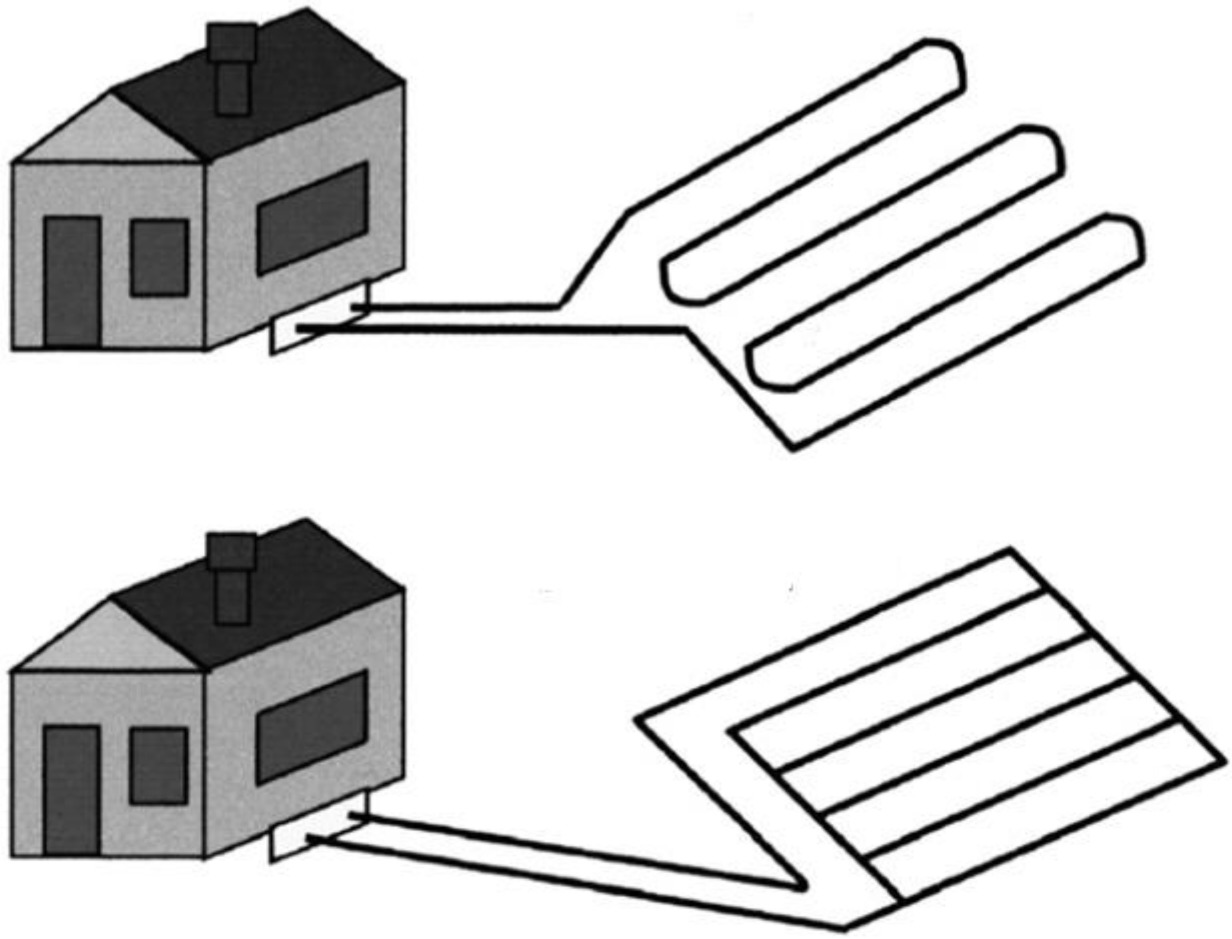

Figure 2.6: Horizontal ground heat exchangers in series (top) and parallel (bottom) configurations (reproduced from [13]).

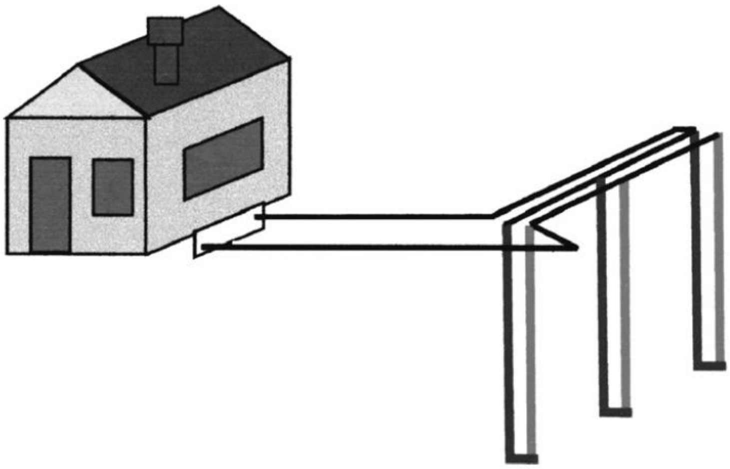

Figure 2.7: Schematic representation of a vertical ground heat exchanger (reproduced from [13]).

If more pipes are to be placed in shorter trenches, “slinky” type ground heat exchangers can be used. The pipes in this configuration are curled into a slinky shape, as is shown in Fig. 2.8. A disadvantage associated with using these types of ground heat exchangers is that curled pipes may cause thermal interference. Thermal interference is an unwanted heat transfer between the downward and upward flowing pipes that can occur when they are placed too close to each other, and tends to reduce the heat transfer between the working fluid and the ground. A summary of ground-heat-exchanger types is presented in Table 2.1, together with their advantages and disadvantages.

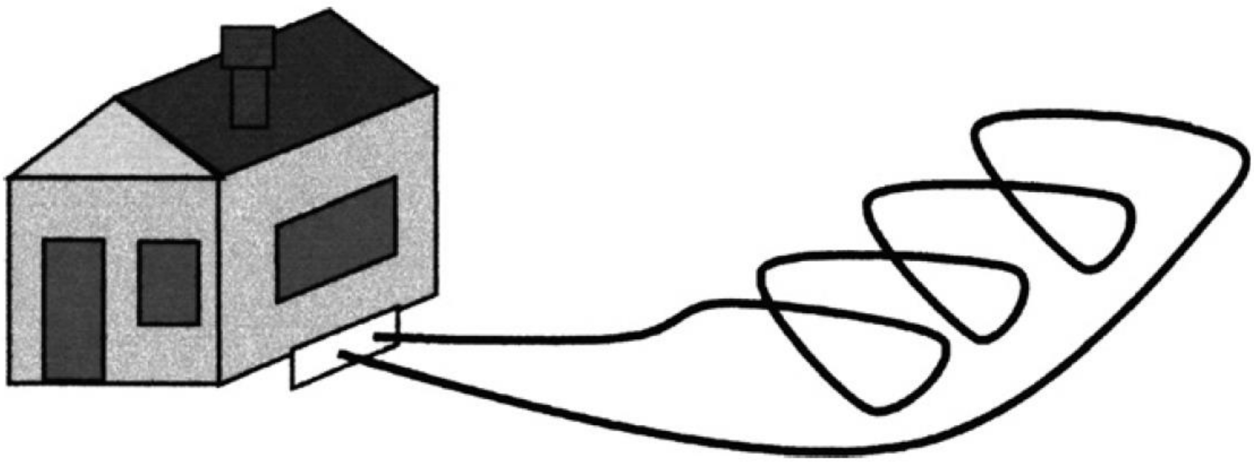

Figure 2.8: Schematic representation of a slinky type ground heat exchanger (reproduced from [13]).

Table 2.1: Summary of ground heat exchanger types considering horizontal loop, vertical loop, and the so-called "slinky" loop configurations

Ground-Heat-Exchanger Type	Advantages	Disadvantages
Horizontal	Cheap, Easy to install	Requires lots of ground space, not suitable for buildings with large heating and cooling demands
Vertical	Provides large amount of heating and cooling with shorter loops, requires less amount of ground space	Expensive, requires large, expensive drilling equipment to install
Slinky	More pipes can be placed in shorter trenches	Curled pipes may cause thermal interference

2.3 GSHP Design Tools

In the literature, one can find design procedures for both open- and closed-loop systems. Based on several ASHRAE (American Society of Heating, Refrigerating and Air Conditioning Engineers) journal articles, a number of design software tools have been developed for GSHPs. A common characteristic of all these packages is that the calculations are based on the peak demands of the system. For a more detailed energy analysis of such a system however, both the COP of the heat pump and the thermal (heating or cooling) demand of the building are required in minor intervals, such as on an hourly basis. The demand of the building can be assessed by using appropriate dynamic building energy analysis software (e.g. eQuest [8], TRNSYS [9] or EnergyPlus [10]). In any case, the COP of the heat pump depends on the fluid temperature at the inlet of the GSHP. Some commonly used design tools in industry are described below. The main output of each software tool is the ground heat exchanger length and heat pump COP as they are crucial in the design of a GSHP system and its economics. Recently, the newest versions of software tools are equipped with a life cycle analysis package that can determine the economics and greenhouse gas emission of specific GSHPs. A short description of each software tool is presented below. For further information about each tool the reader is encouraged to read the software tools' respective user manuals.

GLHEPro [15] is most suitable for designing GSHP systems for commercial buildings. Its design procedure is mainly based on monthly heating and cooling demands making the software less accurate as using hourly building demands.

EED [16] is another software tool for designing GSHP systems. It can only be used to design vertical ground heat exchangers based on monthly building demands.

GshpCalc [17] is a program specifically designed for sizing commercial building ground-coupled heat pump systems. The user provides zone cooling demand and heat loss data, selects the heat pump manufacturer, specifies ground thermal properties, and the desired vertical ground coil arrangement.

GLD [18] is a leading software tool suitable for designing geothermal heat pump and ground heat exchanger systems. This design tool is the most frequently used software in industry because it can design GSHPs of any kind.

CLGS [19] is another software tool used to design GSHP systems. It was developed in Oklahoma State University. Its disadvantage is that it uses monthly demand data to design GSHPs, which is not a very accurate method as compared to using hourly demand data.

2.4 Hybrid Ground Source Heat Pump Systems

2.4.1 Introduction and background

As outlined in Chapter 1, GSHPs offer greener advantages over conventional heating and cooling systems. This has led to their penetration not only in the residential building market, but also increasingly in commercial and industrial ones as well. Large commercial/industrial buildings located in warmer climates usually have larger cooling demands than heating demands; in this case, they are cooling dominant. For GSHPs with vertical ground loops, this high thermal load imbalance rejected to the ground will cause the ground temperature to increase over time, resulting in performance deterioration of the GSHP systems. Two possible options to avoid this problem are either to increase the ground heat exchanger length or to place the vertical boreholes farther apart from each other. However, there may be not enough ground space available to place the boreholes farther apart from each other in every given installation. Also, increasing ground heat exchanger length will result in higher initial costs of the system. As the ground heat exchanger gets longer, it can provide more of the peak building demand; but each additional length segment will only be used for a shorter portion of the year resulting in a longer payback period of the system.

Longer payback periods, lesser return on investment, and higher upfront costs often make GSHP systems unappealing compared to their conventional alternatives. Hybrid GSHP systems, a shematic of which is shown in Fig. 2.9, offer a solution to decrease the initial costs and to make GSHP systems more economically viable. Hybrid systems employ a GSHP for providing base load needs, and conventional systems, such as a boiler or a cooling tower as shown in Fig. 2.9, for supplementing peak demands. Because peak demands only occur for a short period of time in each year, the portion of the total energy supplied by GSHP systems for base load needs can still be very high. For example, as will be shown in the present study, if a hybrid GSHP system is designed so that the ground heat exchanger meets 70% of peak load demand, leaving the remaining 30% for the conventional system to meet, the GSHP can still provide more than 90% of total energy demands in many cases. As compared to the non-hybrid GSHP systems that provide 100% of total energy demands, the hybrid system offers significant reductions in upfront costs while there is a major portion of the total energy demands met by the more environmentally friendly GSHP component.

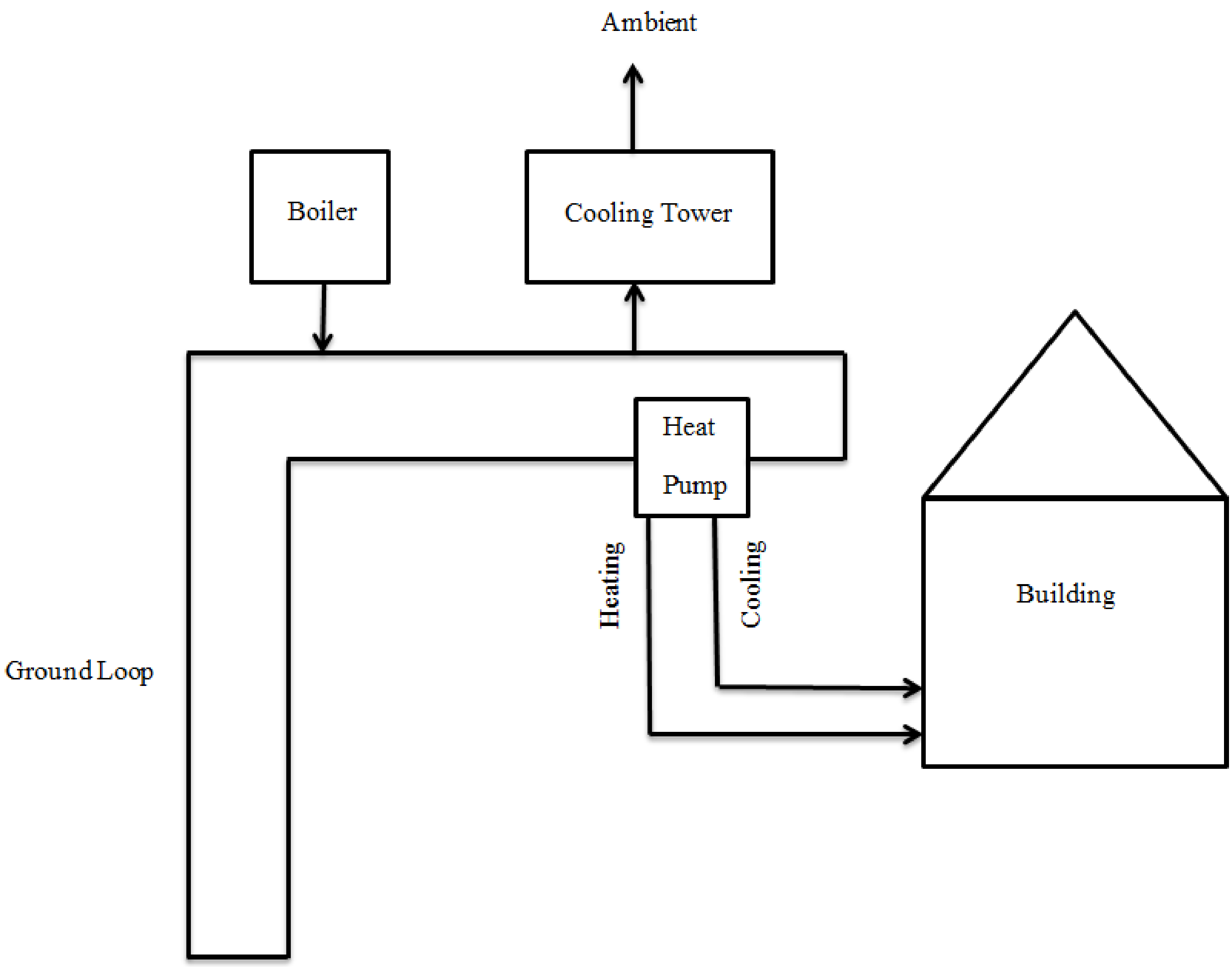

Figure 2.9: Schematic representation of a hybrid GSHP system; the ground loop provides base building heating and cooling demands and the boiler and cooling tower supplement the peak demands.

2.4.2 Approaches to size hybrid GSHPs

There are few research papers available on design strategies of hybrid GSHP systems in the literature. ASHRAE [20] bases the design on the difference between the monthly average cooling and heating demands of a building and suggests sizing the ground loop in such a way that it meets the heating demand. The supplemental cooling system will then be sized in so that it meets the cooling demands in excess of heating demands. In another ASHRAE publication, Kavanaugh and Rafferty [21] recommended that the nominal capacity of the supplemental cooling system can be derived based on the differences between the required cooling and heating ground-heat-exchanger lengths. The methods presented by ASHRAE [20] and Kavanaugh and Rafferty [21] are only valid for cooling-dominant buildings (those that would require a longer ground loop to meet the total cooling demand than to meet the total heating demand) and lack a precise value for the capacity of the GSHP systems.

Kavanaugh [22] makes some revisions and extentions to the existing design procedures as suggested by ASHRAE [20] and Kavanaugh and Rafferty [21]. The issues such as piping arrangements, freeze protection, ground heat exchange, and maintainability are discussed. A multi-story office building was chosen to apply the revised design procedure in order to investigate the appropriateness of the hybrid systems for three different climates. Installation and operation costs are discussed in the study. The author came to a conclusion that hybrid systems are viable only in warmer climates where there is a substantial cooling demand.

A comparative study which investigated some control strategies for hybrid GSHPs was conducted by Yavuzturk [23]. One purpose of this study was to determine the effect of inclusion of a set point control, which operates the auxilary heat rejecter whenever the heat pump entering temperature exceeds a set value, on the installation and operation costs of a hybrid GSHP system. Another control strategy used in this study was to utilize a differential temperature control, which operates the auxilary heat rejecter whenever the difference between the ambiant air temperature and the GSHP fluid temperature exceeds a set value. The authors used a 20-year life-cycle analysis to compare each strategy. Two of the main conclusions that have been drawn from this study are summerized below.

1- For a small office building located in a hot climate, the hybrid GSHP system is beneficial on both installation and operation costs bases. The results show that the higher the building demands with respect to the building cooling demands, the shorter the ground loop length and consequently the lesser the first costs.

2- The use of a differential temperature control strategy results in the lower initial and operational costs in hybrid GSHP systems as compared to the use of set point temperature control.

Although this study has shed light on the viability of using hybrid GSHPs, it fails to provide a method for a cost optimal hybrid GSHP design procedure. This study is only validated for one building so the results may be far from reality for other building types.

Another design strategy, which is currently being used in industry is a rule of thumb presented by the Canadian Standard Associaton [24], which suggests that for a residential building, hybrid systems should be designed in such a way that the GSHP meets 70% of the building's peak heating or cooling demand, whichever is greater, which leaves 30% of the building's peak demand to be met by auxiliary systems. The problem arises, however, when it comes to designing a ground loop system for a commercial or industrial building for which there is no available rule of thumb on which to base the design. In these cases, the 70% rule of thumb is not applicable as the ratio of cooling demand to heating demand can vary wildly from that of residential buildings. For example, restaurants and computing centres generate process heat that would need to be considered. In addition, it has not been thoroughly established whether or not the 70% rule of thumb is truly optimal in each case. A recent study by Ni *et al.* [25] presented a brute force approach to finding the optimal design heating demand ratio of a GSHP with a gas boiler as the auxiliary heat source for a heating-dominant building. In their approach, they considered heating only, and tested 5% increments in GSHP capacity as a portion of peak demand. For the particular building in their study, they found that the optimal design would be reached if the GSHP met 60% of the building's peak demand with the gas boiler meeting the remaining 40%. The disadvantages associated with the brute force approach are that it considers only one particular building at a time and it requires a lot of manual calculations. Furthermore, the study does not consider cooling demand at all and there are no reasons to assume that their conclusions would apply to any other building. Their study is valuable, however, in pointing out that a 70% rule of thumb is far from ubiquitously applicable.

2.4.3 Hybrid GSHP Systems Coupled to a Common Water Loop

As has been mentioned, a sustainable approach for space conditioning of many building types is using ground source heat pump (GSHP) systems. When coupled to a common water loop through a heat exchanger, these systems can be particularly suited to provide the heating and cooling requirements of large, multi-zone commercial buildings or of multiple neighbouring buildings. These systems consist of several individual heat pumps that can be located in multiple zones of a building, or in multiple buildings – either way the governing principles are the same. These heat pumps are linked together via a common water loop. The water loop acts as a heat source when heating is demanded by a zone and as a heat sink when cooling is demanded by another zone. These systems can operate in three modes: cooling only, heating only, or mixed heating and cooling. In the cooling only mode, heat pumps add heat to the loop so the temperature of the water in the loop increases. A chiller and/or a cooling tower will be used to prevent a temperature increase beyond a certain temperature (usually 32 ℃ [26]). In the heating mode, the heat pumps remove heat from the loop decreasing the water temperature in the loop. In this case, a heater keeps the water temperature above a certain temperature, usually 16 ℃ [26]. In the mixed heating and cooling mode, some of the heat pumps are operating in cooling mode while some others are operating in the heating mode. For example, there may be a computer room, which even in winter needs cooling, or zones that get overcooled easily in summer and need to be reheated. Heat pumps that are in cooling mode reject heat to the loop. This heat will serve as a heat source for heat pumps operating in the heating mode. If the heat pumps operating in the cooling mode add more heat to the loop than that being removed from the loop by the heat pumps operating in the heating mode, then the chiller/cooling tower rejects the excess heat to the ambient. If the heat pumps operating in the cooling mode reject less heat to the loop than that being removed from the loop by the heat pumps operating in the heating mode, then the heater adds heat to the loop.

One potential application of these systems is to use them for multiple buildings with numerous heat pumps in the so-called "utility model", in which a utility may install a large hybrid GSHP system and then sell energy to building owners. Multiple neighboring commerical buildings can act as one larger commerical building with several heating and cooling zones. This way, a larger hybrid GSHP system can be installed for multiple buildings. In this study, it will be investigated whether or not it is appropriate to combine multiple buildings onto a single hybrid GSHP system.

2.5 Challenges

GSHP design typically starts with assessing the hourly heating and cooling demands of a building using dynamic building energy analysis software tools such as eQuest [8]. Then, the resulting hourly heating and cooling demands are imported into a design tool such as GLD [18] to determine the length of the ground heat exchanger for a GSHP that would meet those demands. When the full building demand must be met, there is little variation in the required ground-loop length. However, in cases of hybrid systems, existing buildings will have secondary heating and cooling systems or auxiliary heating and cooling systems can be included in new building construction. Therefore, the GSHP system does not need to meet the full demand, which means that there is nearly infinite design freedom for the reduced-capacity GSHP system which is supplemented by auxiliary heating and/or cooling systems.

Design of hybrid GSHP systems should be done with special care because the extent to which the ground-heat-exchanger size can be reduced in a hybrid GSHP system is an important unknown that may vary from case to case. It should be computed in a systematic way. The literature lacks a rigorous mathematical, computational approach to size hybrid GSHP systems as of yet. In this study, first a robust methodology is proposed for determining optimal GSHP size as part of a hybrid system. The methodology simultaneously considers both heating and cooling and is applicable to residential, commercial and industrial buildings that are either heating or cooling dominant. Then, the appropriateness of multiple commercial buildings sharing a single hybrid GSHP system is assessed. For this purpose, the first methodology will be enhanced to handle multiple buildings, and thus a new methodology is introduced. The new methodology will be applied to a utility model of heating and cooling using 100 different representative commercial buildings of various types. The methodology automatically computes the savings potential associated with thousands of potential building combinations so that a statistical analysis can be performed on the potential and viability of combining multiple building heating and cooling demands onto a single hybrid GSHP system with a common water loop.

CHAPTER 3

METHODOLOGY DEVELOPMENT

3.1 Methodology to design hybrid GSHP systems for individual buildings

The underlying principle behind the proposed methodology is to find the GSHP capacity that minimizes total costs to the building owner. The GSHP capacity, as a portion of peak building heating or cooling demand, can vary from zero (no GSHP) to unity (GSHP with no need for an auxiliary system), with values between zero and unity representing a hybrid system that combines a GSHP with an auxiliary heating and/or cooling system. For each value of GSHP capacity between zero and unity, the GSHP and auxiliary system can be sized based on building demands and their initial/installation and annual operating costs over the system lifespan can be determined and summed as a present value to become a total cost. With the total cost as a function of GSHP capacity, an optimal hybrid GSHP system, for which the total cost is minimized, can be determined.

To schematically introduce the new methodology for choosing an optimal, cost effective GSHP capacity in hybrid systems, consider the schematics of monthly heating and cooling demand curves for a building in a seasonal climate, as shown in Figs. 3.1 and 3.2, respectively. Note that not all buildings have heating and cooling demands represented in Figs. 3.1 and 3.2. For example buildings exist which require either heating or cooling all year. An example would be a fast food restaurant (one is considered in detail later in this thesis), which needs cooling even in winter months because of the heat generated in its kitchen and by its occupancy patterns. As depicted in Figs. 3.1 and 3.2, peak heating and cooling demands only occur for short periods in January and July, respectively. Peak cooling demand tends to occur sporadically within a six-week period in the summer, and peak heating demand tends to last for a two- to three-week period in the winter.

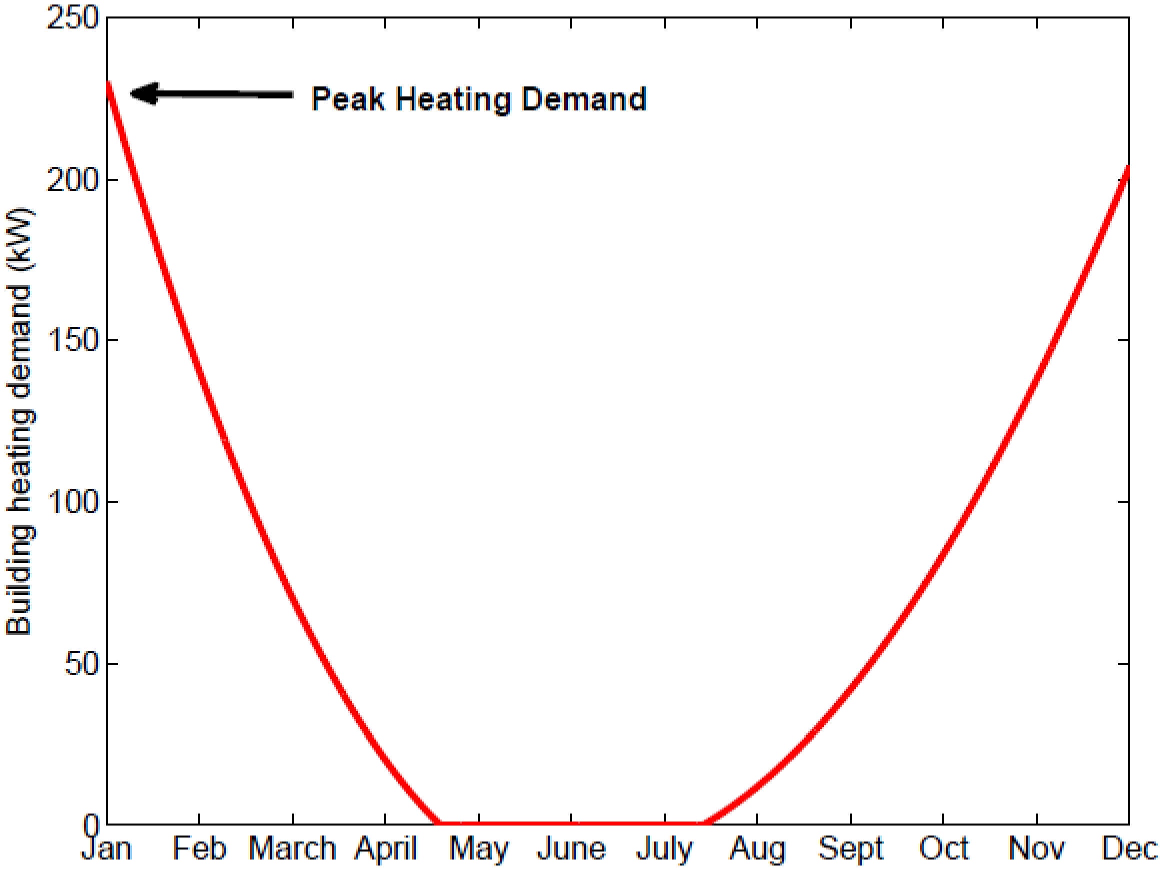

Figure 3.1: A schematic representation of a typical building monthly heating demand curve

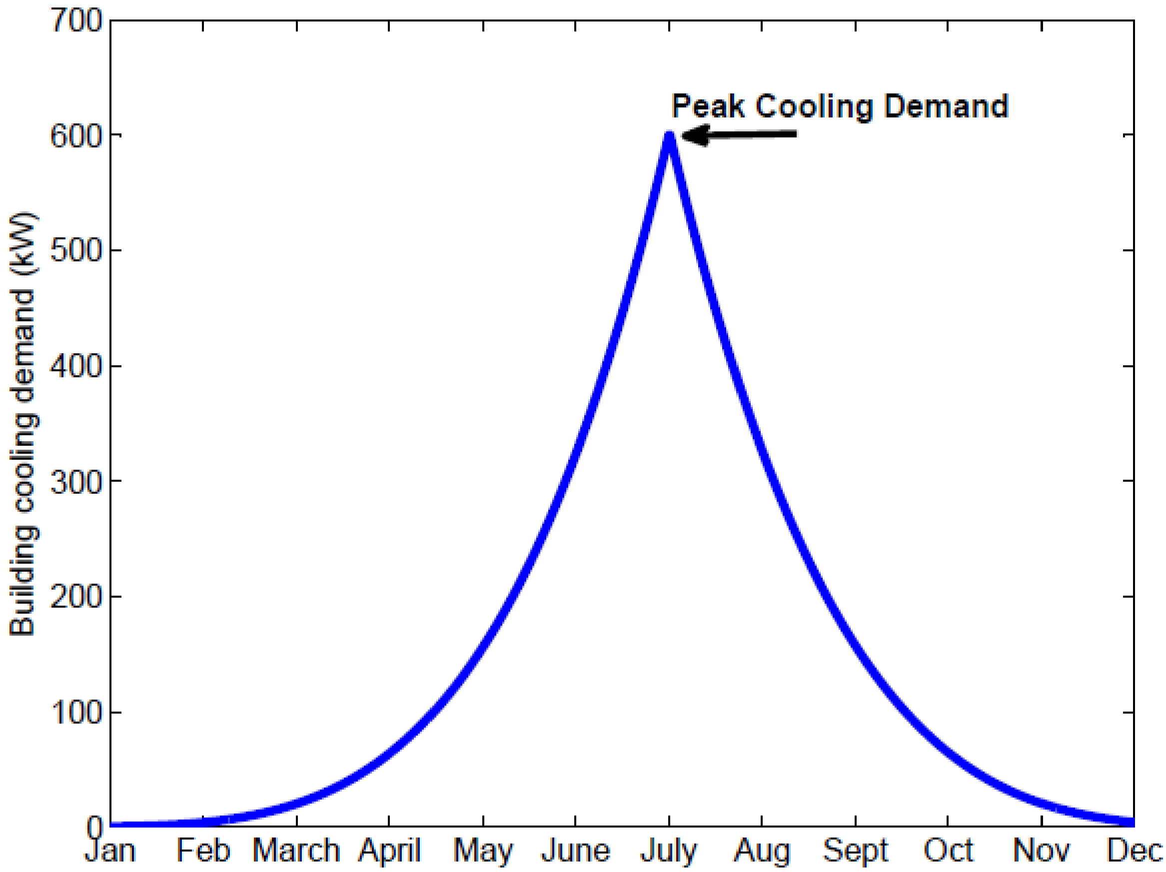

Figure 3.2: A schematic representation of a typical building monthly cooling demand curve

To find an optimal GSHP capacity in a hybrid system, shave factors, α for cooling and β for heating, are introduced. α (β) is the portion of the peak cooling (heating) demand that is to be supplied by the GSHP system. For example, if peak cooling demand of a building is 100 kW at one point in the summer, and a GSHP is designed with $\alpha = 0.6$, then the GSHP can supply up to 60 kW of cooling at any time. The balance must be supplied by an auxiliary cooling system. The benefit is that for this particular system, the 60-kW capacity may be sufficient to meet demand for the majority of the time. As α increases, the GSHP capacity, and thus its drilling and installation costs increase, but the annual costs decrease, as the building owner will be relying less on the conventional systems, which are more expensive to run. These competing economic factors can be balanced to find an optimal value for α (or β depending on the case).

The first step in our methodology is to determine whether a given building is 'heating dominant' or 'cooling dominant'. A 'cooling dominant' building is one for which the ground-loop length required to meet the peak cooling demand is larger than that required to meet the peak heating demand. In other words, if a ground loop were designed to meet the peak cooling demand in a ‘cooling dominant’ building, it would be oversized in the winter when it would need to be providing heating. Determining heating or cooling dominance is done by computing the required borefield length for cooling (L_c) and the required borefield length for heating (L_h). After that, by comparing L_c and L_h when the GSHP is to meet 100% of building demands, the algorithm automatically detects if the building is cooling or heating dominant. If L_c when α =1 is greater than L_h when β = 1, the building is cooling dominant. Otherwise, the building is heating dominant.

Calculations of the required borefield lengths for cooling and heating are based on Eq. (3.1) and Eq. (3.2) presented by Kavanaugh and Rafferty [19].

$$L_c = \frac{q_a R_{ga} + (C_{fc} q_{lc})(R_b + PLF_m R_{gm} + R_{gd} F_{sc})}{t_g - \frac{t_{wi} + t_{wo}}{2} - t_p} \tag{3.1}$$

$$L_h = \frac{q_a R_{ga} + (C_{fh} q_{lh})(R_b + PLF_m R_{gm} + R_{gd} F_{sc})}{t_g - \frac{t_{wi} + t_{wo}}{2} - t_p} \tag{3.2}$$

where q_a can be calculated from Eq. (3.3).

$$q_a = \frac{C_{fc} q_{lc} EFLH_c + C_{fh} q_{lh} EFLH_h}{8760\ Hours} \tag{3.3}$$

The terms used in these equations are:

F_{sc} = Short-circuit heat loss factor, which accounts for heat loss due to heat transfer between the two different legs of the U-tube in the borehole.

L_c = Required ground-loop length to meet the shaved cooling demand (m)

L_h = Required ground-loop length to meet the shaved heating demand (m)

PLF_m = Part-load factor during design month, which represents the fraction of equivalent full load hours during the design month to the total number of hours in that month $PLF_m = \frac{\bar{q}}{q_{max}}$, where $\bar{q}$ and q_{max} are the average demand and peak demand for the design month, respectively.

q_a = Net annual average heat transfer to the ground (Watts)

q_{lc} = Building peak cooling demand (Watts)

q_{lh} = Building peak heating demand (Watts)

R_{ga} = Effective thermal resistance of the ground; annual pulse, which accounts for transient heat transfer from the borehole wall to the undisturbed ground temperature corresponding to annual ground loads (m·K/W) (for calculation details the reader is referred to [19])

R_{gd} = Effective thermal resistance of the ground; daily pulse, which accounts for transient heat transfer from the borehole wall to the undisturbed ground temperature corresponding to daily ground loads (m·K/W) (for calculation details the reader is referred to [19])

R_{gm} = Effective thermal resistance of the ground; monthly pulse, which accounts for transient heat transfer from the borehole wall to the undisturbed ground temperature corresponding to monthly ground loads (m·K/W) (for calculation details the reader is referred to [19])

R_b = Thermal resistance of the borehole; it includes the convective resistance inside each tube, the conduction resistance for each tube, and the grout resistance. (m·K/W) (for calculation details the reader is referred to [19])

t_g = Undisturbed ground temperature (°C)
t_p = Temperature penalty (change in ground temperature over a long run which is due to the thermal interference between adjacent boreholes) (°C) (for calculation details the reader is referred to [19])

t_{wi} = Water temperature at heat pump inlet (°C)

t_{wo} = Water temperature at heat pump outlet (°C)

C_{fc} and C_{fh} = Correction factors that account for the amount of heat rejected or absorbed by the heat pumps. The values depend on the respective EER and COP of the units and are provided in the design manual.

$EFLH_c$ and $EFLH_h$ = Annual equivalent full-load cooling and heating hours (Hours)

The second step is to determine the optimal α (β) for the cooling (heating) dominant building. This is done by varying α, if the building is cooling dominant or β if the building is heating dominant, from 0 to 1. Note that α (β) = 0 corresponds to the case with the total cooling (heating) demand being met by the auxiliary system alone and α (β) = 1 corresponds to the case with the total cooling (heating) demands being met by the GSHP system alone. A schematic representation of the case when $\alpha = 0.6$ is shown in Fig. 3.3. In this case, the GSHP could meet 60% of the peak cooling demand, which, over the course of a year, means that it could meet the cooling demand under the dashed curve. The peak area outlined in the solid curve above the dashed line would need to be met by an auxiliary system, but over the course of a year, would represent a very small portion (much less than 40%) of the total cooling demand.

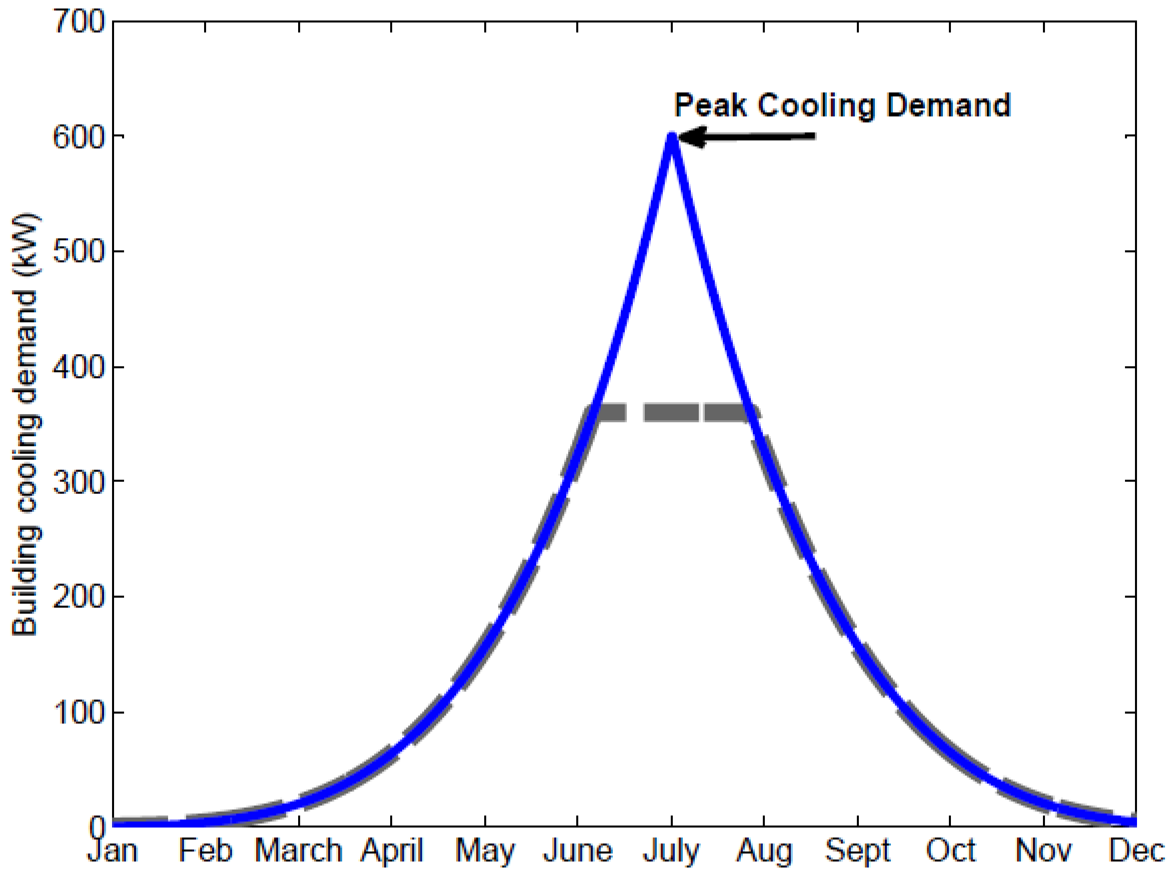

Figure 3.3: Schematic representation of a typical cooling demand curve for α = 0.6 (dashed grey curve)

Shaving the peak cooling (heating) demand by an optimal value of α (β) significantly reduces the high upfront costs of installing GSHPs as compared to the case when α (β) = 1, as the geothermal system size can be much smaller. Still, however, the GSHP can meet a large portion of total annual cooling demands. As depicted in Fig. 3.4, the black portion of the graph is met by the GSHPs and the hatched portion is met by a conventional cooling system.

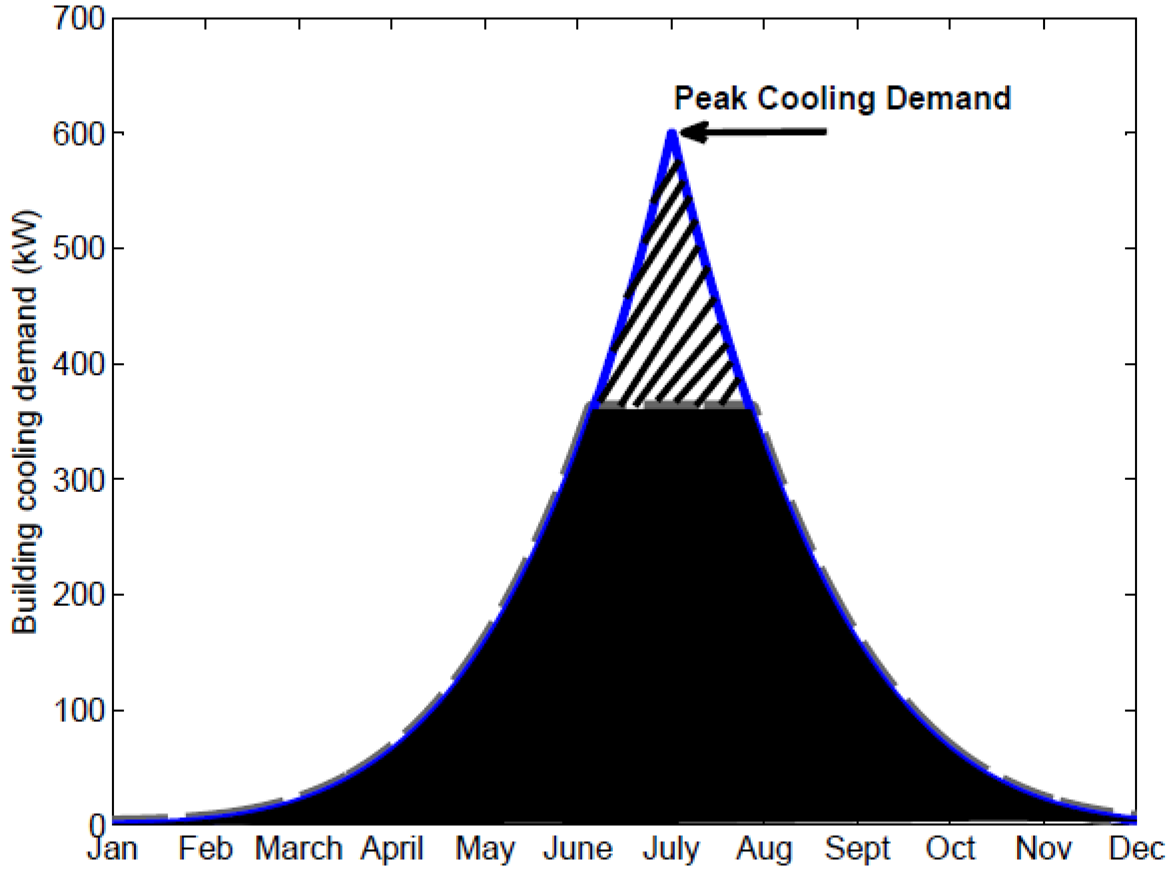

Figure 3.4: Schematic representation of the total annual cooling demands met by the GSHP (black) and by the conventional system (hatched)

In the study, a step size of 0.01 is used resulting in 100 cases of α (β). Using a smaller step size did not have any appreciable effect on the results.

For each of the 100 cases, a corresponding value of β (α) must be found. That is, for a cooling (heating) dominant building, as α (β) is varied from 0 to 1, a value of β (α) is found which corresponds to the portion of peak heating (cooling) demand that would be met by a GSHP that meets the portion of the cooling (heating) demand corresponding to α (β). This value is determined by using the value of the required heating (cooling) borefield length already determined in the first step of the calculations. For each value of α (β), β (α) is determined such that it corresponds to a required heating (cooling) borefield length equal to the associated required cooling (heating) borefield length.

For each of the 100 cases, installation costs, annual operating costs, and total costs can be calculated. Some of the costs are upfront, such as installation costs, others are annual, such as natural gas or electricity costs, while others still are periodic, such as equipment replacement costs. To determine optimal values of α (β), these costs need to be temporally related. This relation can then be obtained from the tabulated data, first by setting a target, such as minimum payback period, or minimum net present value of all costs and then relating all costs to a single point in time, normally the present.

In this study, the target is to minimize the net present value of total costs. For this purpose and for each value of α (β), the initial costs and annual operating costs are combined into a single net present value of total costs for installations, considering 20 years of operation. The duration of 20 years is chosen somewhat arbitrarily and is useful for demonstrative purposes, but similar analyses can be performed for other durations. Using basic economics, Baker and English [27] define the net present value of operation costs as the sum of the present values of all project cash flows given by Eq. (3.4):

$$NPV\ of\ annual\ operation\ costs = \sum_{t=0}^{n} \frac{CF_t}{(1+IR)^t} \tag{3.4}$$

where CF_t is the cash flow at time t (which may include annual natural gas/electricity costs, service/maintenance costs, and periodic equipment replacement costs with the inflation and/or interest rates being factored in), IR is the annual interest rate and n is the number of years of operation.

The net present value of total costs will then be calculated using Eq. (3.5):

$$NPV = NPV\ of\ annual\ operation\ costs + Initial\ (installation)\ costs \tag{3.5}$$

To find the minimum of the net present value of total costs, initial costs of both GSHP and auxiliary heating and cooling systems as functions of α (β) are first determined. Next, annual operation costs of both systems as a function of α (β) are calculated. Finally, initial costs and annual operation costs are combined into a net present value, which accounts for assumed inflation and interest rates, using Eq. (3.5). It should be noted here that this study does not purport to be able to predict inflation rates, interest rates, and costs with great accuracy; rather the purpose of the present analysis is to show the value of the proposed methodology, and analyze the method of optimizing hybrid system ratios. The α (β) that corresponds to the minimum net present value is the optimal α (β) of the system and the required borefield length is determined accordingly.

The methodology presented herein assumes that no conventional system such as a boiler, chiller and/or cooling tower exists in the building before installation (*i.e.*, the conventional system installation costs are included in the initial costs). For buildings in which conventional systems already exist, those installation costs can simply be neglected or adjusted based on age of the equipment. For simplicity and for the purposes of the analysis, constant inflation rates for gas and electricity are also assumed. An inflation rate of 4% and an interest rate of 8% are used in the net present value calculations. It should be noted that the values used for interest and inflation rates are based on the information from industry. However, using different but reasonable values would slightly change the results but not the conclusions. The procedure that the methodology follows is shown in the block diagram in Fig. 3.5.

In step 1, the algorithm is initiated, and all input parameters, such as interest rate, inflation rate, etc. are specified.

In step 2, the hourly heating and cooling demand data, for a building, in a spreadsheet format, which was generated using building simulation software (eQuest [8] in this thesis work), is read into the program.

In step 3, the hourly heating and cooling demand data are processed for a common water loop system. The function of the common water loop will be explained later in section 3.1.1.

In step 4, shaving peak cooling and heating demands by α and β respectively, 100 sets of cooling and heating demands are generated, corresponding to α and β varying from 0 to 1 with a step size of 0.01.

In step 5, the corresponding required cooling and heating borefield lengths (L_c and L_h) are found for the generated demands using the methodology described earlier in section 3.1.

In step 6, a comparison is made between L_c and L_h when α and β are equal to unity to determine if the building is cooling or heating dominant.

In step 7, the next route of the program is determined as follows: if L_c when α is equal to unity is greater than L_h when β is equal to unity, the program follows routes 8a, 9a, 10a, and 11; otherwise, it follows routes 8b, 9b, 10b, and 11.

In step 8, initial costs and operation costs of the GSHP and conventional systems corresponding to each α or β are found using up-to-date cost information from industry.

In step 9, initial and operation costs are combined into a net present value (*NPV*) of total costs.

In step 10, the minimum *NPV* and its corresponding optimum α and β are found.

In step 11, the program is terminated.

The methodology along selected results from Chapter 4 have been published in Alavy *et al.* [28]

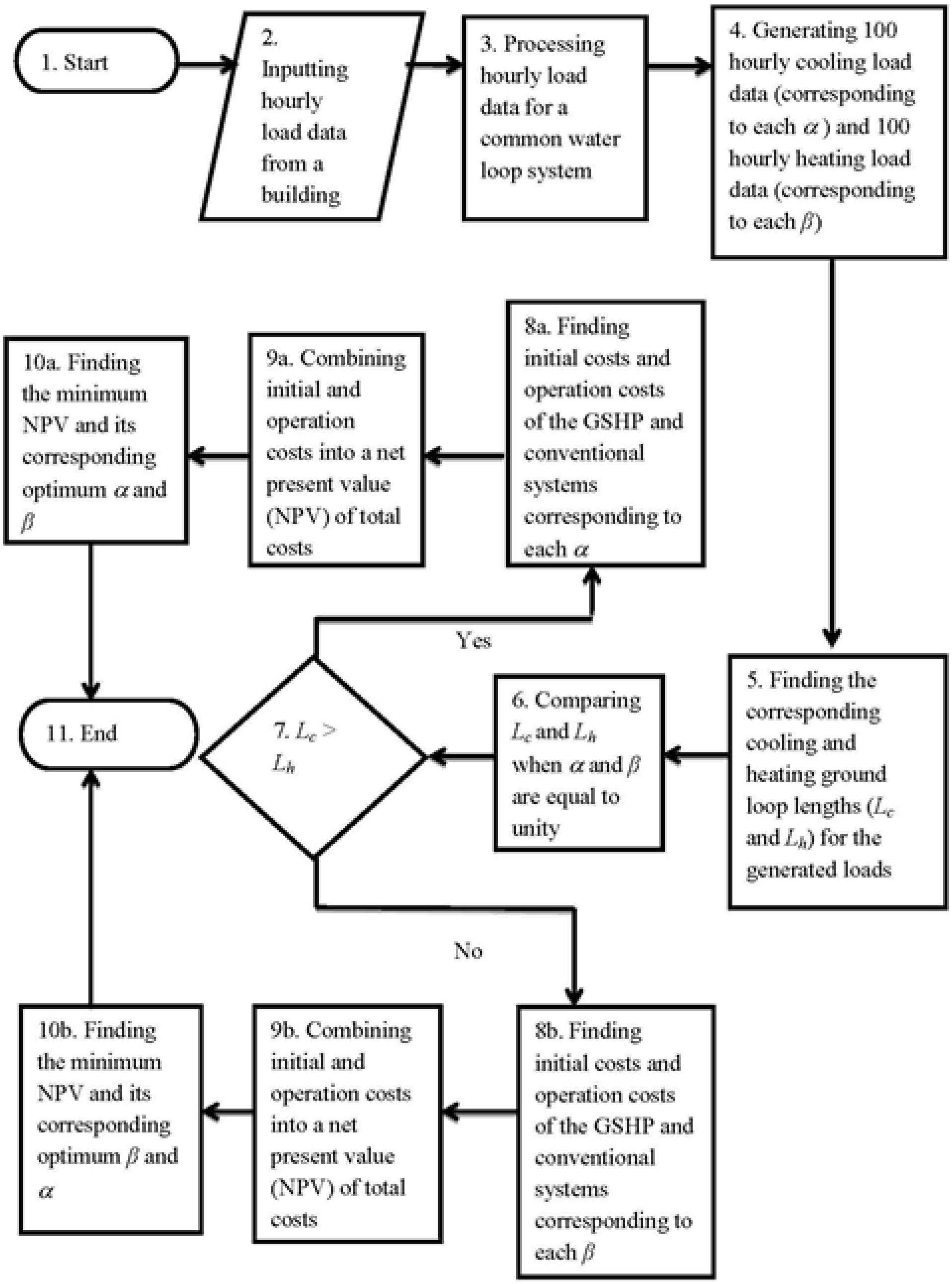

Figure 3.5: Block diagram showing the logical structure of the newly proposed and implemented methodology for hybrid GSHP optimization

3.1.1 Case study

The methodology described in section 3.1 has been implemented into an algorithm, which has been tested for ten buildings in Toronto, Ontario, Canada. To best demonstrate the methodology and the algorithm, a detailed explanation of a single case study is first presented for a cooling dominant transit facility. Summarized results for the other nine buildings will be presented in a subsequent section.

The transit facility's hourly heating and cooling demands have been assessed using a dynamic energy analysis software tool eQuest [6] by CleanEnergy™ staff. The transit facility is an 8500-m^2 building which is occupied seven days a week from 7:00 am to 9:00 pm. Its ceiling is covered by acoustic tile with no insulation and it has framed vertical walls with no insulation. The resulting hourly heating and cooling demands were imported into the algorithm to seek an optimum hybrid GSHP system design.

The predicted hourly cooling and heating demands of the transit facility are shown in Figs. 3.6 and 3.7, respectively. As can be seen from these figures, there are numerous peaks and troughs, but the general shape of the plots are as to be expected, with cooling demand peaking in the summer months, and heating demand peaking in the winter months. As depicted in Figs. 3.6 and 3.7, multi-zone buildings such as this transit facility can have simultaneous cooling and heating demands. For example, there may be a computer room, which even in winter needs cooling, or zones that get overcooled easily in summer and need to be reheated. For this reason, the figures depict some remaining heating demand in the summer months and some remaining cooling demand in the winter months.

To consider this fact in the analysis, it is assumed that the buildings could employ a common water loop. The common water loop runs throughout the building, which serves as a heat source or a heat sink for a heat pump in each zone in the building. If some zones require cooling, the heat pumps for those zones will dump heat to the water loop. At the same time, if other zones require heating, the heat pumps for those zones will extract heat from the water loop. By neglecting the compression effect of the heat pump, the net amount of heat will be provided by the GSHP and auxiliary system to or from the water loop.

While other methods of meeting simultaneous heating and cooling demand are also used in industry, the common water loop was chosen here as a basis for comparison. Simple modifications can be made to the algorithm to consider other options to meet simultaneous heating and cooling demands of a building. These options may include considering a desuperheater in the GSHP system or making use of the cool outside air to provide a portion of the cooling in winter. These configurations will be subject to further study.

After processing the hourly demand data from eQuest [6] for the transit facility, the algorithm automatically generates 200 sets of cooling and heating curves; 100 by varying α from 0 to 1, and 100 by varying β from 0 to 1, in both cases with a step size of 0.01 (corresponding to block number 4 in Fig. 3.5). Sample curves for α = 0.6 and β = 0.6 are shown in Figs. 3.8 and 3.9, respectively. The α and β dashed lines shave the peak demands (the green parts of the figures), and leave the blue and red curves (below the dashed line) for cooling and heating, respectively. The blue and red curves represent the portions of the cooling and heating demands to be met by the GSHP for that particular value of α or β. There are 100 such newly shaved blue cooling and red heating demand curves that are temporarily stored.

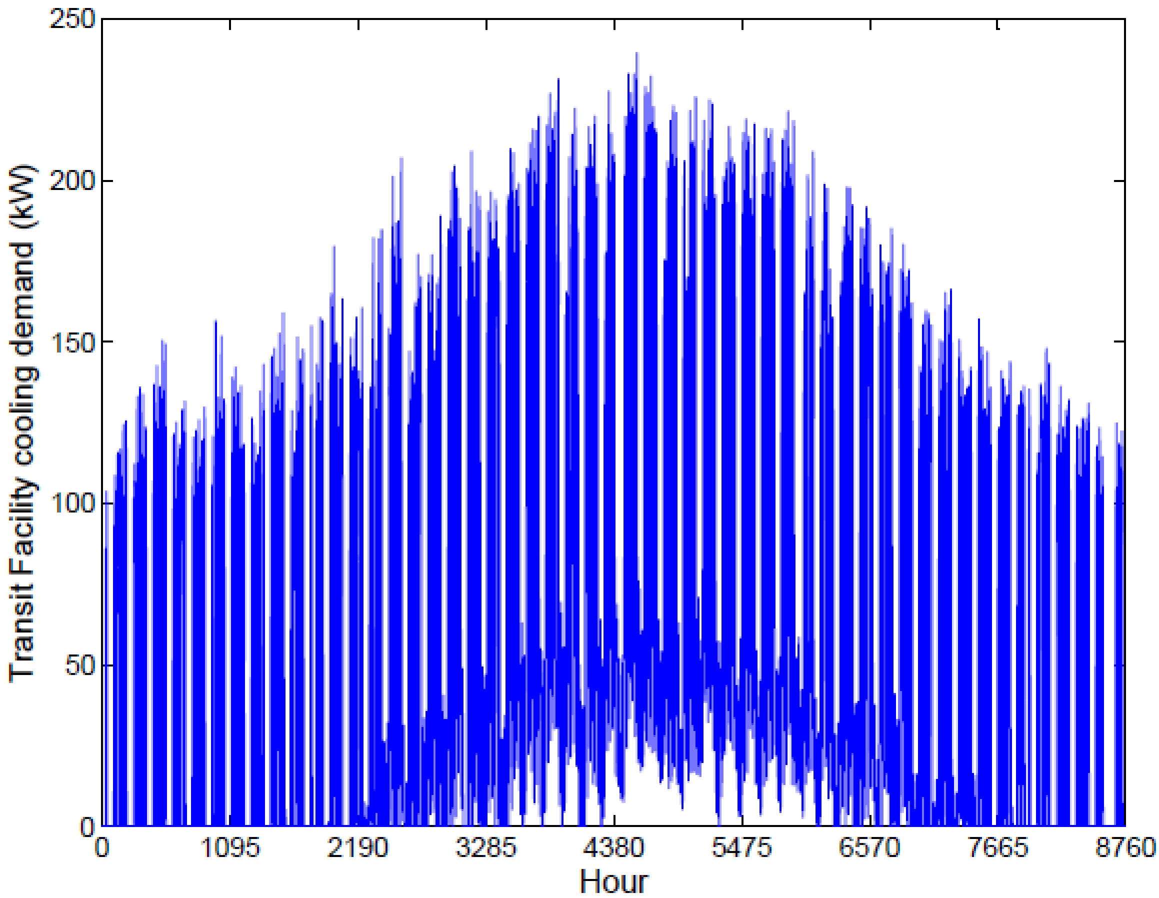

Figure 3.6: Hourly cooling demands for a transit facility in Toronto (Data courtesy of CleanEnergy™)

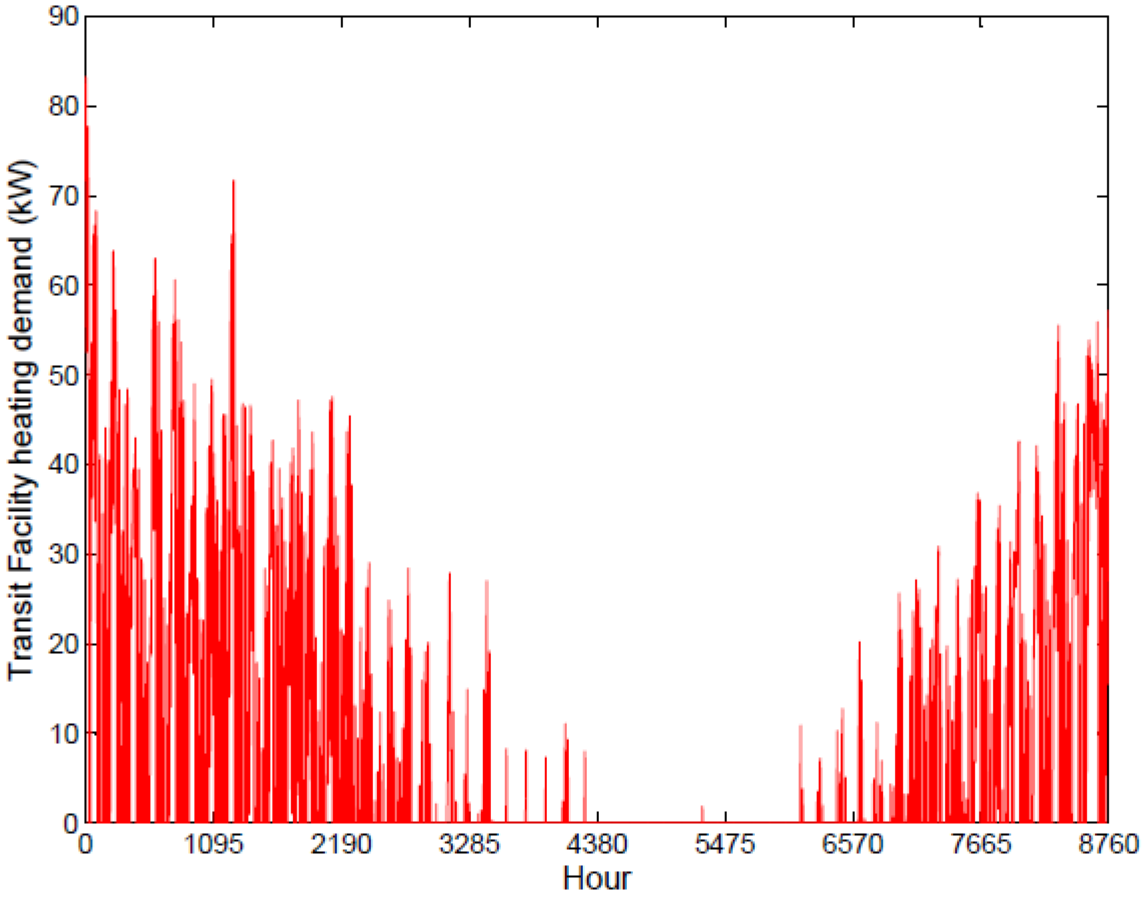

Figure 3.7: Hourly heating demands for a transit facility in Toronto (Data courtesy of CleanEnergy™)

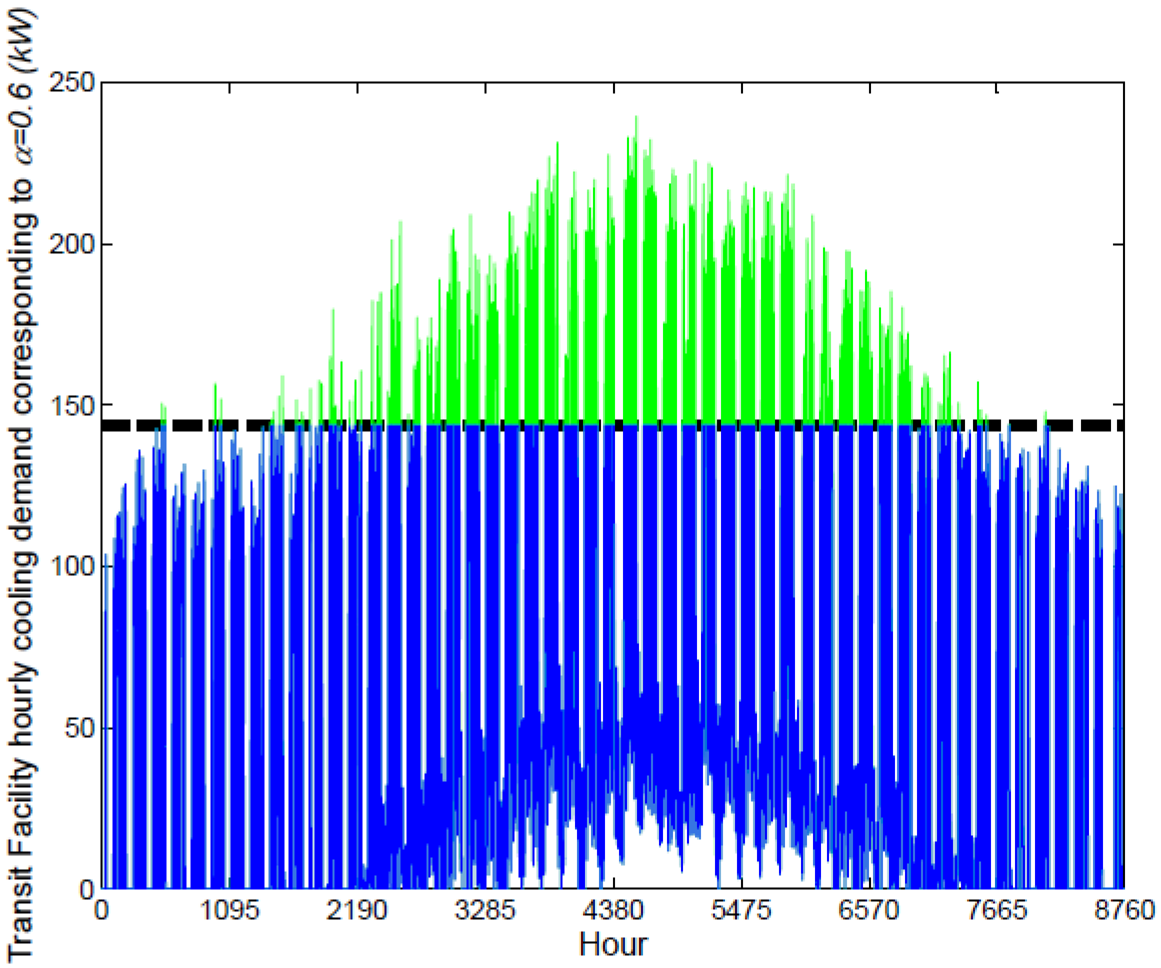

Figure 3.8: Newly shaved cooling demands for α = 0.6

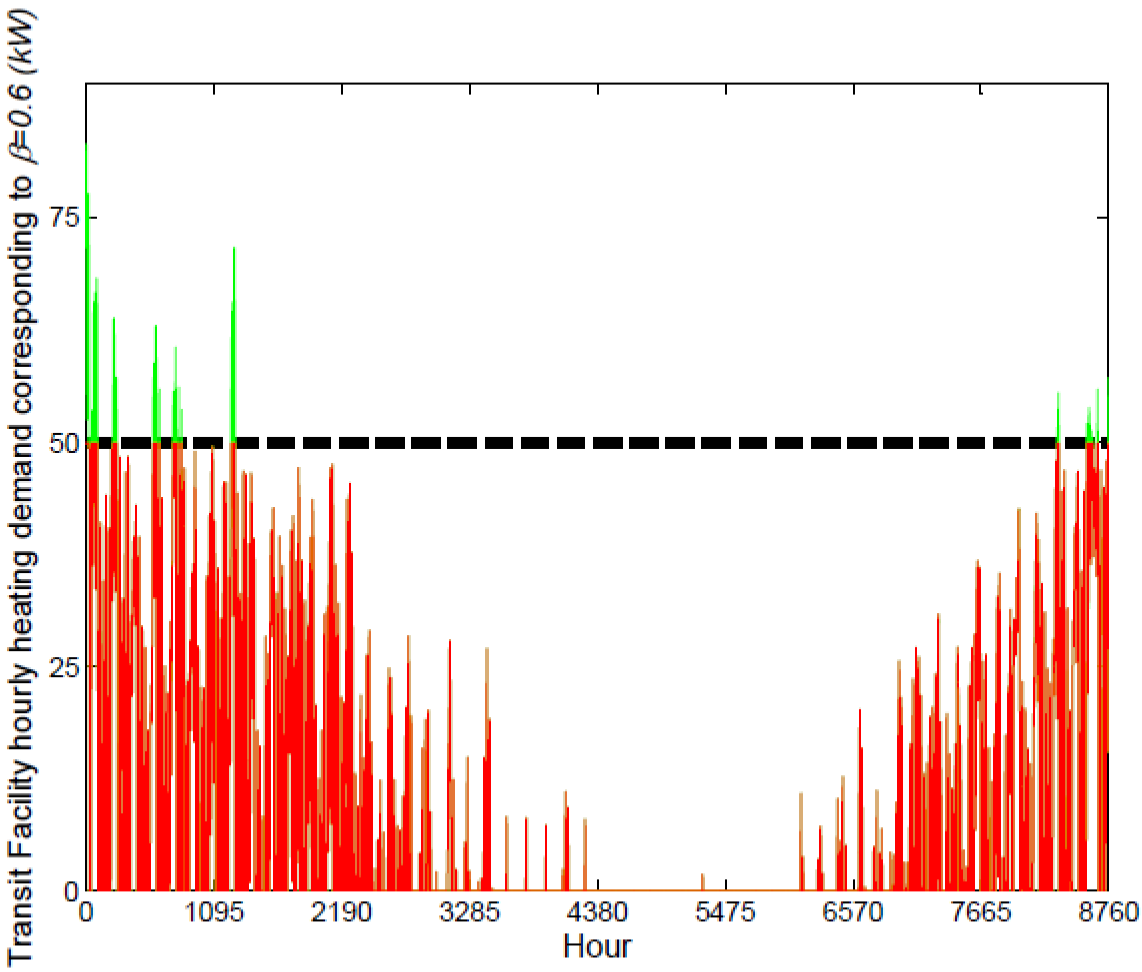

Figure 3.9: Newly shaved heating demands for β = 0.6

The 100 shaved cooling and heating demand curves can now be imported into a design tool such as GLD [16] one by one to find 100 corresponding required cooling and heating borefield lengths. Those ground-loop lengths could then be used to determine costs. Processing the demands one by one would be time consuming and inefficient. One major advantage of the algorithm as compared to design tools such as GLD [18] is that it can calculate the heating and cooling ground-loop lengths in an automated manner. This makes the calculation faster and more efficient.

To show the accuracy of the algorithm with regard to ground loop length calculations, it has been tested and compared with GLD [18] for 100 different values of α and 100 different values of β, an example of which is shown in Fig. 3.10.

Fig. 3.10 compares the cooling ground-loop length L_c as a function of α for the transit facility as computed by both GLD [18] and the present algorithm. The heating ground-loop length L_h is zero for all values of β from both the algorithm and from GLD [18]. This is expected because the transit facility does not need much heating throughout the year (see Fig.3.7) and is extremely cooling dominant.

As can be seen in Fig. 3.10, the calculated cooling ground-loop length L_c of the new algorithm increases smoothly and monotonically with increasing α as expected, whereas the calculated cooling ground-loop length from GLD [18] shows some deviations from monotonic behavior. The causes of the slight differences between the results of GLD [18] and the present algorithm are unknown and cannot be further investigated as GLD [18] is not an open source program. However, the results of the present algorithm are satisfactory in terms of accuracy, and their smooth monotonic behavior.

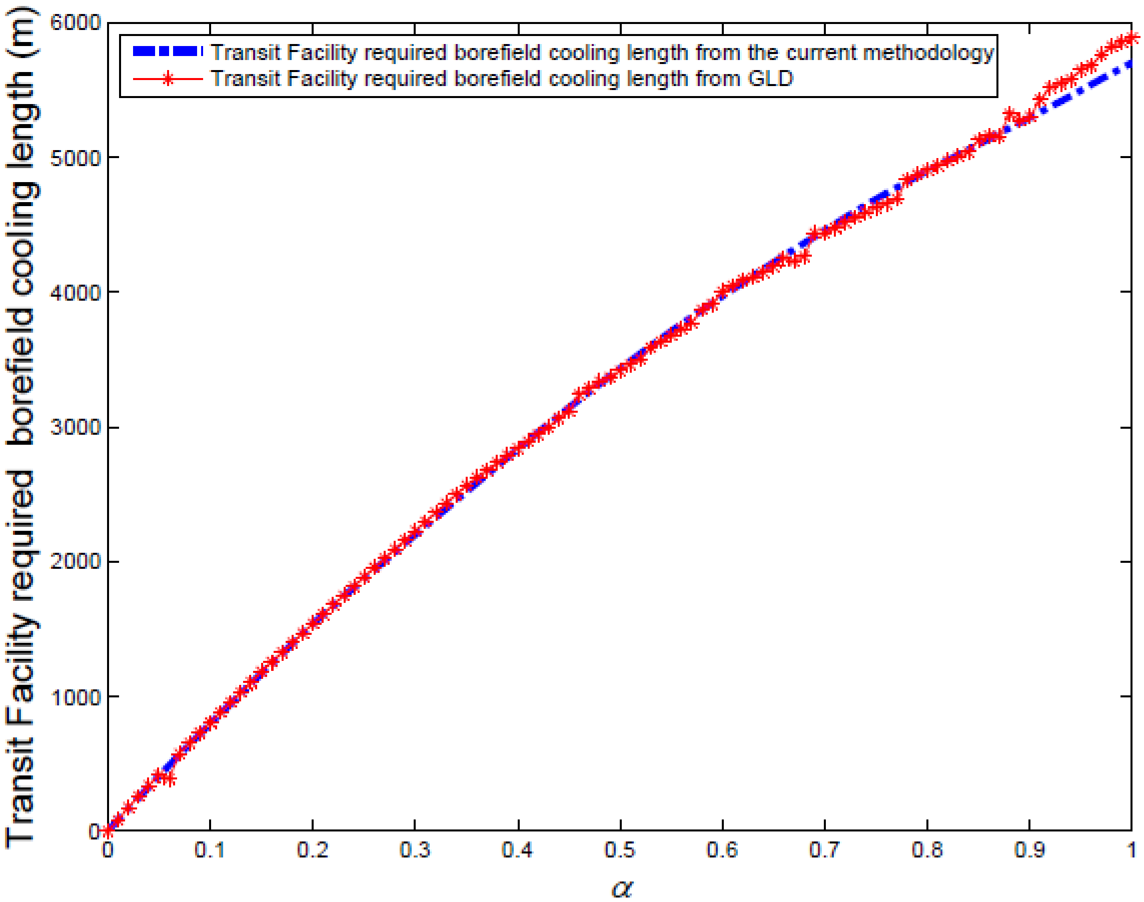

Figure 3.10: Cooling ground-loop length L_c for a transit facility as a function of α from GLD [18] and the present algorithm

Table 3.1 summarizes the input parameters and values used to find the cooling and heating ground-loop lengths both in GLD [18] and in the present algorithm. According to the block diagram of the methodology (Fig. 3.5), in the next step (step 7), the algorithm determines if the building is heating or cooling dominant.

Considering Figs. 3.10 and the fact that L_h is zero for all values of β, it is evident that when α and β are equal to unity, L_c is greater than L_h. This indicates that the transit facility is cooling dominant.

Because the transit facility is cooling dominant, the cooling ground-loop length L_c becomes the length of the ground loop when calculating the initial costs of the GSHP system. The variable β can now be used such that for each value of α varying from zero to one, β represents the portion of the peak heating demand that the GSHP (sized based on cooling demand by α) can meet. For each value of α, the corresponding value of β will be larger because for a cooling dominant building, a ground loop of any given length can meet a larger portion of the peak heating demand than of the peak cooling demand. For demonstrative purposes, the relationship between α and β for a sample cooling dominant building is shown in Fig. 3.11. It is evident from Fig. 3.11 that when α exceeds a certain value, in this case 0.88, β will be unity. β remaining unity after a certain value of α signifies that while the ground loop can only provide portions of the cooling demand, the same ground loop can meet all the heating demand. For values of β less than unity, the ground loop does not meet the entire heating demand; therefore, the costs considered include the initial costs and annual operation costs of the GSHP and both conventional heating and cooling systems. For values of α for which β equals to unity, conventional heating costs do not need to be considered as the GSHP can meet the full heating demand.

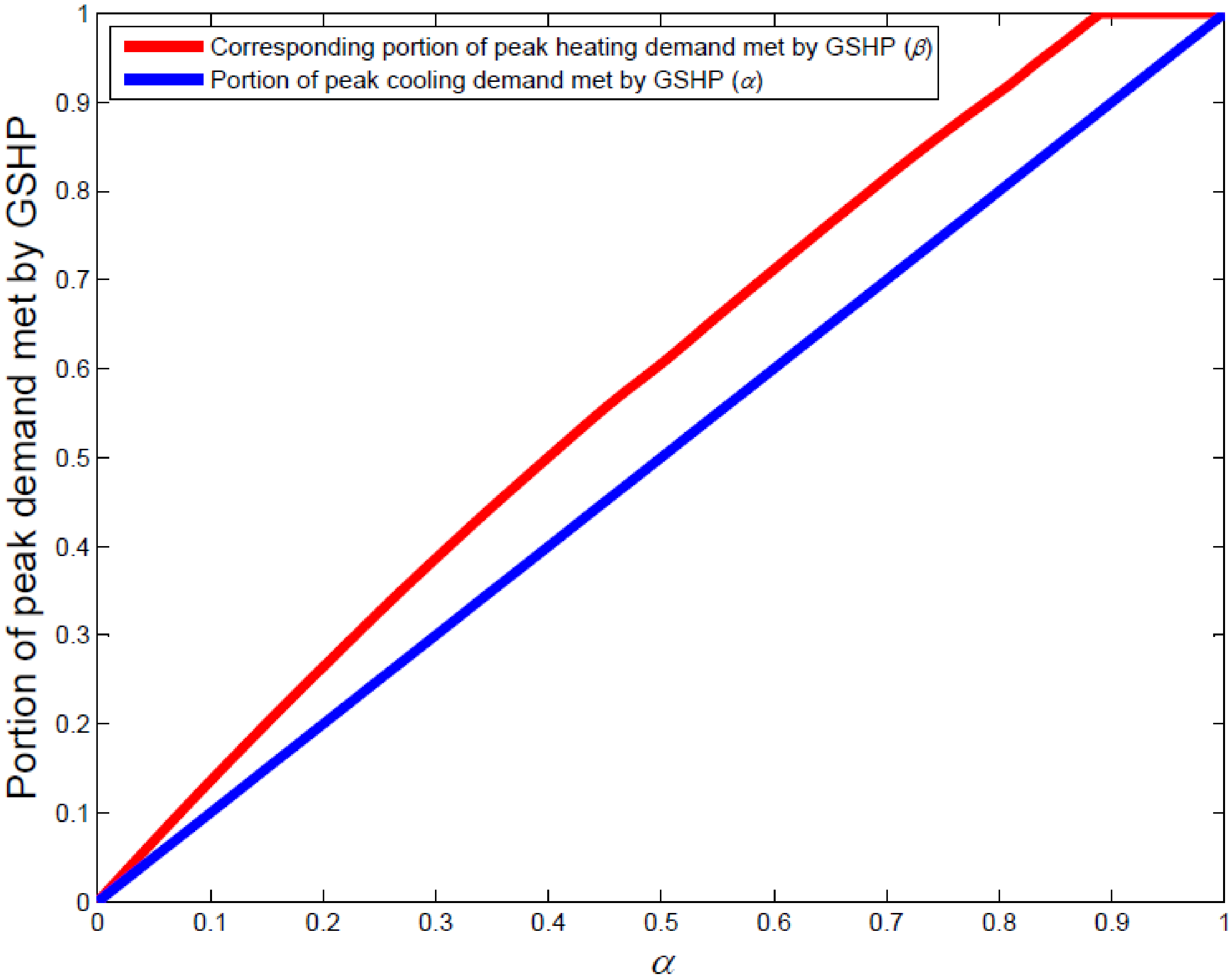

Figure 3.11: Relationship between α and β for a sample cooling dominant building

Table 3.1: Summary of parameters and values used to find the heating and cooling ground-loop lengths (data courtesy of CleanEnergy™)

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™ / PC0018 (COP = 3.1, EER = 12.9)
Ground Temperature	10°C
Soil Thermal Conductivity	2.94 W/m·K
Soil Thermal Diffusivity	0.072 m^2/day
Expected lifespan	20 years
Borehole Thermal Resistance	0.136 m·K/W
Pipe Resistance	0.06 m·K/W
Pipe Diameter	32 mm
Borehole Diameter	127 mm
Grout Thermal Conductivity	1.47 W/m·K
Number of boreholes across from the borehole pattern	11
Number of boreholes down the borehole pattern	4

According to the block diagram of the methodology (Fig. 3.5), the next steps (steps 8, 9, and 10) are to calculate the total *NPV* for each value of α according to Eq. (3.5). Fig. 3.12 shows the variation of initial costs, the *NPV* of annual operation costs, and the *NPV* of total costs of the hybrid GSHP for the cooling dominant transit facility as a function of α. The calculations are based on assumed costs outlined in Table 3.2.

Table 3.2: Cost calculation basis (data courtesy of CleanEnergy™)

Item	Cost/Value
Ground heat exchanger (installation and materials)	\$65.6/meter
Cooling tower, and plate heat exchanger including controls and auxiliary equipment (COP = 2.0); note that the value of COP is chosen as an average over a 20 years of life span, considering performance degradation, but in many cases may be higher.	\$12/kW of tower design capacity
Boiler (efficiency = 78%)	\$20/kW of boiler design capacity
Electricity	\$0.17/kWh
Natural Gas	\$0.35/m^3
Interest Rate (IR)	8%
Inflation Rate	4%

Note that choosing different but reasonable values in Tables 3.1 and 3.2 may slightly change the numerical results but is not expected to significantly affect the conclusions. Thus, it is assumed in the study that the cooling tower will be sized sufficiently large to meet the peak cooling demand of a building when $\alpha = 0$.

As α increases, the proportion of peak cooling demand met by the GSHP increases, necessitating a longer ground loop and therefore higher installation costs. It is evident from Fig. 3.12 that the installation costs increase monotonically with α as expected. It can also be seen that the *NPV* of the operating costs decreases with α because less boiler fuel and chiller/cooling tower electricity are needed as the GSHP capacity is increased. Combining these two effects, we can obtain a total *NPV* curve, shown in dotted lines, the minimum of which corresponds to the optimal α. For this transit facility the optimal value of α is 0.48.

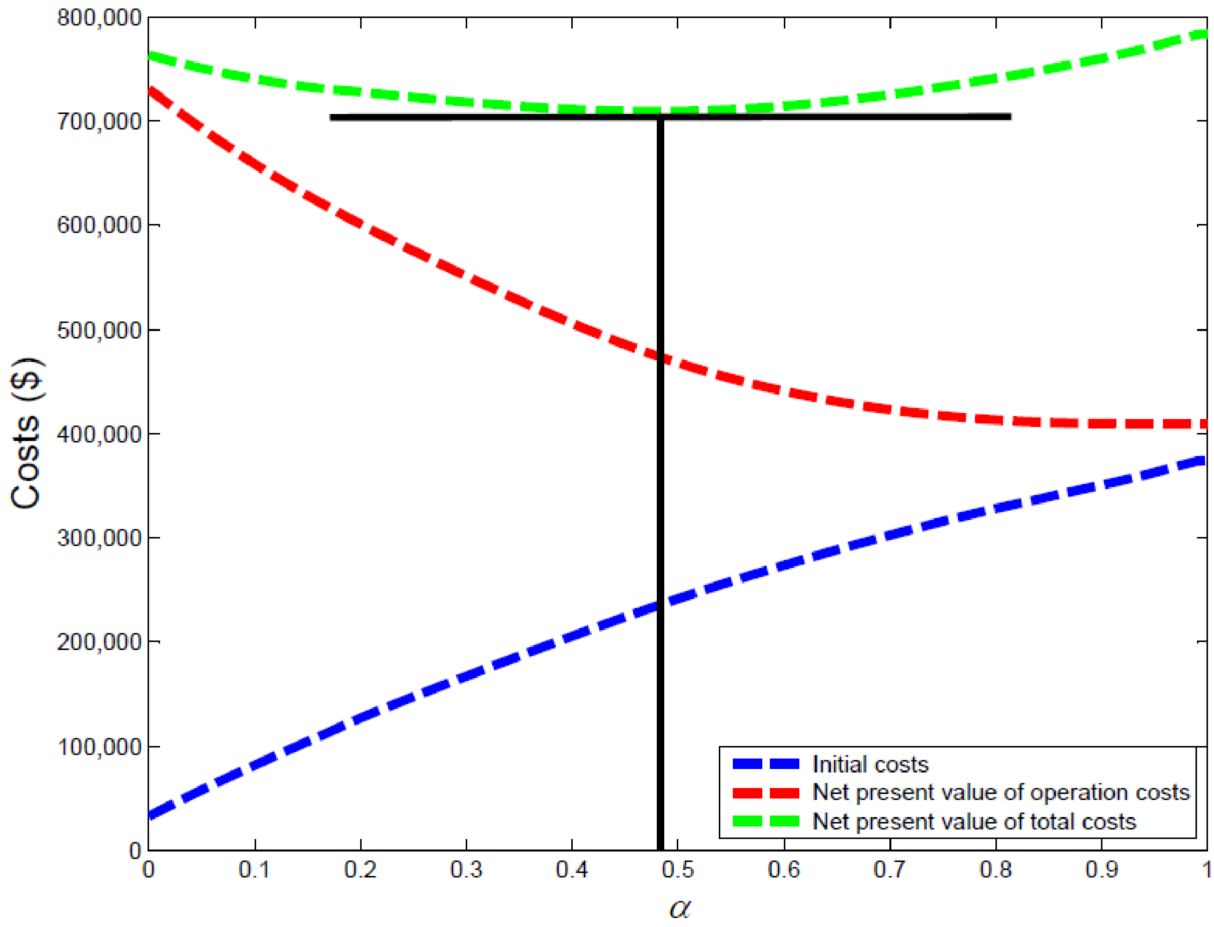

Figure 3.12: Initial costs of a hybrid GSHP system (dashed-blue), net present value of operation costs (dashed-red), and net present value of total costs (dashed-green) for the transit facility as a function of α

In Fig. 3.12, the horizontal and vertical black lines show how the optimal value of α is found, corresponding to the minimum *NPV* of total costs.

A cost analysis is conducted to compare the system specified by the current methodology with three different systems, namely: a GSHP system only (corresponding to α = 1), a conventional system only (α = 0), and a system that follows the CSA rule of thumb for residential buildings (α = 0.7). The results are shown in Table 3.3.

Table 3.3: Cost analysis and comparison between different systems for the transit facility

α (% of peak cooling demand met by GSHP)	Total Ground Loop Length (m)	β (% of peak heating demand met by GSHP)	Total cooling demand met (%)	Total heating demand met (%)	Net Present Value ($)	Initial Costs($)	Payback Period (years)
0 (conventional only system)	0	0	0	0	775,704	51,141	0
48 (optimal system)	3317	1	80	100	709,252	234,680	12
70 (CSA suggested system)	4460	1	95	100	725,382	302,429	17
100 (GSHP only)	5705	1	100	100	783,680	374,294	19

Some important observations may be made from Table 3.3. When the ground heat exchanger is sized based on the optimal α, the ground-loop length required is reduced by 2388 m (~41%) as compared to α = 1, and by 1143 meters (25%) as compared to α = 0.7. This reduction corresponds to a very large amount of savings in initial costs (~$140,000 or 37%, as compared to α = 1 and ~$68,000 or 22%, as compared to α = 0.7). Note that α = 0.7 is specified for residential buildings, and would not normally be used for a transit facility. In fact, before this study, an installation was performed at the site with α = 1.0.

Although the optimal GSHP is only meeting 48% of the peak cooling demand (noting that for the case of α = 0.48, β = 1), it is still able to provide a very large portion of the *total* annual cooling demand (80%) and *all* the total annual heating demand of the transit facility (100%). When considering the value added of each additional unit of ground-loop length, it can be said that the first 3317 m (out of 5705 m) can meet 90% of the total energy demand, and the next 2388 m only meet the remaining 10%. The first 3317 m are likely a good investment for a building owner and the remaining 2388 m likely are not.

Although the initial costs of conventional systems are low compared to hybrid systems, they are not a good choice for heating and cooling in this application in the long term, because they have a higher *NPV* due to high operation costs. Optimally designing the hybrid GSHP for this transit facility would result in a reduction in the payback period from nineteen years to twelve years when compared to the case of $\alpha = 1$ and from seventeen years to twelve years compared to the case of $\alpha = 0.7$. Note that as in common practice, (simple) payback periods have been estimated only roughly, neglecting the effects of interest and inflation.

3.2 Methodology to design hybrid GSHP systems for multiple buildings

Enhancing and utilizing the methodology described in section 3.1, a new methodology is introduced in this section. The methodology aims to determine the *NPV* of total costs, ground loop length (L), and the total heating and cooling demands for a combination of two or more buildings, which is met by the GSHP component of the hybrid system (i.e., in short, total heating and cooling demand met by the GSHP is called "Total Demand Met" (TDM)). Subsequently, the net present values (*NPV*s) of combined buildings are compared with one another, and to the cases in which the buildings are not combined, but rather serviced individually. The methodology is used to automatically compute the savings potential associated with thousands of building combination scenarios, so as to perform a statistical analysis on the potential of the so-called “utility model” for heating and cooling. The procedure of the methodology is shown in the block diagram in Fig. 3.13.

In step 1, the algorithm is initiated, and all input parameters, such as interest rates, inflation rates, etc. are specified.

In step 2, the hourly demand data is read into the program for 100 different commercial/industrial buildings in Southern Ontario. The data, in spreadsheet format, were generated using a building simulation software program called eQuest [6]. The spreadsheet has 200 columns, each having 8760 rows, one for each hour in a year. Odd-numbered columns represent the hourly cooling demands for each building while even-numbered columns represent the hourly heating demands for each building.

Step 3 involves combination of both cooling and heating demands for the buildings. The heating demands of the individual buildings are simply added together and form the heating demands of the building combination. The cooling demands of the individual buildings are added together to form the cooling demands of the building combination. This task is done for 100 different commercial and industrial buildings with various heating and cooling demands. The procedure for this step is best described by introducing a new parameter called NB. NB represents the number of buildings that are combined together out of 100 buildings. Values of NB between two and ten were considered in this study, as it was observed that the results were not influenced by increasing NB beyond ten. To give a clearer explanation of the procedure, suppose that NB = 3. When NB = 3, it means that the cooling and heating demands of three buildings out of 100 buildings are combined. The number of non-repetitive combinations of three buildings is 100-choose-three, written as $\binom{100}{3}$, which gives 161,700 possible combinations. So, there are 161,700 possible ways to combine the demands of three different buildings out of a library of 100 different buildings. Each combination can be treated as a single combined entity requiring both heating and cooling, where the cooling demands are the combined cooling demands of three buildings and the heating demands being the combined heating demands of the same three buildings. Indeed it will take a lot of computational time to consider all 161700 combined entities for NB = 3. By increasing NB from three to ten, the number of combined entities will increase significantly. In order to save computational time, the asymptotic value of average *NPV* of all combined entities is calculated. For this purpose, there is no need to consider all possible building combinations of $\binom{100}{3}$. Rather, a series of systematic numbers of combined entities, for example 100, then 1000, then 5000, then 10000 and so on random cases of $\binom{100}{3}$ are considered until the average *NPV* reaches an asymptotic value to within less than 1% variation. In other words, the program continues to consider combinations of three buildings until the average *NPV* of all the combinations becomes independent of the sample size. It was observed that the average *NPV*s for 5000 and 10000 random combinations are the same for NB = 3 up to NB = 10. This means that considering only 5000 random combinations is statistically satisfactory for this study. Note that all combinations are done for NB = 1 and NB = 2, because for these two cases, the problem of prohibitively long computational time does not exist since $\binom{100}{1}$ is 100 and $\binom{100}{2}$ is 4950.

In step 4, each set of combined buildings will act as a single input building entity for the analysis described in in section 3.1, which determines the optimal hybrid GSHP system design.

In step 5, for each NB, the *NPV*, *L*, and TDM of the combined buildings are compared to the case when each building is serviced individually by its own hybrid GSHP system (i.e., the sum of individual hybrid GSHP systems). A parameter γ is introduced as the ratio of the sum of the *NPV*s of the individual buildings to the *NPV* of a combined building comprising those same individual buildings. The γ will act as a measure to judge the effectiveness of combining buildings onto a single hybrid GSHP system for various scenarios. For example when two (suppose building A and building B) of the one hundred buildings are combined (NB = 2), the *NPV* of the combined entity [*NPV* (A + B)] will be compared to the sum of the NPVs of buildings A and B [*NPV* (A) + *NPV* (B)]. For this case, γ will be calculated using Eq. (3.6):

$$\gamma = \frac{[NPV\ (\mathrm{A})\ +\ NPV\ (\mathrm{B})]}{[NPV\ (\mathrm{A}\ +\ \mathrm{B})]} \tag{3.6}$$

It is clear that when γ is greater than unity, combining buildings onto a single hybrid GSHP system can be effective and worthwhile. The higher the value of γ the more economical it is to combine buildings. Note that in computing γ, no assumptions have been made about energy losses associated with an increased-length common water loop, or with the need for additional heat pumps. Estimating these losses requires further study that would include significant industrial collaboration and system monitoring. Rather the purpose of the calculation and analysis of values of γ is to identify scenarios that are particularly well suited to the utility model, and identify their characteristics. In addition, it will permit the quantification of the proportion of combinations (and thus the appeal of the concept) that is particularly well suited to the utility model.

Step 6 terminates the program.

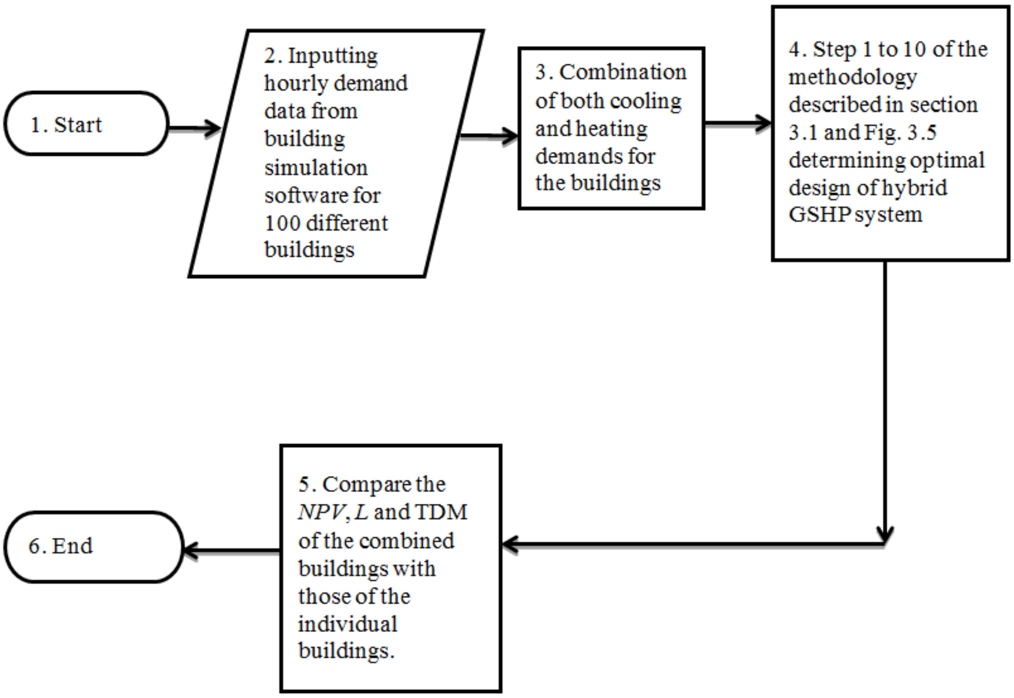

Figure 3.13: Block diagram of the new methodology to assess the potential savings associated with building combinations

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Results and discussions for individual buildings

The calculations and methodology described in section 3.1 have been carried out for a total of ten different buildings of varying size, occupancy, and function. The results are summarized in Table 8.1. In Table 8.1, *NPV* stands for Net Present Value of total costs and *PBP* for Pay Back Period. Consistent with the 0.7 rule of thumb recommendation, for residential buildings only, Eqs. (4.1) and (4.2) are used, while for other building types, Eqs. (4.3) and (4.4) are used:

$$\Delta NPV = NPV_{\alpha=0.7} - NPV_{\alpha_{opt}} \tag{4.1}$$

$$\Delta PBP = PBP_{\alpha=0.7} - PBP_{\alpha_{opt}} \tag{4.2}$$

$$\Delta NPV = NPV_{\alpha=1} - NPV_{\alpha_{opt}} \tag{4.3}$$

$$\Delta PBP = PBP_{\alpha=1} - PBP_{\alpha_{opt}} \tag{4.4}$$

Note that GSHP installations were recently performed for nine of these buildings (all except for #6, the office) with α or β equals to unity, depending on whether the building is cooling or heating dominant.

Apart from the transit facility analyzed in section 3.1.1, the second building analyzed was a cooling dominant fast food restaurant for which the optimal α was 0.64. The corresponding β for this building was unity. This means that the GSHP meets 64% of the peak cooling demand and 100% of the peak heating demand. About 96% of the total building energy demands would be met by the GSHP. The net present value was reduced by \$22,000. The payback period was reduced by three years.

The third building analyzed was another cooling dominant restaurant for which the optimal α was 0.66. The corresponding β for this building was unity. This means that the GSHP meets 66% of the peak cooling demand and 100% of the peak heating demand. About 93% of the total building energy demands would be met by the GSHP. The net present value was reduced by \$14,000. The payback period was reduced by 1.2 years.

The forth building analyzed was a cooling dominant school for which the optimal α was 0.27. The corresponding β for this building was 0.35. This means that the GSHP meets 27% of the peak cooling demand and 35% of the peak heating demand. About 70% of the total building energy demands would be met by the GSHP. The net present value was reduced by \$66,000. The payback period was reduced by eight years.

The fifth building analyzed was a heating dominant hospital for which the optimal β was 0.24. The corresponding α for this building was 0.26. This means that the GSHP meets 24% of the peak heating demand and 26% of the peak cooling demand. About 62% of the total building energy demands would be met by the GSHP. The net present value was reduced by \$85,000. The payback period was reduced by seven years.

The sixth building analyzed was a heating dominant office for which β was 0.0. No GSHP should be installed for this building. As the building is very heating dominant, it has little cooling demand and therefore limited potential to offset air conditioning costs. In addition natural gas prices of Toronto in 2012 (used here) are relatively low and also provide little savings potential.

The seventh building analyzed was a cooling dominant high-rise, multi-residential retirement home for which the optimal α was 0.36. The corresponding β for this building was unity. This means that the GSHP meets 36% of the peak cooling demand and 100% of the peak heating demand. About 88% of the total building energy demands would be met by the GSHP. The net present value was reduced by \$53,000. The payback period was reduced by five years.

The eighth building analyzed was a cooling dominant mid-rise, multi-residential retirement home for which the optimal α was 0.26. The corresponding β for this building was unity. This means that the GSHP meets 26% of the peak cooling demand and 100% of the peak heat demand. About 80% of the total building energy demands would be met by the GSHP. The net present value was reduced by \$50,000. The payback period was reduced by six years.

The ninth building analyzed was a cooling dominant high-rise, multi-residential condominium for which the optimal α was 0.25. The corresponding β for this building was unity. This means that the GSHP meets 25% of the peak cooling demand and 100% of the peak heating demand. About 75% of the total building energy demands would be met by the GSHP. The net present value was reduced by \$10,000. The payback period was reduced by five years.

The tenth building analyzed was a cooling dominant high-rise, multi-residential condominium for which the optimal α was 0.42. The corresponding β for this building was unity. This means that the GSHP meets 42% of the peak cooling demand and 100% of the peak heating demand. About 87% of the total building energy demands would be met by the GSHP. The net present value was reduced by $6,000. The payback period was reduced by four years.

The optimal values of α and β vary over a wide range between 0.25 and 0.66. Indeed these results indicate that the 70% rule of thumb presented by Canadian Standard Association for residential buildings may be far from optimum and can vary case by case. For example, although buildings #7 through #10 are residential, the optimum GSHP capacity is not always 70% and varies from a range of 25% to 42%.

Table 4.1: Cost analysis and comparison among all ten buildings studied

Building #	Type	**HD**/CD	$\alpha\ (\boldsymbol{\beta})_{opt}$	$\beta\ (\boldsymbol{\alpha})$	Total Energy Demand Met	ΔNPV($) ($NPV$ savings)	ΔPBP (Years)
1	Transit Facility	CD	0.48	1	90%	74,500 (11%)	7 (from 19 to 12)
2	Fast Food Restaurant	CD	0.64	1	96%	22,000 (5%)	3 (from 14 to 11)
3	Restaurant	CD	0.66	1	98%	14,000 (4%)	1.2 (from 13 to 11.8)
4	School	CD	0.27	0.35	70%	66,000 (19%)	8 (from 17 to 11)
5	Hospital	**HD**	**0.24**	**0.26**	**62%**	**85,000 (19%)**	**7 (from 15 to 8)**
6	Office	**HD**	**0**	**0**	**0%**	**N/A (N/A)**	**N/A**
7	Mid-rise, Multi-residential retirement homes	CD	0.36	1	88%	53,000 (15%)	5 (from 13 to 8)
8	High-rise, Multi-residential retirement homes	CD	0.26	1	80%	50,000 (17%)	6 (from 14 to 8)
9	High-rise, Multi-residential condominium	CD	0.25	1	75%	10,000 (15%)	5 (from 15 to 5)
10	High-rise, Multi-residential condominium	CD	0.42	1	87%	6,000 (12%)	4 (from 14 to 10)

In Table 4.1, CD stands for 'cooling dominant' and HD stands for 'heating dominant'. As can be seen from Table 4.1, excluding building #6 for which it was not economically viable to install a hybrid GSHP system, the percentage of cost reduction among the buildings ranges from 4% to 19%, with an average of 12.6%. The hospital and the school are the two buildings which have particularly high *NPV* saving potential, each with 19% *NPV* savings. High savings potential for these two buildings may be attributed to the fact that α and β for each of those two buildings is low, very far from the case when the GSHP meets 100% of the peak demands (α =1 and β =1). This means that α = 1 and β = 1 are particularly bad designs for these buildings, worse than for the buildings where α and β are closer to 1, and optimizing the design has a greater benefit. The much lower savings potential for the very heating dominant office building and the very cooling dominant restaurants suggest that it may be less economically appealing (or in some cases ill-advised) to install a hybrid GSHP system for buildings which are extremely cooling or heating dominant.

Another interesting result of the methodology can be best described by looking at the *PBP* values, comparing to the 70% rule of thumb method presented by the CSA [22] for residential buildings or to non-hybrid systems for non-residential buildings, the *PBP* values range from 13 to 17 years. However, using this methodology can lead to a significant reduction (1.2 to 8 years) in the *PBP*, indicating that it may be more logical to install hybrid GSHP systems, when the hybrid systems are properly designed. It is the hope that this new understanding of hybrid system optimization will help remove some of the currently remaining economic obstacles to further market penetration.

4.2 Results and discussions for multiple buildings

The calculations and methodology described in section 3.2 have been carried out for 100 different commercial/industrial buildings. The results can be categorized for values of NB from two to ten.

Case I) NB = 2:

Out of 4950 ways to combine two out of 100 buildings, 4863 combined entities (about 98.2% of all possible combinations) had a value of γ greater than unity, where values of γ greater than unity indicate potential savings associated with combining buildings. Table 4.2 provides a summary of the results for this case in descending order with respect to γ.

Table 4.2: Summary of the results for NB = 2 with comparison to individual buildings

Case #	Building # (HD or CD)		$L_A + L_B$ (m)	L_{A+B} (m)	TDM_A	TDM_B	TDM_{A+B}	*NPV* Savings	γ
	A	B							
1	77(CD)	95(HD)	17,809	10,470	97%	0%	89%	49%	1.98
2	87(CD)	95(HD)	17,117	9049	98%	0%	85%	48%	1.93
3	27(CD)	95(HD)	13,499	5953	98%	0%	80%	44%	1.78
4	37(CD)	95(HD)	13,502	5953	98%	0%	80%	44%	1.78
5	83(CD)	95(HD)	20,902	13,700	91%	0%	84%	41%	1.71
….	….	….	….	….	….	….	….	….	….
2475	13(CD)	29(CD)	23,918	23,714	75%	80%	76%	4%	1.05
….	….	….	….	….	….	….	….	….	….
4863	49(CD)	59(CD)	14367	14368	76%	72%	74%	0%	1.00
….	….	….	….	….	….	….	….	….	….
4946	47(HD)	80(HD)	71,353	71,346	78%	62%	70%	-0.8%	0.99
4947	19(CD)	69(CD)	15,910	15,219	87%	56%	66%	-0.9%	0.99
4948	69(CD)	79(CD)	16,295	13,038	56%	88%	65%	-0.9%	0.99
4949	29(CD)	69(CD)	16,426	14,096	85%	56%	63%	-1%	0.99
4950	69(HD)	89(HD)	15,687	14,239	56%	85%	63%	-1.1%	0.98

In Table 4.2, heating dominant buildings are shown by 'HD' and cooling dominant buildings are represented by 'CD'. The '*NPV* Savings' represents the potential savings associated with combining buildings, *i.e.*, it is the relative difference between servicing the two buildings individually versus combining them. For example, the percent of *NPV* savings associated with combining two buildings, *A* and *B* is calculated via Eq. (4.1):

$$NPV \text{ savings } (\%) = \frac{[NPV_A + NPV_B] - NPV_{A+B}}{NPV_A + NPV_B} \times 100 \tag{4.1}$$

Recall from the methodology previously described in section 3.1 that α (β) is the portion of the peak building demand that the GSHP component of the hybrid system meets for a cooling (heating) dominant building. It can be seen from Table 4.2 that in cases 1 through 5 (the most economical combinations), a heating dominant building with $\beta = 0$ (#95) is combined with a cooling dominant building (#77, #87, #27, #37, or #83, respectively). These combinations will lead to greater values of *NPV* savings, ranging from 41% to 49%. Interestingly, including building #95, for which an individual installation was not economical, in a combination with a cooling dominant building, not only results in a viable installation and overall savings, but results in some of the greatest savings potential. Therefore, as GSHPs become more and more commonplace, building combinations may provide a way in which some buildings could have heating and cooling provided by GSHPs as part of a utility model or combination when it would otherwise not be economically viable.

High *NPV* savings in cases 1 through 5 in Table 4.2 are mainly caused by the noticeable reduction in L compared to the summed ground loop length of individual loops. This is because when a cooling dominant building is combined with a heating dominant building, they partially offset the heating and cooling demands of one another leaving a small balance for the hybrid GSHP system to provide, thus resulting in a much smaller ground loop size. For instance, the ground loop length of the combined buildings (L_{A+B}) in case 1 is 7339 m shorter than that of sum of the individual buildings ($L_A + L_B$).

Another perspective which shows the value of combining buildings can be best described by looking at the total building energy demand met (TDM) by the GSHP system. When a heating dominant building (e.g., #95) is combined with a cooling dominant building, the smaller GSHP size can still meet a significant amount of the total energy demand (more than 80%) of the combined entity, leaving less than 20% of the total heating and cooling demands to be met by the conventional systems.

The cases for which the values of γ are less than unity (the last five cases in Table 4.2) are when two cooling dominant buildings or two heating dominant buildings are combined. As an example, the restaurants considered in this study are cooling dominant buildings as they generate a lot of heat in their kitchens, and require a significant amount of cooling to maintain a comfortable indoor temperature, sometimes even in the winter months. The results in Table 4.2 show that in many cases, it is not economically viable to combine two cooling or two heating dominant buildings onto a single hybrid GSHP system. Two buildings that require a substantial amount of simultaneous heating or a substantial amount of simultaneous cooling do not take advantage of being connected by a common water loop, which would otherwise allow heat transfer from one building to another. In fact, two such buildings are best serviced by individual hybrid systems, eliminating losses associated with conveying heat throughout a common water loop.

A statistical representation of the results for NB = 2 is shown in Table 4.3. γ_{cutoff}, in the first column of Table 4.3 is defined as the minimum value of γ of building combinations considered in each row of the Table. In the second column, Table 4.3 shows the number of building combinations, out of a possible 4950, with a value of $\gamma \geq \gamma_{cutoff}$. For example, 14 out of 4950 building combinations had a value of γ greater than or equal to 1.6. The third column of Table 4.3 shows the minimum amount of savings that could potentially be realized for the building combinations with $\gamma \geq \gamma_{cutoff}$. For example, considering the building combinations with γ_{cutoff} =1.6, the savings potential would be 40% or greater.

Table 4.3: Statistical analysis for NB = 2

γ_{cutoff}	Number of buildings out of 4950 with $\gamma \geq \gamma_{cutoff}$	Minimum *NPV* Savings
1.9	2	48%
1.8	2	48%
1.7	5	42%
1.6	14	40%
1.5	23	34%
1.4	41	29%
1.3	84	24%
1.2	281	17%
1.1	1068	9%
1	4863	0%

Recalling from section 3.2 that in computing γ, no assumptions have been made about energy losses associated with an increased-length common water loop, or with the need for additional heat pumps, therefore, the third column of Table 4.3 can only be described as a best case potential, which neglects some inevitable losses. It is beyond the scope of this work to quantify those losses but it would be a worthwhile study. It can be seen from Table 4.2 that combining two out of 100 buildings will give an *NPV* savings of between 49% and -1%. This range demonstrates that the savings potential is much greater than loss potential.

As can be seen from Table 4.3, two of the combinations had a minimum savings potential of 48%. This means that as long as the losses associated with the common water loop is less than 48%, their combination is worthwhile.

Moving down the list in Table 4.3, very few building combinations have $\gamma \geq \gamma_{cutoff}$ until $\gamma_{cutoff} = 1.1$. Here, it can be seen from Table 4.3 that 1068 of 4950 buildings (21%) have a minimum savings potential of 9% which means that as long as there is less than 9% losses associated with the heat pumps and the common water loop, 21% of combinations become worthwhile. The table also demonstrates the need to use the present type of quantification and analysis when considering combining buildings onto a single system, as in many cases, combining two buildings would be ill-advised.

Case II) NB = 3:

Out of a random sample of 5000 ways to combine three out of 100 buildings, 4993 combined entities had a value of γ greater than unity. Table 4.4 provides a summary of results in this case in descending order with respect to γ.

In Table 4.4, only buildings #95 and #92 are heating dominant; all others are cooling dominant. It can be seen from Table 4.4 that in cases 1 through 5, a heating dominant building (#95) with $\beta = 0$ (*i.e.*, no viable hybrid GSHP system) is combined with two cooling dominant buildings. These combinations will lead to a great value of *NPV* savings, ranging from 46% to 50%. Similar results as Case I can be concluded from Table 4.4

Table 4.4: Summary of the results for NB = 3 with comparison to individual buildings

Case #	Building #			L_A+L_B+L_C (m)	L_{A+B+C} (m)	TDM_A	TDM_B	TDM_C	TDM_{A+B+C}	*NPV* Savings	γ
	A	B	C								
1	6	77	95	60,449	40,228	94%	97%	0%	90%	50%	2.00
2	26	87	95	57,344	34,111	95%	98%	0%	90%	49%	1.95
3	50	77	95	74,141	36,172	75%	97%	0%	82%	47%	1.90
4	60	87	95	72,610	38,017	74%	98%	0%	82%	47%	1.89
5	87	72	95	81,065	45,963	98%	90%	0%	88%	46%	1.85
….	….	….	….	….	….	….	….	….		….	….
2500	92	41	58	43,399	42,520	60%	79%	70%	68%	7%	1.07
….	….	….	….	….	….	….	….	….		….	….
4996	37	36	80	118,586	115,842	76%	78%	60%	67%	-0.05%	0.99
4997	29	19	59	33,110	31,103	58%	82%	68%	65%	-0.11%	0.99
4998	47	37	80	110,692	109,662	56%	75%	69%	65%	-0.21%	0.99
4999	34	80	57	133,810	129,432	59%	77%	68%	64%	-0.30%	0.99
5000	59	69	19	22,157	21,801	56%	70%	60%	63%	-0.56%	0.99

A statistical representation of the results for NB = 3 is shown in Table 4.5. It can be seen from Table 4.4 that combining three out of 100 buildings will give an *NPV* savings of between 50% and -1%. This range again demonstrates that the savings potential is much greater than loss potential.

Table 4.5: Statistical analysis for NB = 3

γ_{cutoff}	Number of buildings out of 5000 with $\gamma \geq \gamma_{cutoff}$	Minimum *NPV* Savings
1.9	3	48%
1.8	8	45%
1.7	19	42%
1.6	30	40%
1.5	52	34%
1.4	80	28%
1.3	139	23%
1.2	394	17%
1.1	1748	9%
1	4993	0%

As can be seen from Table 4.5, the three most appealing building combinations had a minimum savings potential of 48%. This means that as long as the losses associated with the common water loop is less than 48%, their combination is worthwhile.

Moving down the list in Table 4.5, again the results are comparable to those of combining two buildings. Very few building combinations have $\gamma \geq \gamma_{cutoff}$ until $\gamma_{cutoff} = 1.1$. Here, it can be seen from Table 4.5 that 1748 of 5000 buildings (35%) have a minimum savings potential of 9% which means that as long as there is less than 9% losses associated with the heat pumps and the common water loop, 35% of combinations become worthwhile. The table also demonstrates the need to use the present type of quantification and analysis when considering combining buildings onto a single system, as in many cases, combining three buildings would be ill-advised. Comparing Table 4.5 to Table 4.3 (the summary of the data for two-building combinations), one notes that for each γ_{cutoff}, the number of buildings in Table 4.5 are always higher. Therefore, a larger portion of the approximately 5000 combined entities have associated values of γ above any given threshold. The indication is that as the number of buildings combined is increased from two to three, the savings potential increases. However, as the number of buildings in a combined entity increases, a larger heat distribution system or common water loop would be needed, introducing more losses. Therefore, although the present study provides a methodology for understanding the effects of combining buildings onto a single hybrid system, conclusions about optimal numbers of buildings to combine will be beyond the scope of this work.

Case IV) NB = 4, 5, and 6…10:

5000 ways to combine four, five, six, seven, eight, nine and ten out of 100 buildings have also been analyzed. Similar results to the earlier presented cases are obtained and can be found in appendix A. The results suggest that to have significant energy and cost savings, it is best to combine heating dominant buildings with cooling dominant buildings and that it may not be beneficial to combine only cooling dominant buildings or only heating dominant buildings onto a single hybrid GSHP system. As NB is increased, the maximum γ among the 5000 samples decreases but the minimum γ increases, indicating that range of γ is narrowing as NB increases. Furthermore, the median and mean γ, and thus the potential benefit, increase with NB. . However, still, the best cases to combine the buildings economically are when heating dominant and cooling dominant buildings are combined. More detailed description as to what happens when NB increases will follow in the next section.

4.2.1 Statistical Analysis

A statistical analysis of the number of buildings with a value of γ greater than or equal to γ_{cutoff} for NB = 2 through 10 is shown in Table 4.6. γ_{cutoff}, the first column (in bold) of Table 4.6, ranges from 1.0 to 1.9 with a step size of 0.1. NB, the first row (in bold) of Table 4.6, shows the number of building combined into an entity, ranging from two to ten. For example, when combining four buildings out of 100 hundred buildings (NB = 4), there are 197 entities (building combinations) which have a value of γ greater than or equal to 1.3 (γ_{cutoff}).

Table 4.6: Statistical analysis for NB = 2 to 10

		NB								
		2	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
γ_{cutoff}	**1.9**	2	3	0	0	0	0	0	0	0
	1.8	2	8	6	5	0	0	0	0	0
	1.7	5	19	10	6	5	0	0	0	0
	1.6	14	30	27	16	8	7	6	4	0
	1.5	23	52	66	60	51	30	19	9	8
	1.4	41	80	120	140	152	119	110	79	59
	1.3	84	139	197	227	275	292	314	309	315
	1.2	281	394	507	536	545	569	590	625	662
	1.1	1068	1748	2221	2536	2771	2999	3141	3307	3413
	1.0	4863	4993	5000	5000	5000	5000	5000	5000	5000

As can be seen from Table 4.6, generally, by increasing the number of buildings combined (NB) greater than four, less entities tend to have high values of γ (around 1.5 or 1.6) and more entities will have low values of γ. For example, consider γ_{cutoff} = 1.4, until NB = 6, the number of entities which have a value of $\gamma \geq 1.4$ increases, but beyond NB = 6, the number of entities which have a value of $\gamma \geq 1.4$ decreases (from 152 to 119, then 110, 79, and 59, respectively). The reason for this decrease is that, beyond NB = 6, more entities will have a lower value of γ than 1.4. In Table 4.6, it is evident that this increasing and then decreasing pattern is only present for $\gamma_{cutoff} \geq 1.4$. For $\gamma_{cutoff} < 1.4$, the number of entities increases monotonically. As the number of buildings combined is increased from two to ten, the range of γ values tends to get narrower. The fact that the range of γ values gets narrower is very interesting. This means that as NB increases, there may be less potential benefit to the best cases combinations, but less risk in combinations in general.

As NB increases, both median and average γ among the 5000 samples increases. This is an indication that combinations are generally becoming more worthwhile and there will be more potential for savings. For each increment in NB, average γ increases by approximately 0.3%. This result is a promising one for the movement toward larger and larger building groupings, however, losses associated with the common water loop are still unknown, and will likely work to counteract this benefit to some extent

Based on the analysis above, some important recommendations can be drawn for the designers of hybrid GSHP systems for multiple buildings. This type of methodology can indicate what number of buildings is best combined. For example, for the building types considered in this study, if a γ_{cutoff} of 1.4 is required for the design, it would be best to consider combinations of up to six buildings. Combining more than six buildings would lead to lower γ and thus less savings. The same recommendations can be made for $\gamma_{cutoff} \geq 1.4$ by examining Table 4.6. For example, if a γ_{cutoff} of 1.5 is desired, it is recommended that only up to 4 buildings are combined. The calculations would have to be repeated, however, for different buildings, different price structures, or different weather patterns, etc. The numbers may vary from dataset to dataset but the trends and concepts discussed here would remain consistent.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

A new strategy has been introduced for determining the optimal GSHP capacity in hybrid systems. A rigorous computer program determines the optimum extent to which a GSHP as part of a hybrid system should be sized to meet peak building demands. The methodology works with a target of minimizing the net present value of total costs over a twenty year system lifespan, including installation and operating costs of both the GSHP and the conventional system. It has been tested for ten buildings that include large residential, and commercial or industrial structures. Using this methodology can potentially lead to significant reductions in initial costs of installation, payback period, and operation costs, while still having the GSHP system meet a very large portion of heating and cooling demand of a building. Among the ten buildings studied, the optimum α (β), which is the ratio of GSHP capacity to the peak cooling (heating) demand of a building, varied between 0.25 and 0.66. The results indicate that the rule of thumb presented by Canadian Standard Association of 0.7 for residential buildings may be far from optimum, and shows that for commercial and industrial buildings, hybrid system optimization should be performed as well. High savings potential is predictable for buildings which have much lower values of α and β than the CSA [22] rule of thumb of 0.7, or the standard design procedure of having a GSHP only. Much lower savings potential can be obtained for very heating dominant or very cooling dominant buildings. Using this methodology can also lead to a significant reduction (1.2 to 8 years) in the *PBP*, making it more logical to install hybrid GSHP systems with a faster return on investment.

In the second part of this study, enhancing and utilizing the first methodology, a second methodology is introduced in which one hundred commercial/industrial buildings are randomly combined into groups of two to ten buildings, sharing a hybrid GSHP system and common water loop, to understand the effectiveness of employing a district hybrid GSHP system for multiple buildings. It was found that combining multiple commercial/industrial buildings onto a single hybrid GSHP system is most effective when heating and cooling dominant buildings are combined together. The main reason for that is because when multiple heating and cooling dominant buildings are combined together, they meet the heating and cooling demands of each other, thus reducing the required capacity of the hybrid GSHP system. Such intelligently chosen combinations would result in reducing the *NPV*, increasing the potential savings, and still having a GSHP meet a significant amount of the heating and cooling demands of the combined entity. An interesting result is that when combining buildings, the savings potential is much greater than loss potential. As long as the losses associated with the common water loop are less than the potential gains, the combination of buildings is worthwhile. Another interesting conclusion is that, while the savings potential of the most intelligently chosen (best suited) combinations decreases with the number of buildings combined, the average savings potential increases.

While this study has shed light on the utility of mathematical optimization of hybrid systems, many questions have also arisen that may now become the subjects of further inquiry. The sensitivity of the observations presented herein to the potential use of time-of-use electricity rates, annual weather data and soil thermal properties for various geographic locations should be investigated. The potential savings associated with combining multiple *residential* neighboring buildings onto a single district system will also be explored. Optimization should also be considered with the target of minimizing CO_2 emissions instead of the *NPV*. A sensitivity study on soil properties, such as soil thermal conductivity and diffusivity will also be investigated. Furthermore, there is also a need to assess and quantify the losses that would be incurred associated with connecting multiple buildings onto a common water loop. Such a study would likely involve monitoring installed systems, as well as calculation, optimization, and data analysis.

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APPENDIX A

In the appendix A the results according to section 4.2 are presented. Tables A-1 through A-7 present the summary of the results for NB = 4 to NB = 10 respectively.

Table A-1: Summary of the results for NB = 4 with comparison to individual buildings

Case #	L_A+…L_D (m)	$L_{A…+D}$ (m)	TDM_A	TDM_B	TDM_C	TDM_D	$TDM_{A…D}$	*NPV* Savings	γ
1	80,719	46,287	93%	86%	97%	0%	91%	45%	1.85
2	73,643	37,901	0%	60%	90%	70%	88%	45%	1.83
3	96,014	56,411	56%	76%	97%	87%	87%	44%	1.81
4	98,089	60,401	56%	98%	97%	0%	87%	44%	1.80
5	102,580	63,468	98%	97%	0	82%	87%	44%	1.80
….	….	….	….		….	….	….	….	….
2500	43,399	42,520	60%	56%	74%	63%	65%	8%	1.09
….	….	….	….		….	….		….	….
4996	118,586	115,842	56%	76%	68%	53%	62%	0%	1.00
4997	33,110	31,103	59%	61%	97%	39%	62%	0%	1.00
4998	110,692	109,662	54%	60%	63%	59%	60%	0%	1.00
4999	133,810	129,432	59%	80%	77%	38%	60%	-0.48%	0.99
5000	22,157	21,801	56%	31%	69%	80%	59%	-0.55%	0.99

In Tables A-2 to A-7, L_T represents the sum of ground loop lengths of the individual buildings whereas L_C represents the ground loop length of the combined buildings. TDM_C represents the total energy demand met by the GSHP system for the combined buildings.

Table A-2: Summary of the results for NB = 5

Case #	L_T (m)	L_C (m)	TDM_C	*NPV* Savings	γ
1	24,109	13,460	92%	46%	1.86
2	34,391	21,126	89%	45%	1.81
3	26,195	18,195	86%	43%	1.75
4	35,338	22,630	86%	42%	1.74
5	37,782	24,053	85%	42%	1.72
….	….	….	….	….	….
2500	42,172	40,955	66%	9%	1.10
….	….	….	….	….	….
4996	79,108	81,372	63%	0.15%	1.00
4997	81,775	81,373	63%	0.14%	1.00
4998	65,693	67,046	59%	0.13%	1.00
4999	62,768	63,405	59%	0.12%	1.00
5000	66,215	66,812	58%	0.12%	1.00

Table A-3: Summary of the results for NB = 6

Case #	L_T (m)	L_C (m)	TDM_C	*NPV* Savings	γ
1	34,617	21,847	90%	42%	1.74
2	21,659	17,614	88%	42%	1.73
3	34,632	21,190	87%	41%	1.70
4	42,917	26,916	86%	40%	1.66
5	29,568	18,107	86%	39%	1.64
….	….	….	….	….	….
2500	62,675	60,435	66%	9%	1.10
….	….	….	….	….	….
4996	72,458	75,777	61%	0.37%	1.00
4997	76,026	77,914	62%	0.37%	1.00
4998	76,274	77,117	58%	0.36%	1.00
4999	99,027	99,477	58%	0.35%	1.00
5000	88,380	94,524	56%	0.35%	1.00

Table A-4: Summary of the results for NB = 7

Case #	L_T (m)	L_C (m)	TDM_C	*NPV* Savings	γ
1	30,340	18,233	89%	40%	1.65
2	34,338	22,926	87%	39%	1.64
3	32,414	20,429	87%	39%	1.63
4	32,926	21,084	85%	38%	1.63
5	45,099	31,973	85%	38%	1.62
….	….	….	….	….	….
2500	36,738	34,561	64%	10%	1.11
….	….	….	….	….	….
4996	75,622	77,128	61%	0.95%	1.01
4997	135,729	133,039	61%	0.95%	1.01
4998	136,808	134,203	57%	0.94%	1.01
4999	176,507	180,223	57%	0.93%	1.01
5000	167,265	169,904	55%	0.93%	1.00

Table A-5: Summary of the results for NB = 8

Case #	L_T (m)	L_C (m)	TDM_C	*NPV* Savings	γ
1	38,570	20,465	88%	38%	1.61
2	31,568	21,778	86%	37%	1.60
3	33,521	22,725	86%	37%	1.59
4	30,759	20,166	84%	37%	1.59
5	43,099	32,571	84%	37%	1.58
….	….	….	….	….	….
2500	47,544	44,212	63%	10%	1.11
….	….	….	….	….	….
4996	185,326	187,228	60%	1.06%	1.01
4997	145,839	143,256	60%	1.05%	1.01
4998	146,758	144,421	58%	1.05%	1.01
4999	96,268	100,567	56%	1.04%	1.00
5000	177,385	179,254	54%	1.04%	1.00

Table A-6: Summary of the results for NB = 9

Case #	L_T (m)	L_C (m)	TDM_C	*NPV* Savings	γ
1	46,321	21,785	84%	38%	1.61
2	41,368	24,278	82%	36%	1.56
3	43,732	24,695	82%	34%	1.52
4	40,725	31,256	81%	33%	1.51
5	33,178	25,641	80%	33%	1.50
….	….	….	….	….	….
2500	57,677	55,326	67%	11%	1.12
….	….	….	….	….	….
4996	96,123	98,335	61%	1.42%	1.02
4997	123,226	122,166	61%	1.41%	1.02
4998	117,728	115,389	55%	1.41%	1.02
4999	186,758	187,267	54%	1.40%	1.02
5000	157,655	159,334	53%	1.40%	1.02

Table A-7: Summary of the results for NB = 10

Case #	L_T (m)	L_C (m)	TDM_C	*NPV* Savings	γ
1	45,313	28,561	83%	34%	1.53
2	49,074	34,237	81%	34%	1.51
3	39,032	29,935	81%	33%	1.49
4	45,020	32,914	80%	33%	1.48
5	63,532	48,532	80%	32%	1.48
….	….	….	….	….	….
2500	68,526	66,668	66%	12%	1.13
….	….	….	….	….	….
4996	183,704	169,802	60%	2.33%	1.02
4997	98,463	98,491	60%	2.31%	1.02
4998	146,416	145,910	53%	2.09%	1.02
4999	153,668	143,170	52%	1.96%	1.02
5000	152,701	146,890	52%	1.96%	1.02