TORONTO ATMOSPHERIC FUND

Global Heat Pump Performance Review

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FINAL REPORT

E2S Environmental Consulting

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Executive Summary

Nearly half of citywide emissions in Toronto are a result of heating water, homes and buildings. In the coming years, emphasis needs be placed on sustainable energy options to reduce consumption and emissions, particularly in urban environments like Toronto. One solution to this problem is to invest in energy efficient technologies through upgrades and retrofitting current heating and cooling systems. Heat pump technology provides an excellent solution to reduce emissions and reliance on primary fossil fuels. As one of the most energy efficient mechanical systems on the market today, it can sufficiently provide space heating, space cooling and domestic hot water in metropolitan settings. Working alongside Toronto Atmospheric Fund, a consolidated global heat pump technology performance review was conducted to compare current research findings with an emphasis on multi-unit residential buildings (MURB). Thus, the scope for this project was to conduct research on global heat pump technologies, and the feasibility of installing heat pump technologies.

Research was conducted primarily from countries with similar climatic conditions to Canada. This included reviewing academic literature, manufacturer data and third-party studies on actual performance data. The specific heat pump technologies investigated included ground, air, water sourced systems as well as electricity and natural gas fuel sourced systems. This included engine-driven heat pump technologies with an emphasis on low temperature systems. Through concept and issue mapping, as well as consultation with the various heat pump manufacturers and review boards the team chose five criteria areas to analyze the current research findings. These areas included performance, cost analysis, ease of retrofit, applicability to Toronto as well as overall environmental performance. In addition, a technology gap analysis was conducted. This included comparing each of the technology types based on the availability of current data.

The major findings of the report concluded that heat pump performance particularly energy usage and savings, should be based on an estimated Seasonal Coefficient of Performance (SCOP) that can be achieved and sustained over the expected operating life of the system. This will ensure all components including additional fans, pumps, and auxiliary heater electricity requirements are accounted for. These components are not included in AHRI/CSA certified test standards commonly used for manufactured performance results. Furthermore, the operating costs of gas absorption and gas engine driven heat pumps are lower than electric driven heat pumps however, their coefficient of performance (COPs) are also often lower. In relation to the most feasible heat pump option for a multi-unit residential building, given the spatial restrictions of an urban center such as Toronto, vertical closed loop systems are the most feasible ground source option as well as mini split ductless air source heat pumps for a multi-unit retrofit. Overall, heat pumps show excellent potential as an emerging renewable technology however, further research is required in the areas of standardization of installation in addition to long term monitoring of North American MURB retrofit case studies. It should not be assumed that all heat pump technologies will work in urban settings, each installation needs to be assessed on a case by case basis taking into consideration factors such as the climate, land availability, budget, thermodynamic conditions, energy prices, energy requirements, original heating and cooling system and building size. Only through continuous monitoring will researchers be able to conclude the true performance and feasibility of urban heat pump installations.

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Glossary

GSHP	Stands for “ground source heat pump”
ASHP	Stands for “air source heat pump”
MURB	Stands for “multi-unit residential building”
DX	Stands for “direct exchange”, describing a unit that circulates a refrigerant through a ground loop, often copper piping, exchanging heat directly with the soil
GAHP	Stands for “gas absorption heat pump”
GEDHP	Stands for “gas engine driven heat pump”
GHE	Stands for “ground heat exchanger”
GHG	Stands for “greenhouse gas”
COP or SCOP	“Coefficient of performance” or “seasonal coefficient of performance” describes the efficiency of a heat pump. It is a ratio of the heat delivered over the electrical energy consumed. COP is an instantaneous rating of performance at a single temperature. Seasonal COP divides heating by the number of hours, it is a weighted average of performance over various temperatures.
EER	“Energy efficiency ratio” is commonly used to quantify the cooling mode efficiency of a heat pump. It is the cooling mode COP multiplied 3.41 to provide units of Btu/h per W
EST	Stands for “entering source temperature”, being the entering fluid temperature on the source side of the heat pump
HVAC	Stands for “Heating, Ventilation, and Air Conditioning”

1.0 Introduction

In Toronto, approximately 40% of total city-wide emissions are due to providing heating and hot water to homes and buildings[1]. To reduce urban energy consumption and emissions, significant deployment of alternative energy technologies is required. In Canada, the increase of commercial and institutional facilities' energy demands grew by over 35% between 1990 and 2009[2]. With increased expansion in urban environments like Toronto, the number of households as well as building sizes has increased significantly resulting in energy consumption of the housing sector rising by 37% in the same time period[3]. Furthermore, as of 2008 space heating, space cooling, and water heating accounted for 28% of the total greenhouse gas (GHG) emissions in Canada[3].

To reduce emissions in the building sector, one approach could involve upgrading and retrofitting current heating and cooling systems. Heat pump technology provides an excellent solution to reduce emissions and reliance on primary fossil fuels. As one of the most energy efficient mechanical systems on the market today, it can sufficiently provide space heating, space cooling and domestic hot water (DHW) in urban as well as many other housing settings. One of the most viable retrofit options in the building sector is the replacement of electric baseboard system. The CMHC has estimated that electric baseboard heating is used in anywhere between 53 to 81 percent of multi-unit residential buildings—depending on regional location[3]. By cataloging commercially available heat pump technologies on a global scale in addition to comparing cost, manufactured and field performance data, this report provides a multi-sectorial resource for those looking to learn more about heat pumps in both the building and environmental sector.

Figure 1: Vaillant Air Source Heat Pump[4]

1.1 Project Description

The topic of heat pump technology is now receiving attention in Canadian markets. From countries in Europe, it has become evident that the technology can be cost effective and beneficial in certain situations, generating higher efficiencies compared to common household heating and cooling technologies. As there are many kinds of heat pump technologies available, Toronto Atmospheric Fund (TAF) is interested in seeing what type of heat pumps can be most effective when applied to multi-unit housing and Southern Ontario climatic conditions. One issue associated with any new technology is the availability of literature and findings.

The Toronto Atmospheric Fund, an arm's length agency of the City of Toronto, focuses on reductions of local greenhouse gas and air pollution emissions. It is also responsible for promoting public understanding of global warming and air quality problems within the city. As a result of this, TAF is interested in exploring the different types of heat pump technologies available: ground, water and air sources fuelled by electricity and natural gas. To this effect, TAF engaged E2S Environmental Consulting to identify which heat pump technologies will be most efficient and applicable to multi-unit housing and residential buildings in Toronto. It is the organization's intention that this report will function as a preliminary resource for a much larger heat pump study that TAF and the Ontario Power Authority will be completing in the coming months.

Research was completed on global heat pump technologies, primarily from countries with similar climatic conditions to Canada including academic literature, manufacturing data, and third-party studies. Analysis was completed specifically looking at both manufacturer's rated data and field performance data for various heat pump models and types. Emphasis was placed on studies including low temperature climates as well as multi-unit residential building systems.

1.2 Project Scope

The heat pump technology types reviewed in this study include ground, water, air sourced systems in addition to gas absorption and gas engine driven technologies. In some cases, studies highlighting hybrid designs of heat pumps were also analyzed. The fuel sources discussed in this report include electricity and natural gas. Although heat pumps have many applications, this report focused on evaluating the space heating and cooling performance of the heat pump types listed above with an emphasis on collecting data from cold-climate geographical locations. However, when relevant studies from warmer climates were found and able to enhance the discussion of the report, they were included. For each study reviewed the location, model, specifications and parameters were recorded in addition to the data analysis.

For the analysis section, specific criteria relevant to the heat pump sector were investigated. Based on the location and environment of Toronto, emphasis was made on finding studies where multi-unit residential buildings were investigated. To compare the study findings several criteria were used including data availability, performance (generally coefficients of performance), cost, applicability to Toronto/cold climate data, environmental performance and retrofits. For data availability, the type and depth of information in the studies found was reviewed. In terms of performance, efficiency based measurements including coefficient of performance (COP) of the different heat pump types were compared. For cost analysis, emphasis was made on operational and maintenance cost as well as payback periods. For the section on applicability to Toronto and cold climate data, the review focused primarily on countries with similar climatic conditions to Toronto, Ontario, Canada. For environmental performance, CO_2 emissions, environmental, human health hazards and noise pollution were considered. In terms of retrofit feasibility, research findings focused on the ability to retrofit the design in an urban setting like Toronto.

1.3 Background Information

A heat pump system, similar to a traditional air conditioner or refrigerator, extracts heat from one location and transfers it to another location. There are multiple types of heat pump systems for given heating and cooling loads, building types, and locations. The breakdown of the different heat pump technologies discussed in this report are outlined in Figure 2 below.

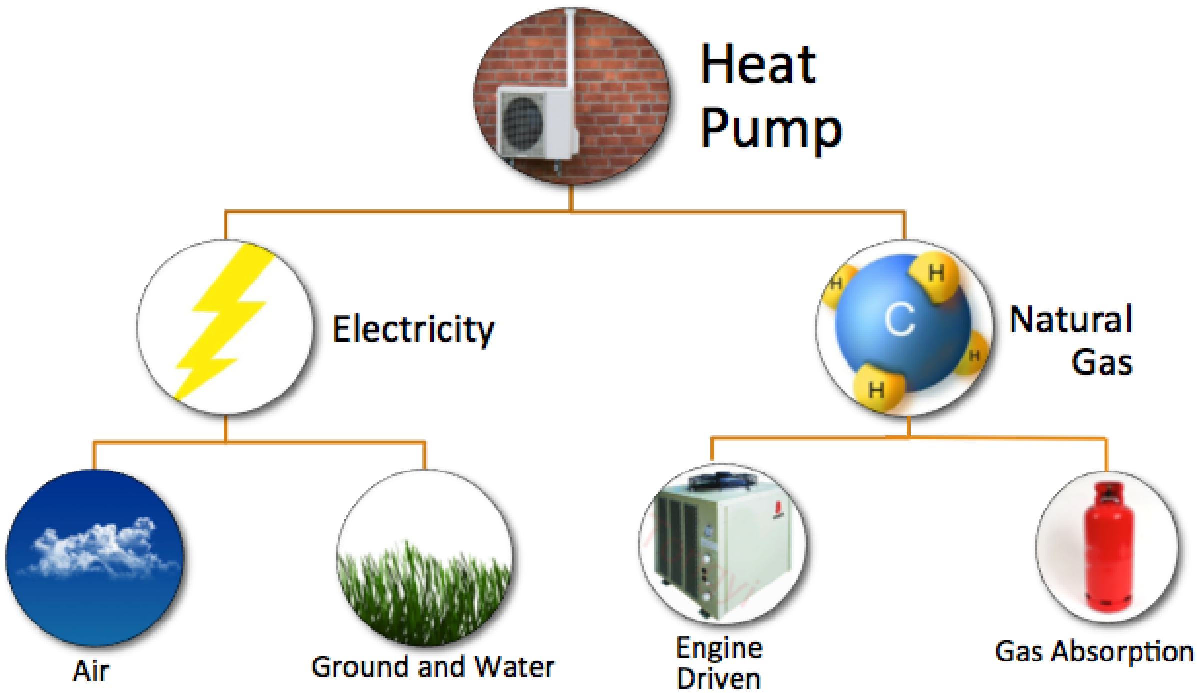


Figure 2: Common Heat and Fuel Sources for Heat Pump Technology[5]

Heat Pump Process

Within a heat pump system, heat is transferred using a refrigerant that is cycled through an evaporation and condensation stage. A compressor pumps the refrigerant between the two heat exchanger coils. As it passes through the evaptorator coil absorbs heat from its surroundings, changing from a liquid to a gas. The compressor then moves the low pressure refrigerant gas to the condensor coil where it is compressed into a high pressure gas. The heat absorbed in the evaportation phase is released, delivering heat to the heat sink. As the high pressure liquid gives up heat, the vapor then condenses to a high pressure liquid. The final stage sees the high pressure liquid expand in the expansion valve which allows the refrigerant to become a low pressure liquid, preparing it for another cycle[6].

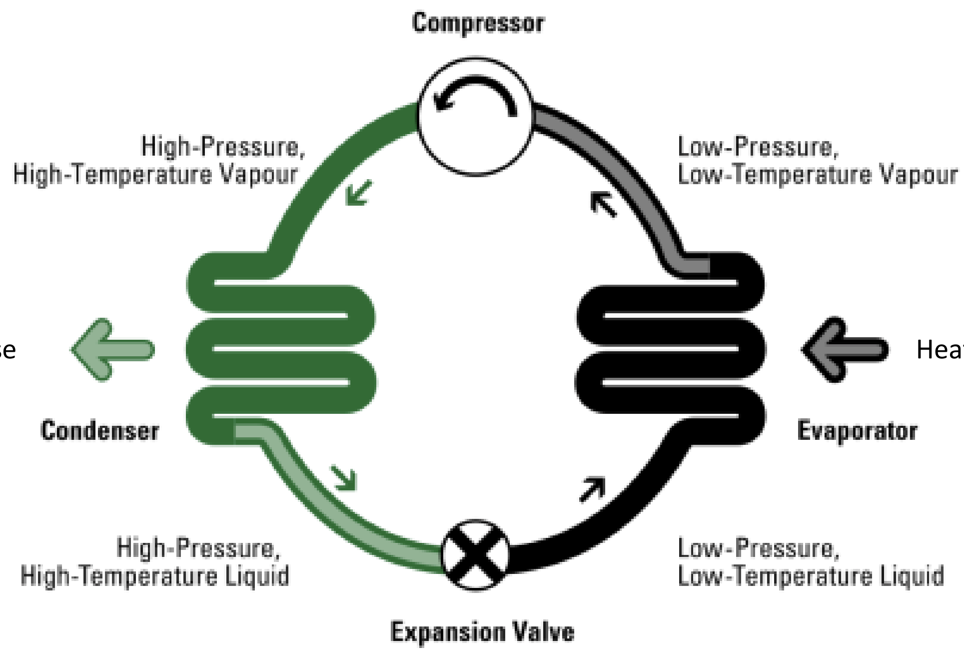


Figure 3: Heat Pump Process[7]

Since heat pumps extract heat from the environment, most systems deliver more heating output than the equivalent of electrical input the system is using. A heat pump system can deliver 250% to 400% more heat than its equivalent electric resistance heating system. The most common type of heat pump has an electrically driven compressor[5].

Heat Pump Components

As outlined and explained above, there are many components that go into a heat pump system: compressor, heat exchanger coils (evaporator and condensor), blower, reversing valve, expansion device, defrost sensor and control, accumulator, heat exchanger, and refrigerant.

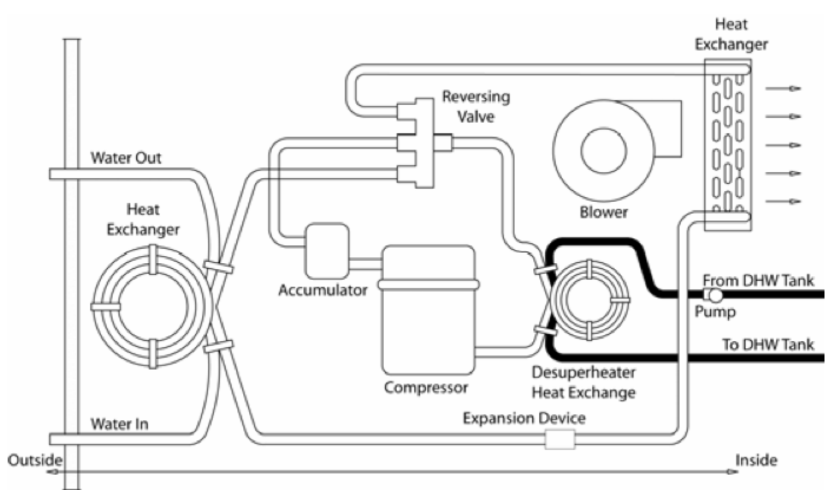


Figure 4: Components of GSHP[5]

1.4 Ontario, Greenhouse Gas Emissions and Heat Pumps

The province of Ontario phased out coal-fired plants by the end of year 2014, primarily focusing on hydro power and nuclear power sources moving forward. This move set precedence for focus on efficient low-carbon energy solutions for homes and the industry[7]. Fitting well with the provincial mandate, heat pumps offer an exceptionally efficient way to heat and cool a building in comparison to conventional technologies. Heat pumps have many applications in residential buildings, commercial buildings, industry, and district heating and cooling systems. Their impact on GHG emissions depends on the fuel source used by the building owner as well as by the electricity generators[8].

1.5 Overview of Regulations and Standards

CSA and AHRI Standards for Heat Pumps

The standards outlined below are from the Canadian Standards Association (CSA) and the Air Conditioning, Heating, and Refrigeration Institute (AHRI). The purpose of these heat pump standards is to compare efficiencies and rate the different heat pump systems and types. Heat pump systems in North America also have to meet the safety requirements of the Canadian Standards Association (CSA) in Canada and Underwriter Labs (UL) in the U.S. Some specific differences exist between the CSA and UL requirements, for example with respect to ground source heat pumps (GSHPs), CSA Standards C448 offers installation and design standards that are not offered by UL. When referring to published testing methods for GSHPs, the American Society of Heating and Air-Conditioning Engineers (ASHRAE) is often the group that publishes such guidelines[5]. Below is a chart outlining the various types of heat pumps and their associated standards, rating points, measured variables, and temperatures.

Table 1 displays the current heat pump performance standards for both the Canadian Standards Association (CSA) and Underwriter Lab (UL) for ten heat pump types. These types of heat pumps (unitary air-source, through-the-wall, small duct, water-source, ground and ground-water source, direct expansion, packaged terminal, single packaged terminal) will be further explained in the following technology review section. Heating seasonal performance factor (HSPF), as displayed between Table 1 and 2, is an efficiency measure that takes into consideration an entire heating season; total heat provided during season in Btu, divided by the total energy used by system in watt-hours[5].

Table 1: CSA and AHRI Standards for Heat Pumps[5]

Heat Pump Type	Standard		Rating Point	Measured Variable	Temperature
	CSA	AHRI			
Unitary Air-Source <65,000 Btu/h	CSA C656	AHRI 210/240	Seasonal HSPF	-	-
Through-the-Wall <30,000 Btu/h	CSA C656	AHRI210/240	Seasonal HSPF	-	-
Small Duct High Velocity <30,000 Btu/h	CSAC656	AHRI 210/240	Seasonal HSPF	-	-
Water-Source <135,000 Btu/h	CSAC13256-1	ISO-13256-1	Heating Cooling	Entering Water Temperature	68°F 86°F
Ground & Groundwater Source <135,000 Btu/h	CSA C13256-1	ISO-13256-1	Heating Cooling	Entering Water Temperature	32 °F and 50°F respectively 77°F and 59°F respectively
Unitary-Air Source ≥ 65,000 Btu/h and <135,000 Btu/h	CSA C746	AHRI 340/360	Heating Cooling	Entering Outdoor Air	47°F 95°F
Unitary-Air Source ≥ 135,000 Btu/h	CSA C746	AHRI 340/360	Heating Cooling	Entering Outdoor Air Temperature	47°F 95°F
Direct Expansion Ground Source	CSA C748	AHRI 810	Heating Cooling	Fluid Temperature in Tank	41°F 77°F
Packaged Terminal	CSA C744	AHRI 310/380	Heating Cooling	Entering Outdoor Air Temperature	47°F 95°F
Single Package Vertical	CSA C746	AHRI 390	Heating Cooling	Entering Outdoor Air Temperature	47°F 95°F

Table 2 references the heat pump efficiency requirements for AHRI Region V, the applicable region for this study. It also outlines both the minimum and maximum efficiency requirements for 7 types of heat pump systems. The efficiency ratings are published to provide standardized ratings as outlined by the AHRI. Efficiencies are expressed for both heating and cooling cycles; energy efficiency ratios (EER), coefficient of performance (COP), heating seasonal performance factor (HSPF) and seasonal energy efficiency ratio (SEER):

$$\text{EER}= \frac{\text{energy output in Btu/hour}}{\text{energy input in watts}} \qquad \text{COP}= \frac{\text{energy output (heating)}}{\text{energy input}}$$

$$\text{SEER}= \frac{\text{total cooling provided during season in Btu}}{\text{total energy used by system in watt-hours}} \qquad \text{HSPF}= \frac{\text{total heat provided during season in Btu}}{\text{total energy used by system in watt-hours}}$$

ES- Energy Star Program, CEE- Consortium for Energy Efficiency, HSPF V- heating seasonal performance factor for region V, Cap- rated cooling capacity in Btu/h, EER- energy efficiency ratio, COP- coefficient of performance

Table 2: Heat Pump Efficiency Requirements[13]

Type	Capacity	Minimum Efficiency	High Efficiency
Air-Source (Split System)	<65,000 Btu/h	HSPF V=6.7 SEER= 13.0	HSPF V=7.1 (ES) SEER=14.0 HSPF V=7.4 (CEE) SEER=14.0
Air-Source (Single Package)	<65,000 Btu/h	HSPF V=6.7 SEER=13.0	HSPF V=7.0 (ES) SEER=14.0
	≥65,000 <135,000 Btu/h	COP @ 8.3°C=3.2 COP @ -8.3°C=2.1 EER=10.1	No Definition
	≥135,000<250,000 Btu/h	COP @ 8.3°C=3.2 COP @ -8.3°C=2.0 EER=9.3	No Definition
	≥250,000 Btu/h	EER=9.0 (no COP requirement)	No Definition
Air-Source (through-the-wall) Split	<65,000 Btu/h	HSPF V= 6.2 HSPF V= 6.4 > Jan.23/10 SEER= 12>Jan.23/10	No Definition
Air-Source (through-the-wall) single package	<65,000 Btu/h	HSPF V=6.1 HSPF=6.4>Jan.23/10 SEER=10.6 SEER=12>Jan.23/10	No Definition
Packaged Terminal	All	COP=3.2-(0.026xCap/1000) (new construction) COP=2.9-(0.026xCap/1000) (replacement market) EER=12.3-(0.213xCap/1000)(new construction) EER=10.8-(0.213xCap/1000)(replacements)	No Definition
Water-Source	<17,000 Btu/h	COP=4.2, EER=11.2	No Definition
	≥17,000-135,000 Btu/h	COP=4.2,ERR=12.0	
Ground-Source	<135,000 Btu/h	COP@0°C=3.1 EER@15°C=16.2	COP@0°C=3.3 (ES)

2.0 TECHNOLOGY REVIEW

There are both subtle and major differences found throughout the various types of heat pump systems. This section will outline and explain each type of heat pump system by reviewing the advantages and disadvantages. The technologies reviewed include ground and water source, air source, natural gas fuel sources including both gas absorption and gas engine driven.

2.1 Ground and Water Sourced Heat Pump

What is a Ground Sourced Heat Pump (GSHP)?

One of the main types of heat pumps is the ground source heat pump (GSHP), sometimes refered to as a water-source or geothermal heat pump. GSHP are separate units that work only when connected to heat exchanger piping that is installed either vertically, horizontally, or to an open or closed loop piping system, explained below. These systems use the earth as a heat source as well as a heat sink making them more stable than air source heat pumps due to the consistency of the heat source[9]. These systems can reduce up to 66% of greenhouse gas emissions compared to conventional heating and cooling systems[9]. In Ontario, the average cost of a geoexchange system was found to be $8,132 per ton[10]. Within the GSHP classification, there are two main types: an *open loop system* and *closed loop system*.

What is an Open Loop System?

The open loop system depends on a body of water being located within close proximity to the building. The water is extracted from the ground or body of water and pumped into the heat pump unit where the heat is extracted during the heating season (winter months) or discharged during the cooling season (summer months). It is necessary for open loop systems to have a constant supply of fluid to circulate[10]. Discharged water is sent to a water source, being an open source such as a pond or lake or underground water aquifer which is referred to as the “open discharge” method. Open loop systems are therefore more difficult to install and source in an urban area or area with strict regulations. An alternative method of water release is through a rejection well, with specific parameters around an acceptable well. It should be noted that poor water quality can have negative impacts on the heat pump system, with issues such as organic matter, low temperatures (less that 5°C), and high acidity clogging and creating poor working conditions for the system. Open loop system installations are also subject to local zoning bylaws and local restrictions[5].

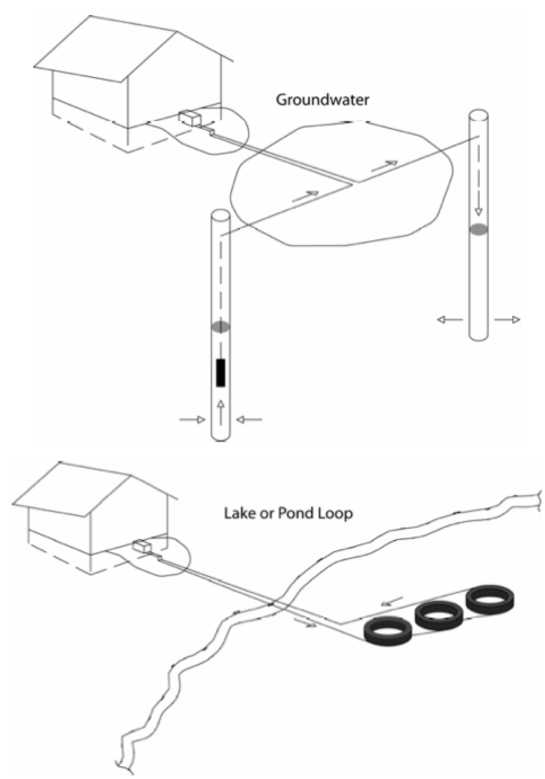


Figure 5: Open Loop Heat Pump Design[5]

The advantages of an open loop system include better performance than air-source and the fact that no defrosting is required. Some disadvantages include a higher capital cost than air-source heat pump installation, compliance needed with local zoning and bylaws, reliability of water source quality, and the need for energy in order to run the pump.

What is a Closed Loop System?

Closed loop systems depend on a series of tubing buried vertically through boreholes or horizontally that act as a ground heat exchanger (GHE)[11]. The GHE is sealed and connected to the heat pump unit, located in the building, and has a refrigerant (heat transfer fluid) circulated through it to absorb the geothermal energy. Differing from open, closed loop recirculates the heat transfer fluid through the systems plastic, pressurized piping. There are two types of arrangements for closed loop systems: vertical or horizontal. For vertical installation, piping is placed in boreholes that can range from 10 to 60 meters in depth, dependent on the size of the system. Traditionally 80 to 110 meters of piping is needed for every ton of heating capacity[5].

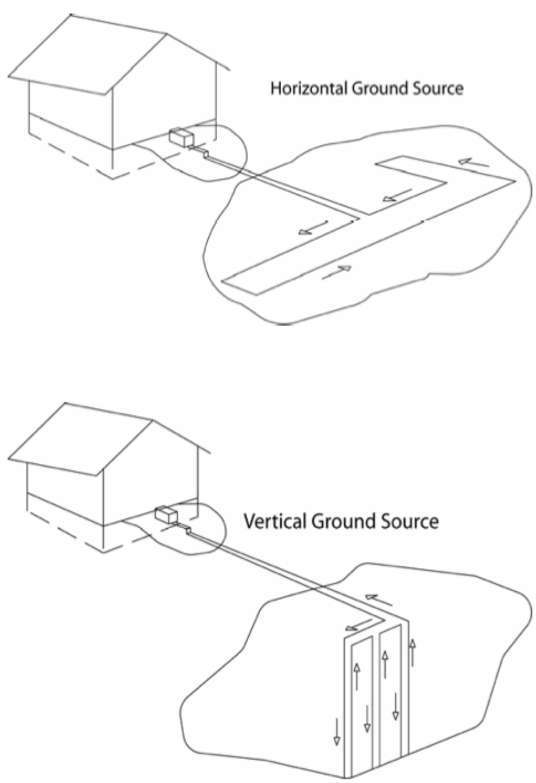


Figure 6: Closed Loop Heat Pump Designs[5]

Aspects effecting decisions to install a vertical closed loop system include limited site space therefore this type of system is ideal for suburban locations. For horizontal systems, 1.0 to 1.8 m trenches are dug out of a large area where ground heat exchanger piping is laid, however the depth of such trenches is dependent on the frost line depth in a particular area. For every ton of heat pump capacity, 120 to 180 m of piping is needed. Piping needs to be at a minimum series 100 polyethylene or polybutylene with joints that are thermally fused so that heat transfer fluid is able to properly circulate. Properly installed piping typically lasts between 25 to 75 years[5].

Some advantages for a closed loop system is that there is no defrosting required, it is efficient, there is often no outdoor equipment or supplementary heating necessary, although it is recommended. The disadvantages include the noise potential because of the unit's indoor location, compared to air-source types, the closed loop system is complicated, and similar to open loop systems, energy used to run the pump. System owners also run the risk of accidental refrigerant leaks directly into the ground through the system's horizontal or vertical pipes.

What is a Direct Exchange (DX) system?

This type of system includes refrigerant grade copper piping which is inserted into narrow boreholes which is the main difference between DX and traditional ground-source heat pumps. DX ground-source units are similar to traditional closed-loop GSHP in that they both use a refrigerant to transfer the heat. The copper pipe is connected to the refrigerant circuit which allows the ground heat exchanger to transfer the heat as it travels through the ground[5]. The advantages of the DX system is that there is no defrosting required, the unit is located indoors, less looping equals a lower installation cost than traditional GSHP systems. DX systems are typically more efficient than ground-source due to the fact that water-based systems rely on two transfer stages and a circulating pump while DX systems have only one thermal transfer through the copper tube[12]. Despite the high cost of copper in comparison to plastic piping, the loop lengths and layout as shown in Figure 7 result in lower installation costs. Some disadvantages include needing a refrigerant to properly operate the system, costly repairs to the copper piping, local noise made by the indoor unit, and a certified refrigeration mechanic must complete the final connection to the refrigerant circuit. Overall the DX system is considered a more complicated option due to the specific installation procedures.

Figure 7: Vertical Loop Field (top left), Horizontal Loop Field (top right), Pond or Lake Loop Field (bottom left) and DX Copper Loop Fields (bottom right)[12]

2.2 Air Source Heat Pump

What is an Air Source Heat Pump (ASHP)?

Air source heat pumps operate by using the temperature differences between outdoor air and indoor air. During the heating season heat is drawn from the outside into the home and during the cooling season hot air is rejected from the inside the home. The most common type of air source heat pump is air-to-air in which the system transfers heat from the outside air into indoor air. The different variations of air source heat pump systems include mini-split, ducted central split, single-package system through-the-wall and rooftop, and hybrid (burner assisted). It is important to note that in a split system, the compressor is located outside and the refrigerant piping goes through the wall. Inside is the air handling unit. This differs from a single packaged unit where all the components are placed together in one unit[13].

What is a Mini-Split System?

Mini-splits are usually of the ductless variety and consist of both an outdoor unit, the compressor, and an indoor fan unit. The lack of need for ductwork is a considerable advantage for mini-split systems. If desired, mini-splits can also be used to power a ducted set-up. Today, mini-split heat pumps are commonly outfitted with variable speed, inverter compressors. This allows the heat pumps to gently increase and decrease power to intermediate operational levels as needed, leading to smoother performance. Non-inverter, single speed compressors only have two states of operation: on or off. Mini-split units are often a good solution for controlling the temperature in a given room but have the ability to control different zones as well in a building using a single compressor[5]. Applications include but are not limited to small commercial buildings, rooms needing specific attention to temperature levels, and homes with hydronic heating. The advantages of this type of ASHP is that the units have an extremely low installation cost, provides temperature settings for specific rooms in a home and is quiet in comparison to other heat pump types. The disadvantages include higher costs to other ASHPs, cabinet size constraints and refrigerant line loss affecting performance, the need for backup heat, and the need for a defrost cycle which affects efficiency. Manufacturers include Mitsubishi, Fujitsu, Sanyo, and LG[13].

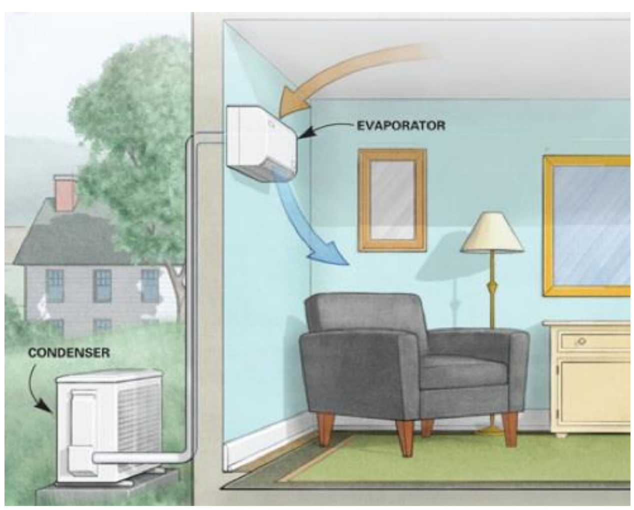


Figure 8: Ductless Mini-Split System[14]

What is a Central Split System?

The central split system is another common ASHP type. It consists of two heat exchanger coils, both indoors and outdoors, connected by refrigerant piping. The indoor coil, the air handling unit, is connected to the house's ducts through which the heat is delivered. Unlike mini-split systems, ductwork is required. The unit closely resembles a common central air-conditioner. The most common applications for this type of system are in residential settings and small commercial applications[13]. Some advantages for the ducted central split system include low noise levels and ease of installation. Disadvantages include the need for back-up heat and defrost cycle which affects the efficiency ratings, as well as the requirement of a refrigeration specialist to install the unit. Manufacturers include Carrier, ICP, Lennox, and Trane[13].

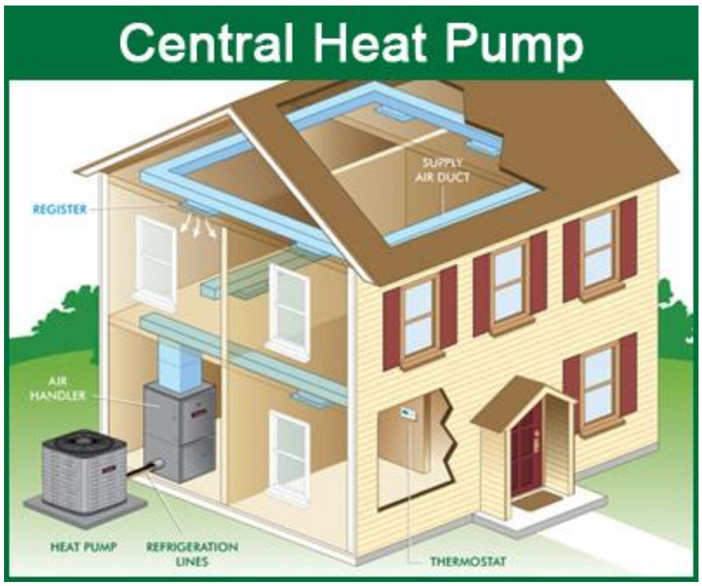


Figure 9: Ducted Central Split System[15]

What is a Single-Package - Through-the-Wall System?

Like the name implies, the compressor and air handler units are contained in a single package, and it is installed through the wall. Common in motels, hotels or other commercial settings but not in residential, these units resemble a window air conditioner. Similarly to the ductless mini-split, the single-package offers heating and cooling to a specific room without the need for ductwork. Some advantages include the low noise levels, no need an installation specialist, and that it can be quickly removed. These units have limited applications as only buildings need to have enough room on the outside wall for every room or zone that will be heated and cooled by a through-the-wall unit. This requirement also limits the sizes of the cabinets and subsequently their capacity[13].

Figure 10: Single-Package Through-the-Wall System[16]

What is a Single-Package Rooftop System?

The compressor and air handler unit for a rooftop system are also within the same housing. Rooftop system differ from through-the-wall systems in that they are installed on the roof of the building and are ducted. Single units can be controlled individually to serve different zones or multiple units can be staged together to meet larger demand. Some advantages include the location of the unit, being outside resulting in lower noise levels, quick installation, and the similarity to other HVAC rooftop units. Disadvantages include the need for lifting equipment for installation, defrost cycles, the need for back-up heat and inconvenience of winter maintenance[13].

Figure 11: Single Package Rooftop System[17]

What is a Hybrid (burner assistance) System?

This type of ASHP comes in both single-package and split configurations. The main difference with the burner-assisted system is the gas burner that is under the outdoor coil which operates when temperatures drop below 0^{o}C (32^{o}F) and provides supplementary heat to the building. This type is used in both residential and commercial settings. Some advantages include the high efficiency due to the combination of air-to-air with the gas furnace, meaning when air source heat pumps get to a temperature where they no longer operate efficiently, the gas burner can turn on to maintain temperatures, the safety of having the fuel source located outside the building, alternative use of gas lessens the load on electrical peak times, for example Energy Star Qualified natural gas furnace can have an efficiency of 98%[18]. The system issue is associated with potential compressor failure which renders the system inoperable as well as the fact that there is only one supplier for the combined system type.

Figure 12: Hybrid (burner assistance) System[15]

2.3.1 Natural Gas Fuel Source - Gas Absorption Heat Pump

A gas absorption heat pump uses natural gas instead of electricity as the primary fuel. It can extract heat from air, water and ground, similar to electric heat pumps. Due to using natural gas, it lowers the demand placed on the gird and also proves to be cheaper than using electricity.

What is a Gas Absorption Heat Pump?

Gas Absorption heat pumps (GAHP) transfer heat from one fluid at a lower temperature to another at a higher temperature. GAHPs combine the heating technologies of gas boilers and electric heat pumps[19]. GAHPs are commonly fired by natural gas, but biogas can also be substituted. Although this heat pump is primarily fueled by natural gas, electricity still plays a nominal role to run the controller pumps and the generator. To function, it uses a water-ammonia solution instead of a harmful refrigerant such as R-22. Although ammonia has some disadvantages which are discussed later on, it does not have any compounds which deplete the ozone layer. Gas absorption heat pumps get the necessary energy from unlimited heat sources and sinks such as air, ground and water. Through a heat exchanger it can be used to supply chilled water for cooling in the summer and hot water for heating in winter. GAHPs can be installed outdoors so that it won't occupy indoor living space and customers will be safe in the case of an ammonia leakage.

How does a Gas Absorption Heat Pump Work?

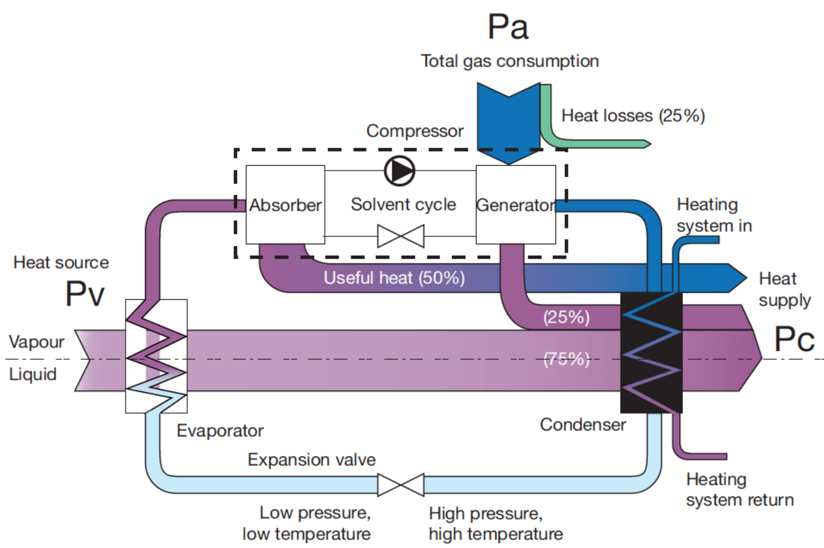


Figure 13: Diagram of a gas absorption heat pump

Absorption machines are based on the capacity of a liquid or a salt to absorb the flowing refrigerant. The most common fluids uses are water (refrigerant) and lithium-bromide (absorbent) or ammonia (refrigerant) and water (absorbent). In the case of the ammonia and water, the gas burner heats ammonia and the water solution. Ammonia gas enters the condenser where it condenses and releases heat. High-pressure ammonia liquid is then converted into low-pressure ammonia liquid through an expansive valve. Exposure to low grade heat causes the ammonia liquid to evaporate and draw in heat. Ammonia gas becomes absorbed into the water solution and it is this solution that pump powers the process[19]

2.3.2 Gas Engine Driven Heat Pump

What is a Gas Engine Driven Heat Pump?

Gas engine driven heat pumps differ from a conventional heat pump by the fact that the compressor is driven by a natural gas fuelled engine rather than an electric motor[20]. One of the major differences with electrical driven heat pumps is that part of the heat released by the engine is recovered and used for heating the water or for augmenting space heating. Although natural gas is primarily used, electricity still plays a nominal role in its functioning. Gas Engine-Driven Heat Pumps (GEDHP) require heat-bearing refrigerant-filled piping, compressors, and heat exchangers. The refrigerants are similar to those of electric ground, water and air heat pumps.

How does a Gas Engine Driven Heat Pump Work?

Gas engine heat pumps comprise of a gas engine, heat exchangers (evaporator and condenser), an expansion valve and a compressor (Figure 14)[21]. The gas engines in GEDHP have a longer lifespan than car engines and run at lower speeds for longer period of time to maintain temperature levels. The engine-driven gas heat pump utilizes an efficient engine running on natural gas to produce the needed horsepower to turn a vapor compressor using a refrigerant such as R22. The compressor is a key component in gas engine driven heat pumps. The efficiency of the compressor largely determines the Coefficient of Performance (COP) of the heat pump. The compressor turns the liquid refrigerant into a gas. As it does this, it absorbs heat from its surroundings and conversely when a gas is concentrated and turned into a liquid it generates heat. Expansion valves cause the pressure to drop and are a constriction in the refrigerant pipe. The purpose of an expansion valve is to control the supply of refrigerant to the evaporator. Expansion valves are responsible for fine-tuning the amount of refrigerant needed.

The heat exchangers consist of the evaporators and condensers. Evaporators are responsible for withdrawing appropriate heat from the heat source, which is a main part of the process. If the heat source is air, then large amounts of air must be blown into the evaporator since air has a small heat capacity. The condenser contains two types of liquids: the condensing refrigerant vapour and central-heating water. These liquids allow for heat exchange to occur within the gas engine-driven heat pump. Heat exchangers must be made of a material that matches the choice of refrigerant, since some refrigerants are corrosive, the heat exchanger must be corrosion resistant[21]. Using these principles, the compressor, driven by an economical engine circulates the refrigerant through the gasification and liquefaction cycles. This circulation accomplishes the cooling and heating. As the basic principle of operation is the same as an electric heat pump, the primary advantage of an engine-driven heat pump is the operating cost, since natural gas is cheaper than electricity.

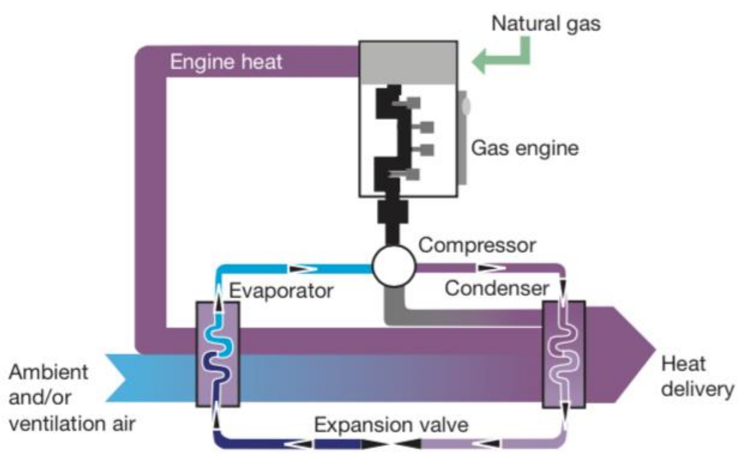


Figure 14: Diagram of Japanese Gas Engine Heat Pump[20]

3.0 METHODOLOGY

As mentioned in the *Project Description*, heat pumps are receiving attention in Canadian markets as the technology can be a cost effective and beneficial in multi-unit household heating and cooling systems compared to common household heating and cooling technology. To complete this report, manufactured data and third-party studies specifically looking at both rated and actual performance data for different heat pump models were sought from many international databases. As discussed above, ground, water, and air were investigated for both fuel sources: electricity and natural gas. For all heat pump technology types, an emphasis was placed on cold climate data. Multi-unit residential buildings was given top priority and cold climate data from any residential property was accumulated. Studies of all heat pump technologies included space heating and cooling but excluded applications of domestic hot water (DHW).

For air source heat pumps, selected studies were no older than 10 years old. Studies that did not test at temperatures of at least 0°C (32°F) were excluded. Studies that did not contain field or lab test performance data were also excluded. Databases from the following institutions were used: UWO Library Database, NREL (National Renewable Energy Laboratory Database), NEEP (North East Energy Efficiency Partnership), ACEEE (American Council for an Energy Efficient Economy) and BPA (Bonneville Power Administration).

For the ground and water sourced heat pumps only studies with current models available in the market were chosen. Many government sources and databases were utilized for ground and water source heat pumps including UWO library database, CGC (Canadian Geoexchange Collation), IGSHPA (International Ground Source Heat Pump Association), GHPC (Geothermal Heat Pump Consortium), Waterfurnace International, Enertran Technologies and McQuay.

For the gas absorption and engine driven heat pump sections, first a list of the manufacturers on the market was complied. Then, specific case-studies for different heat pump models were searched for. In the case that a third party study was found without manufacturer stated information, attempts to search for manufacturer reports and catalogues were made. This involved an individual search effort for different manufacturers. In these two sections, a case-study was selected only if it mentioned which manufacturer designed the heat pump. This helped to ensure that there would be numerical data from the manufacturer which could be compared to the case-study data.

3.1 Map

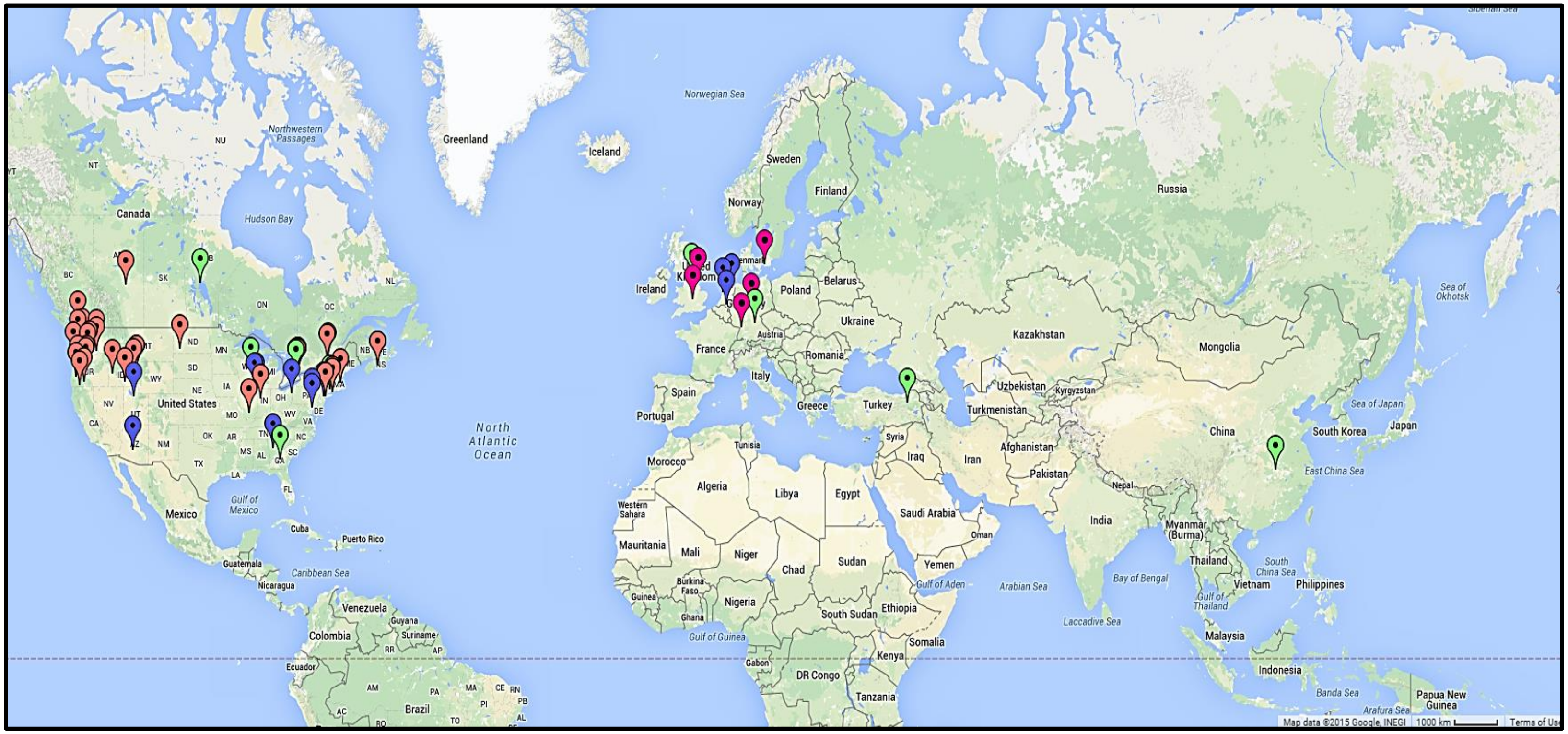


Figure 15: The Study Locations for Each Heat Pump Type

Marker	Heat Pump Type	Marker	Heat Pump Type
	**Ground Source**		**Gas Absorption**
	**Air Source**		**Gas Engine Driven**

3.2 Criteria Explanation

To complete the global technology review several areas of interest were chosen to compare the available data and findings from each study. The data reviewed included academic literature, manufactured data and third-party studies on both rated and actual performance data. Through concept and issue mapping, as well as consultation with the various heat pump manufacturers and review boards the team chose five criteria areas to analyze the current research findings. These areas included performance, cost analysis, ease of retrofit, applicability to Toronto as well as overall environmental performance. In addition, a technology gap analysis was conducted. This included scoring each of the technology types based on the availability of current data. A detailed description of each of these five criteria is provided below.

Data Availability

This criterion summarizes the quality of the data as well as how well studied the technology type is and where further research could be found.

Performance

To evaluate the performance of each heat pump technology, common performance rating schemes including COP (coefficient of performance), EER (energy efficiency ratio) / SEER (seasonal energy efficiency ratio), GUE (gas utilization efficiency), SPF (seasonal performance factor) as well as life expectancy and reliability were taken in to consideration. These metrics provided by manufacturers were compared to data collected from third-party test results where possible.

Costs

To analyze the costs of each heat pump, installation, maintenance, labour and capital costs were taken into consideration. When available data existed payback period calculations were provided.

Applicability to Toronto

When trials were conducted in Canadian cities applicable data and results were provided. If this data did not exist, studies conducted with outdoor temperatures within -10°C to 27°C or geographic areas similar to Toronto were included.

Ease of Retrofit

To evaluate the ease of retrofit associated with each heat pump technology several parameters including applicability to an urban environment like Toronto, how well suited the technology is to a multi-unit building, is a retrofit even applicable with the technology type as well as geological and thermodynamic conditions that would need to occur at the proposed location for a retrofit to be installed.

Environmental Performance

This criterion will take into consideration energy savings, significant reductions in greenhouse gas emissions relative to conventional alternatives as well as any environmental hazards (ex. noise, potential for leaks) associated with the technology.

4.0 Analysis and Results

To assess the different heat pump types, the criteria outlined above were used to guide the discussion and present the findings of the global literature review. For more detailed information including model types, design schemes, full performance evaluations and other details, full study reviews are located in the Appendix section. Each study that is referenced in this section has been numbered correspondingly to the order that they appear in the Appendix.

4.1 Air Source Heat Pumps

This report uses the term mini-split heat pump or MSHP. MSHPs are also commonly referred to as ductless heat pumps (DHPs). Both of these terms refer to a split-system heat pump, generally ductless, with variable-speed fan and inverter-driven compressor that decrease cyclic performance loss and improved part load control.

The eleven studies were reviewed for the air source heat pump analysis detailed performance for more than nineteen heat pumps. Nineteen distinct heat pump performance trials were identified; in addition average performance data from a meta-study that had examined 40 studies was included. Table 3 outlines the type of data available from the studies considered.

Table 3: Comparing Data Availability for the Air Source Heat Pump Review

Study Number	Study Source	Location	Field Data	Manufactured Data	Cold Climate Data	Cost	Environmental Performance	Retrofit
ASHP #1	Safa (2012)	ON, NS, BC, AB, QC	✓	✓	✓	✓	✓	✗
ASHP #2	Winkler (2011)	IN	✓	✓	✓	✗	✗	✗
ASHP #3	Bugbee & Swift (2013)	CT	✓	✓	✓	✓	✓	✗
ASHP #4	Davis (2009)	WA	✓	✓	✓	✗	✗	✗
ASHP #5	Dentz et al. (2014)	NY, MA, ME, IL	✗	✗	✓	✓	✓	✓
ASHP #6	Larson et al. (2012)	WA, OR	✓	✓	✓	✓	✓	✓
ASHP #7	Faesy et al. (2014)	Pacific Northwest, Atlantic, New England, USA	✓	✓	✓	✓	✓	✓

Study Number	Study Source	Location	Field Data	Manufactured Data	Cool Climate Data	Cost	Environmental Performance	Retrofit
ASHP #8	Hadley et al. (2006)	OR, ID	✓	✓	✓	✗	✗	✓
ASHP #9	Reichmuth et al. (2006)	OR	✓	✓	✓	✗	✗	✓
ASHP #10	Davis & Robinson (2008)	OR, ID	✓	✓	✓	✗	✗	✓
ASHP #11	Johnson (2013)	CT	✓	✓	✓	✓	✗	✓

Studies were excluded if they did not discuss field or laboratory performance so all the studies fulfilled the Field Data criteria (an exception was made for Dentz et al. due to the report's valuable case studies regarding MSHP retrofits in multiunit residential buildings). Similarly, studies had to discuss performance in cold climates to be included. Cost, environmental performance, and retrofits were discussed less frequently. All of the research was performed in North America; the majority of the papers were from the US Pacific Northwest and the US Northeast.

The majority of recent air source heat pump literature in North America has been focused on newer cold climate ductless mini-split models (CC-MSHPs). Improvements in technology have made them a viable and intriguing option for colder North American climates. Organizations such as the National Renewable Energy Laboratory (NREL), the Northeast Energy Efficiency Partnerships (NEEP), and the Bonneville Power Administration (BPA) are interested in the technology and have funded recent and on-going research on these newer heat pumps. This trend was reflected in this literature review as the majority of studies were on CC-MSHPs.

Performance Evaluation

Key information on heat pump performance was extracted from the eleven reviewed studies and is briefly summarized below. This proved to be challenging as methodology and approach varied from study to study. For example, some studies provided COP values for a range of temperature while others provided only a seasonal average. Faesy et al. (2014) encountered similar difficulties while performing their meta-study[59].

From the selected studies, performance on seven ductless mini-split heat pumps and eleven ducted central split system heat pumps were extracted. Average MSHP performance data from Faesy et al.'s (2014) meta-study of 40 studies was also included.

Performance curves were not always readily available for each heat pump model. Even when detailed manufacturer data was available, researchers found it difficult to replicate the conditions for standard COP testing protocol which is to measure steady state performance in a laboratory. Heat pumps in the field spend a substantial amount of time in cyclic performance, modulating compressor and fan speeds. That made data collection and calculations more difficult. Even in a laboratory setting Winkler (2011) was unable to completely match manufacturer testing conditions[49]. Furthermore, single COP values and even average COPs cannot be directly compared to advertised HSPF and SEER. These rated values are calculated by weighting average efficiencies at specific temperatures[22].These factors weighed heavily into the decision to assess field performance as Exceeding, Matching, or Not Achieving manufacturer ratings. Whether a heat pump Exceeded, Matched, or Not Achieved manufacturer ratings was decided by analyzing the quantitative data and/or the authors' own conclusions. For more in-depth analysis refer to Appendix A.

Table 4: Performance Review of Air Source Heat Pump Technology Types

Study Number	Study Source	Heat Pump Type	Location	Building Size (ft²) and Type	Model	Heating Field Performance Data (COP)	Performance Compared to Manufacturer Data	Cooling Field Performance Data (COP)	Performance Compared to Manufacturer Data
ASHP #1	Safa (2012)	Ductless Mini-Split	ON, NS, BC, AB, QC, CAN	3,708 House	Mitsubishi PUZ-HA36NHA	Seasonal Average of 3.23	Exceeded	Seasonal Average of 5.27	Exceeded
ASHP #2a	Winkler (2011)	Ductless Mini-Split	IN, USA	N/A Laboratory	Fujitsu 12RLS	1.9-3.8 (-20°C to 17°C)	Matched	5.0-3.3 (19°C to 43°C)	Matched
ASHP #2b	Winkler (2011)	Ductless Mini-Split	IN, USA	N/A Laboratory	Mitsubishi FE12NA	1.9-2.9 (-23°C to 15°C)	Matched	5.7-2.6 (23°C to 47°C)	Matched
ASHP #3	Bugbee& Swift (2013)	Ductless Mini-Split	CT, USA	550 Apartment	Fujitsu AOU9RLQ	Seasonal Average of 2.9	Matched	N/A	N/A
ASHP #4	Davis (2009)	Ductless Mini-Split	WA, USA	N/A Laboratory	Fujitsu 12RLQ	3.8-5.6 (0°C to 13°C)	Exceeded	Average of 5.6 (26°C to 32°C)	Matched
ASHP #6a	Larson et al. (2012)	Ductless Mini-Split	WA, USA	479, 759 Apartment	Mitsubishi FE12NA	Seasonal Average of 3.3	Matched	N/A	N/A
ASHP #6b	Larson et al. (2012)	Ductless Mini-Split	OR, USA	576-900 Apartment	Mitsubishi FE09NA	Seasonal Average of 3.4	Matched	N/A	N/A
ASHP #7	Faesy et al. (2014)	Ductless Mini-Split	Pacific Northwest, mid-Atlantic, New England, USA	Houses and Apartments	Various	Seasonal Average of 2.4-3.0	Matched	N/A	N/A
ASHP #8	Hadley et al. (2006)	Ducted Central Split System	OR; ID, USA	Unspecified House	Nyle Cold Climate Heat Pump	1.4-1.7 (-25°C to 11°C)	Not Achieved	N/A	N/A
ASHP #9a	Reichmuth et al. (2006)	Ducted Central Split System	Sunriver, OR, USA	Unspecified House	Unspecified HSPF>8, Single-Stage Scroll Model	1.5-2.4 (-11°C to 17°C)	Not Achieved	3.1-2.5 (20°C to 31°C)	Not Achieved

Study Number	Study Source	Heat Pump Type	Location	Building Size (ft²) and Type	Model	Heating Field Performance Data (COP)	Performance Compared to Manufacturer Data	Cooling Field Performance Data (COP)	Performance Compared to Manufacturer Data
ASHP #9b	Reichmuth et al. (2006)	Ducted Central Split System	Ashland, OR, USA	Unspecified House	Unspecified HSPF>8, Two-Stage Scroll Model	2.3-1.8 (-5°C to 17°C)	Not Achieved	2.6-2.4 (28°C to 36°C)	Not Achieved
ASHP #9c	Reichmuth et al. (2006)	Ducted Central Split System	Manzanita, OR, USA	Unspecified House	Unspecified HSPF>8, Single-Stage Scroll Model	1.9-1.0 (0°C to 17°C)	Not Achieved	1.4-2.6 (20°C to 31°C)	Not Achieved
ASHP #10a	Davis & Robinson (2008)	Ducted Central Split System	Boise, ID, USA	2,550 House	Unspecified HSPF 8.6, EER 11.7 Model	Seasonal Average of 2.2	Matched	Seasonal Average of 3.4	Matched
ASHP #10b	Davis & Robinson (2008)	Ducted Central Split System	Ashton, ID, USA	1,960 House	Unspecified HSPF 8.8, EER 12.0 Model	Seasonal Average of 2.7	Not Achieved	Seasonal Average of 2.8	Not Achieved
ASHP #10c	Davis & Robinson (2008)	Ducted Central Split System	Moses Lake, WA, USA	1,568 House	Unspecified HSPF 9.1, EER 12.5 Model	Seasonal Average of 2.9	Not Achieved	Seasonal Average of 3.4	Not Achieved
ASHP #10d	Davis & Robinson (2008)	Ducted Central Split System	Deer Island, OR, USA	1,837 House	Unspecified HSPF 9.6 Model	Seasonal Average of 2.4	Matched	N/A	N/A
ASHP #10e	Davis & Robinson (2008)	Ducted Central Split System	Shelton, WA, USA	3,100 House	Unspecified HSPF 8.9 Model	Seasonal Average of 2.4	Not Achieved	N/A	N/A
ASHP #10f	Davis & Robinson (2008)	Ducted Central Split System	Roseburg, OR, USA	1,960 House	Unspecified HSPF 9.05, EER 12 Model	Seasonal Average of 2.4	Not Achieved	Seasonal Average of 3.5	Matched
ASHP #11	Johnson (2013)	Ducted Central Split System	CT, USA	Unspecified House	Acadia 048	Seasonal Average of 3.22, 2.68	Matched	N/A	N/A

*MURB- multi-unit residential building

N/A = Data was either unavailable or outside of the study's scope

Mini-Split Heat Pumps

Cold climate mini-split heat pumps in third party field and laboratory trials were demonstrated to have heating performance that were reasonably in line with manufacturer data, even in outdoor temperatures well into the -20's °C. Faesy et al. (2014) arrived at a similar conclusion in their meta-study[59]. Table 5 shows that all the MSHPs considered in this review at least matched rated performance. Two units, the Mitsubishi PUZ-HA36NHA and Fujitsu 12RLQ managed to surpass expectations[32,62]. Cooling Performance was also demonstrated to match labelled specifications. However, cooling performance was not considered in the majority of the studies that were examined.

A readily apparent shortcoming of this analysis is the lack of manufacturer variety, Fujitsu and Mitsubishi products were very prominent in the literature. Other manufacturers such as Carrier, Daikin, LG, Panasonic, and Sanyo are not well represented in the currently available research on MSHPs. This can be partially explained by the fact that Mitsubishi, Fujitsu, and Sanyo account for 80% of the MSHP market in the US[23].

Table 5: Mini-Split Heat Pump Actual Performance Compared to Expected Performance

	Performance		
	Exceeded	Matched	Not Achieved
Heating (n=7)	2	5	0
Cooling (n=4)	1	3	0

The observed relationship between heat pump performance and temperature was as expected, with efficiency and capacity decreasing as outdoor temperatures got colder. The variability of COPs across studied heat pump models at various temperatures ranges is reported in Table 6, which was modified from Faesy et al. (2014) to include additional data points from Table 4.

Table 6: MSHP Heating COP at Various Temperatures

Outdoor Temperature	Coefficient of Performance (COP)
≥ 4°C	≥ 3.5
-7°C to -12°C	≈ 2.5 to 3.5
-23°C to -29°C	≈ 1.4
Average Seasonal	2.4-3.4

Although these MSHPs were shown to operate well in cold climates, defrost cycles negatively impacted efficiency in most of the studies that examined them[49,54,59]. While the performance penalties were minor or even negligible (comparing COP values before, during, and after a defrost cycle), a 10% COP penalty was reported under extremely cold conditions (-19°C). This is an issue that will require further research as it is not uncommon for a heat pump to run several defrost cycles in a single day.

It is important to note that testing sites for many of these trials where often built to high energy efficiency standards that are not representative of typical housing in the real world. Furthermore, climate zone changed from study to study. These issues are discussed in more detail under *Applicability to Toronto.*

Ducted Central Split System Heat Pumps

Table 7 displays the performance of the more conventional central split system heat pumps considered in this review. Performance was rather disappointing overall, the majority of the examined heat pumps underperformed substantially. However, the number of studies looking at central split system heat pumps was limited as the majority of recent cold climate heat pump research in North America has been focused on MSHPs.

Table 7: Ducted Central Split System Heat Pump Performance Compared to Manufacturer Ratings

	Performance		
	Exceeded	Matched	Not Achieved
Heating (n=11)	0	3	8
Cooling (n=7)	0	2	6

Researchers found that at some sites short compressor runtimes prevented constant steady-state performance. There were also issues with installation as poor placement of return ducts, air handling units, and thermostats all reduced efficiencies. Reichmuth et al. experienced losses in efficiency when the return duct and air handling unit were installed in the attic of the home. These components were subject to temperature extremes that were much colder in the winter and much hotter in the summer compared to the rest of the house and efficiency suffered accordingly. They recommended not installing those components in the attic of a home located in a colder climate. Furthermore, thermostats should be placed away from vents, in areas that come up to temperate last. Having the thermostat too close to supply air flow will skew temperature readings and can induce short cycling[61].The majority of the examined heat pumps were older models, all using some variation of single speed compressor technology which also likely contributed to the issue of short cycling. The Acadia 048, a newer model build for low temperatures, did perform to expectations[63]. More research needs to be done on newer central split system heat pumps built on the variable speed, inverter driven compressor technology found in MSHPs. Johnson (2013) citied the Carrier Infinity Series Heat Pump with Greenspeed Intelligence as an example of a central split heat pumps with a variable speed compressor.

Cost Evaluation

Installed mini-split heat pump costs were available from Safa (2012), Bugbee & Swift (2013), Dentz et al. (2014), and Faesy et al. (2014). This data was used to calculate installed cost normalized to heating capacity and heating area in square footage (Table 8). Prices were converted to CDN$ to make comparisons with other heat pump types. Cost per area heated values should be used with precaution as ASHPs are not always properly sized. Choosing undersized ASHPs is a popular method for homeowners to reduce initial costs and Bugbee & Swift (2013) suggested that the MSHP in their own study may have been slightly undersized. Furthermore, it was unclear how accurate the costs given for ASHP Case #6 (Larson et al. 2012) were as the authors referred to the USD$3,000 figure as “assumed measured costs”[57]. Installed costs for central split systems were not available in the reviewed literature.

Cost can be heavily influenced by the availability of rebates, incentives and credits. Examples of initiatives encountered in the literature review included Efficiency Maine’s Low Income Multifamily Weatherization Program, Connecticut Energy Efficiency Fund’s Income-Eligible program, and non-income dependent programs from Belmont Municipal Light Utility and Bangor Hydro Electric and Main Public Service. Familiarity with the process and the availability of qualified contractors also decreases costs. Under the Efficiency Maine program which started in 2012, costs fell to $2,229 per unit ($1,041 for equipment and $1,188 for labour) from a budgeted $4,500 after a learning curve and an increase in available qualified contracts[56].

Table 8: Installed Costs of Mini-Split Heat Pumps

Study Number	Heat Pump Type	Rated Heating Capacity (Btu/h)	Area Heated (ft^2)	Equipment and Installation Cost (One Indoor Unit) (CDN$)	Capital Cost Per Btu/h of Heating Capacity (CDN$)	Capital Cost Per Area Heated (ft^2) (CDN$
ASHP #1	Ductless Mini-Split	38,000	3,708	$14,500	$0.38	CDN$3.90
ASHP #3	Ductless Mini-Split	9,000	550	CDN$ USD$2,000	USD$0.22	USD$3.64
ASHP #5	Ductless Mini-Split	18,000	N/A	USD$2,800-3,257	USD$0.16-$0.18	N/A
ASHP #5	Ductless Mini-Split	12,000	N/A	USD$2,300-2,711	USD$0.19-$0.23	N/A
ASHP #5	Ductless Mini-Split	9,000	N/A	USD$2,100-$2,577	USD$0.23-$0.29	N/A
ASHP #6	Ductless Mini-Split	13,600	479-759	USD$3,000	USD$0.22	USD$3.95-$6.26
ASHP #6	Ductless Mini-Split	10,900	576-900	USD$3,000	USD$0.28	USD$3.33-$5.21
ASHP #7	Ductless Mini-Split	18,000	N/A	USD$3,800-$4,800	USD$0.21-$0.27	N/A
ASHP #7	Ductless Mini-Split	12,000	N/A	USD$3,500-$4,000	USD$0.29-$0.33	N/A
ASHP #7	Ductless Mini-Split	9,000	N/A	USD$2,800-$3,600	USD$0.31-$0.40	N/A

When installing a mini-split heat pump in settings with larger heating areas (such as a single family home or a larger apartment with multiple bedrooms), more than one indoor unit (head) becomes necessary to distribute the heat throughout the dwelling. Table 9 below displays the results of a 2012 survey of contractors from Long Island, New York used to estimate the capital costs of single and multi-head systems. One system refers to the installation of a unit in a single family home, while multiple systems refers to the per unit cost of multiple installations in a multi-unit residential building.

Table 9: MSHP Costs for Single and Multi-Head Systems

Contractor	Configuration	Installed Cost (Multiple Systems)	Installed Cost (One System)
1	9,000 Btu (one head)	$2,100	
	12,000 Btu (one head)	$2,300	
	18,000 Btu (one head)	$2,800	
	18,000 Btu (two 9k heads)	$4,200	
	24,000 Btu (two 9k and one 7k head)	$5,000–$6,500	
2	9,000 Btu (one head)	$2,250	$2,550–$3,050
	12,000 Btu (one head)	$2,400	$2,650–$3,150
	18,000 Btu (one head)	$3,150	$3,150–$3,650
	18,000 Btu (two 9k heads)	$3,650	$3,950–$4,350
3	9,000 Btu (one head)	$2,577	
	12,000 Btu (one head)	$2,711	
	18,000 Btu (one head)	$3,257	

Faesy et al. analyzed the incremental costs of buying higher efficiency and cold climate specific heat pumps over standard MSHP models (Table 10)[59]. It is unclear what heating capacity these costs are for.

Table 10: MSHP Incremental Costs

HSPF Base	HSPF Improvement	Incremental Cost
8.2 HSPF standard	11.0 HSPF high efficiency	$400 - $600
11.0 HSPF high efficiency	12.0+ HSPF Cold Climate	≈ $300
8.2 HSPF standard	12.0+ HSPF Cold Climate	$700-$900

Several instances of realized energy bill savings were reported in Dentz et al. (2014). A three-story apartment complex in Centralia, IL that contains studio, one bedroom, and two bedroom units had their baseboard heaters replaced by HSPF 8.0, SEER 16 MSHPs. Utility bills at the complex were reduced by $150-$275 per month. A housing agency in Sharon, CT is expecting heating energy savings of 25 to 50% for its apartment residents after replacing electric resistance heaters with MSHPs. Dentz et al. also estimated the potential savings from retrofitting a midsize New York apartment with a MSHP. The savings were found to be substantial when converting from fuel oil (39%), propane (55%), and electric resistance heating (60%)[56]. Johnson (2013) calculated a cold climate central split heat pump (Acadia 048) to have the third lowest operating cost behind a ground source heat pump with a COP of 4.0 and a 90% efficient natural gas furnace[63]. Obviously, potential energy costs savings depends heavily on the local energy market but the literature strongly suggests that switching to MSHPs from fuel oil and electric baseboards in cold climates is a worthwhile investment.

Ease of Retrofit

Ductless mini-split heat pumps are quite easy to install compared to other heat pump technologies such as central air source heat pumps and ground source heat pumps. MSHPs are compact, combine heating and cooling, do not require ducts, can be mounted outside, are available in smaller capacities for apartment and individual rooms, have been demonstrated to work at high efficiencies, and require only electricity as fuel. These characteristics make them an intriguing option for new construction and retrofits of old, inefficient HVAC systems where space comes at a premium. The literature on MSHP retrofits in multi-unit residential buildings (MURBs) is relatively small but Dentz et al. (2014) and Larson et al. (2012) have attempted to fill this knowledge gap by examining case studies which have been summarized below[56,57].

Efficiency Maine

Efficiency Maine's Low Income Multifamily Weatherization Program has been providing cash incentives for MSHP installations since 2012. Approximately 600 MSHPs have been installed as of 2014. Retrofitted apartment have been mostly one bedroom apartments that are part of either one floor or two storey complexes. MSHPs replaced electrical resistance heating and window air conditioner units. The MSHP were wall mounted. Only three broken units have been reported so far (two to abuse and one to failure).

The major lessons learned over the duration of the program have been that: metal covers are needed to protect the outdoor compressor from roof melt water and rain to prevent excessive ice formation (example in Figure 16), extra care is need when installing the fragile plastic fan cover on the indoor unit, and that education is needed to teach residents the more complex control scheme of the MSHPs (one page starter guides have shown to be useful).

So far feedback from the residents has been positive. The fact that seasonal installation and storage of window air conditioners is no longer needed offsets the need to clean filters. The removal of window A/C units has also improved aesthetics.

Figure 16: Heat Pump Cover[24]

Connecticut Energy Efficiency Fund

3,576 MSHP units were installed at 51 sites in 2011 under the Connecticut Energy Efficiency Fund Home Energy Solutions—Income-Eligible program. Most retrofits were for one-bedroom apartments in a single story public housing property. The MSHPs replaced electric baseboard heaters and window A/C units. Residents received training in the form of a kickoff meeting and feedback has been reported to be positive.

The Wethersfield Housing Authority (which administers state, federal, and local housing programs for low-income families, the elderly, and the disabled) has been less enthusiastic with their MSHP retrofit of 112 units that previously used baseboard heaters. The utility costs are passed on to the state or federal program, however maintenance costs are not. So the Wethersfield Housing Authority itself gains very little from the retrofit as they have been saddled with the all the additional costs of maintaining a MSHP over a baseboard heater without the benefits of reduced energy consumption. The regular filter cleaning, having to protect the units from excessive icing, and repairs of complicated equipment has added to the management's costs.

B.C.M.W. Community Services

B.C.M.W. Community Services is a weatherization agency (an organization that aids in the provision of Low Income Home Energy Assistance Program grants) in Centralia, IL. It has installed MSHPs in a three-story apartment complex that contains studio, one bedroom, and two bedroom units. The MSHPs replaced baseboard heaters. Several efficiency retrofits were made to the apartments, vinyl, argon-filled windows, ENERGY STAR exterior doors, and R-49 insulation was installed.

According to the contractor, residents and the landlord has been pleased so far. The landlord has cleaned the MSHP filters every two to three months.

Jadwin Village and Oakwood Manor

Jadwin Village in Richland, WA was built in 1975 and is comprised of 155 units (28 one-bedroom, 56 two-bedroom, and 32 three-bedroom). Oakwood Manor in Eugene, OR was built in 1966; the complex has 72 units (one bedroom, two bedrooms, and three bedrooms). All units in both complexes were previously heated by electric baseboards before being retrofitted with MSHPs. Energy savings were less than expected because residents were heating their units to a higher average temperature post-installation and resistance heating still made up a significant percentage of input heat. In many of these retrofits the old electric resistance heater was not dispose of but left in the unit. This led to tenants operating the MSHP and the electric resistance heater at the same time. Education was needed to discourage residents from using resistance heat unless absolutely necessary.

Other factors that Dentz et al. (2014) discussed in regards to retrofitting MURBS include[5656]:

- That placing the outdoor compressor close enough to the indoor unit may require wall mounting
- Building codes may restrict the placement of outdoor compressors
- Balancing cost and comfort when deciding whether one indoor fan units is needed for larger apartments with additional rooms or additional indoor units are needed
- The fact that MSHPs are more fragile and require more maintenance than baseboard heaters

Environmental Performance

Only Safa (2012) discussed environmental performance in terms of CO_2 Emissions Reductions (Table 11). The findings were for a MSHP heating a 3,705 ft^2 home in Toronto[32].

Table 11: ASHP Annual CO_2 Emissions Reductions

	Electric Baseboard Heating + Air Conditioner	Natural Gas Furnace + Conditioner
Reduction in CO_2 (kg eCO_2)	2,330	3,329
Reduction per m^2 (kg eCO_2)	6.76	9.37

Bugbee & Swift (2013) found that a MSHP could reduce energy consumption in a 550 ft^2 Connecticut apartment by 70%. However, when an electric resistance heater was used in conjunction to the MSHP, energy savings fell from 70% to 30%[52]. A simulation by Dentz et al. (2014) found that replacing fuel oil and electric resistance heaters with MSHPS in an 11 unit New York or Boston MURB reduced energy consumption[56]. Faesy et al. (2014) found that energy savings ranged from 1,200 kWh/ton to 4,500 kWh/ton compared to electric baseboard heating in their review of the literature[59]. All of which would lead to CO_2 emissions reductions due to reduced energy demands.

Applicability to Toronto

Although all the studies reviewed had cold climate data, the intensity and duration of cold weather varied across each trial. In terms of the AHRI Climate Regions, Toronto is considered to be in Region V[25].The climate regions for the other test locations are as listed in Table 12. The greatest proportions of test locations were also in Region V, meaning that those locations experience a similar amount of full heating load hours and have the same outdoor design temperature (T_{OD}). Full heating load hours (HLH) are the amount of hours a full load system would operate at annually if it was designed exactly for the peak heating load[26]. Outdoor design temperature (T_{OD}) refers to the outside temperature that the location stays above for 99% of all the hours in a year[27]. Region V is characterized as having 2,750 HLHs and a T_{OD} of -23°C, Region IV has 2,250 HLHs with a T_{OD} of -15°C, while Region VI has 2,750 HLHs with a T_{OD} of -1°C. Therefore, studies in Region V can be considered most relevant to Toronto climate-wise, studies from Region IV can also be considered very relevant, and studies from Region VI less so. Figure 17 illustrates AHRI Climate Regions in the US.

Figure 17: AHRI Climate Zones in the US with Heating Load Hours

Table 12: AHRI Climate Zones of Selected Studies

AHRI Climate Zone	Location	Study Number
V	Toronto, ON, Canada	ASHP #1
V	Goldendale, WA, USA	ASHP #4
V	Boston, MA, USA	ASHP #5
V	Maine, USA	
V	Richland, WA, USA	ASHP #6
V	Eugene, OR, USA	
V	Chiloquin, OR, USA	ASHP #8
V	Rigby, ID, USA	
V	Ashton, ID, USA	
V	The Dalles, OR, USA	ASHP #9
V	Eugene, OR, USA	
V	Ashton, ID, USA	ASHP #10
IV / V / VI	Pacific Northwest, USA	ASHP #7
IV / V	Mid-Atlantic, USA	
Mostly V	New England, USA	
IV	Lafayette, IN, USA	ASHP #2
IV	Middletown, CT, USA	ASHP #3
IV	New York, NY, USA	ASHP #5
IV	Centralia, IL, USA	
IV	Paul, ID, USA	ASHP #8
IV	Burley, ID, USA	
IV	Sunriver, OR, USA	ASHP #9
IV	Ashland, OR, USA	
IV	Bend, OR, USA	ASHP #10
IV	Boise, ID, USA	
IV	Moses Lake, WA, USA	
IV	Madison, CT, USA	ASHP #11
VI	Manzanita, OR, USA	ASHP #9
VI	Roseburg, OR, USA	ASHP #10
VI	Deer Island, OR, USA	
VI	Shelton, WA, USA	

Furthermore, many of the performance trials were performed in dwellings designed with energy efficiency in mind. For example, the semi-detached home in Safa (2012) was built to LEED Platinum and ASHRAE 90.1 standards and the apartment in Bugbee & Swift (2013) was built with low-e argon-filled windows, blown-in insulation (in the walls, floors, and ceiling), and advanced air sealing[32,52]. Property managers and home owners should not expect to experience the same level of performance achieved in these studies if their properties have not been retrofitted with similar energy efficiency upgrades.

4.2 Ground Source Heat Pumps

Data Availability

To complete the ground source heat pump review seventeen studies were referenced including a total of thirty-two ground sourced heat pumps reviewed. Table 13 outlines the availability of data based on accessibility of Field Data, Manufactured Data, Cold Climate Data, Cost, Environmental Performance and Information on the Ease of Retrofit. These criteria deferred slightly from the five used during the analysis of all of the studies included and thus only pertain to the data examination.

Table 13: Comparing Data Availability for the Ground Source Heat Pump Review

Study Number	Study Source	Location	Field Data	Manufacturer Data	Cold Climate Data	Cost	Environmental Performance	Retrofit
GSHP #1	Canada Mortgage and Housing Corp. (2002)	Toronto, CAN	✓	✓	✓	✓	✓	✓
GSHP #2	Shapiro, A. & Aldrich, R. (2008)	Connecticut & Vermont, US	✓	✓	✓	✓	✗	✗
GSHP #3	Stetcher, D. & Allison, K. (2012)	Georgia, US	✓	✓	✗	✗	✗	✗
GSHP #4	Puttagunta, S. & Shapiro, C. (2012)	Wisconsin, US	✓	✓	✓	✓	✗	✗
GSHP #5	Janssen, E. et al. (2015)	Peel, CAN	✓	✓	✓	✗	✓	✗
GSHP #6	Janssen, E. et al. (2015)	Peel, CAN	✓	✓	✓	✗	✓	✗
GSHP #7	Janssen, E. et al. (2015)	Toronto, CAN	✓	✓	✓	✗	✓	✗
GSHP #8	Janssen, E. et al. (2015)	Vaughan, CAN	✓	✗	✗	✗	✗	✓
GSHP #9	Luo, J. et al. (2014)	Nuremburg, Germany	✓	✓	✓	✓	✗	✗
GSHP #10	Ozyurt, O. & Ekinci, D.A. (2010)	Erzurum, Turkey	✓	✗	✓	✗	✗	✗

Study Number	Study Source	Location	Field Data	Manufactured Data	Cold Climate Data	Cost	Environmental Performance	Retrofit
GSHP #11	Boait, P.J. et al. (2011)	North Yorkshire, UK	✓	✓	✓	✗	✗	✗
GSHP #12	Healy, P.F. & Ugursal, V.I (1997)	Halifax, CAN	✓	✗	✓	✓	✗	✓
GSHP #13	Safa (2012)	Vaughan, CAN	✓	✓	✓	✓	✓	✓
GSHP #14	Alzahrani (2009)	Vaughan, CAN	✓	✓	✓	✓	✓	✗
GSHP #15	Zhu et al. (2014)	Wuhan, China	✓	✗	✓	✓	✗	✓
GSHP #16	Rad et al. (2009)	Milton, CAN	✓	✓	✓	✓	✗	✗
GSHP #17	Manitoba Hydro (2009)	Manitoba, CAN	✓	✓	✓	✓	✓	✓

The data areas with the least information available included the ease of retrofit as well as the environmental performance information on each ground sourced heat pump type. All seventeen studies included information on field based data with thirteen including manufactured information for direct comparisons. 88% of the data collected also referenced cold climate data, with the maximum external temperature being 0^{o}C for testing during the heating season. Furthermore, 76% of the studies referenced for ground source feasibility and performance were completed in North American cities.

Figure 18 below outlines the types of ground source heat pump technology assessed in this study. A total of 13 vertical closed loop systems, 10 horizontal closed loop systems, 5 vertical open systems, 2 direct exchange designs with closed vertical loops, 1 vertical closed loop- hybrid system with solar thermal collectors as well as 1 lake loop closed system. In relation to the types of buildings reviewed in this GSHP performance evaluation, Figure 19 outlines the number of housing types reviewed. This includes 3 MURBs, 4 commercial buildings, 24 residential houses and in addition to 1 building type that was not disclosed. A total of 32 GSHPs were reviewed.

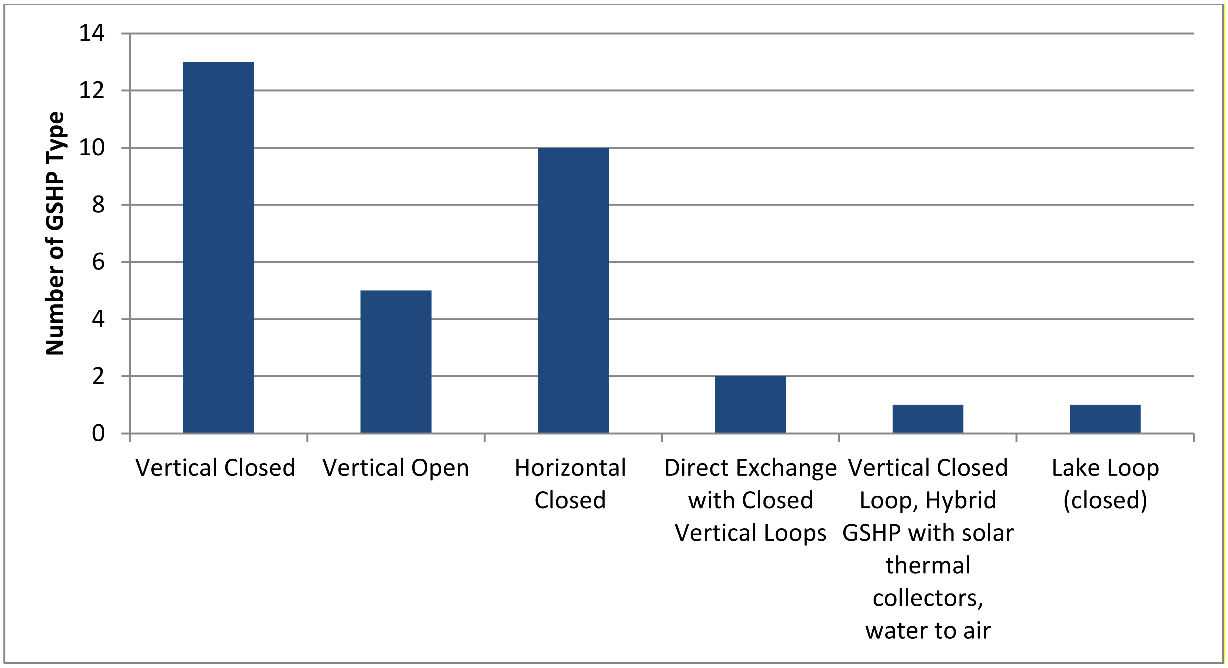


Figure 18: Comparing the number of ground sourced heat pumps included in the review

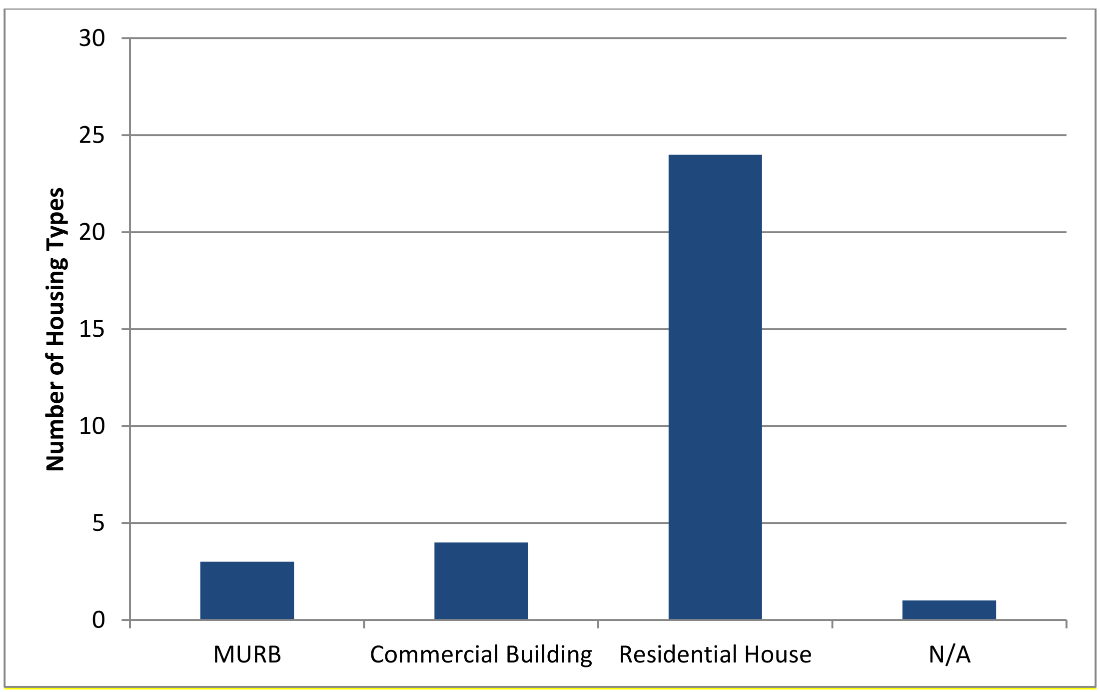


Figure 19: Comparing the number of housing types included in GSHP review

Performance Evaluation

To complete the performance evaluation COPs (coefficients of performance) were most commonly used in the studies referenced. Table 15 below compares the ground source heat pump type, the model, the collected field performance data with either entering source temperatures or entering water temperatures used in the study as well as the manufactured COPs with corresponding entering temperatures used in the lab testing. When the manufactured data was not included in the study itself, values were referenced directly from the manufacturer's website or equipment manuals. Although challenging to make direct comparisons on performance data based on the nature and specifications of ground source heat pump designs (ex. location, climate, ground material), it appears only seven of the thirty two GSHPs reviewed had field tested COPs meeting or exceeding the manufactured values under similar cold climatic temperature conditions (Table 14).

What is COP again?

The coefficient of performance (COP) is a measure of a heat pump's efficiency. It is determined by dividing the energy output of the heat pump by the electrical energy needed to run the heat pump, at a specific temperature. The higher the COP, the more efficient the heat pump. This number is comparable to the steady-state efficiency of oil- and gas-fired furnaces.

From the studies reviewed, there does not appear to be a direct correlation between a specific ground source heat pump type (vertical closed loop systems, horizontal closed loop systems, open loop water to water systems, direct exchange designs with closed vertical loops and vertical closed loop - hybrid system with solar thermal collectors) and field performance COPs. Of the thirty studies reviewed (that included manufactured COP values), twenty three of the field COPs did not achieve the manufacturer value.

Table 14: GSHP Performance Compared to Manufacturer Ratings

	Performance		
	Exceeded	Matched	Not Achieved
Heating (n=30)	3	4	23

*Two studies were not included as manufactured COPs were not available

From the literature reviewed many field performance COPs were lower compared to the manufacturer published counterpart. Potential factors that may explain these discrepancies are outlined below:

- efficiency calculations
- climatic data
- the age of the technology
- maintenance procedures
- controlled settings and issues with the manufacturer lab results
- fluid pumping power, the ground material
- the geothermal gradient as well as thermodynamic conditions
- variations in entering source water temperatures

- equipment malfunctions
- variable homeowner operation

Furthermore, when comparing manufacturer and field tested performance values several design elements may explain the discrepancies in the COP values. When conducting the manufacturer tests it was found that:

- the energy consumed by an auxiliary heater (that may be required) is often not taken into consideration
- the fluid pumping power required to overcome the external resistance of the ground loop heat exchanger piping in the field can vary significantly from the lab
- the fan motor power required to overcome the external resistance of the connected ductwork is often not taken into consideration
- the manufacturer testing standard only includes the internal resistance of the unit itself
- start-up and shut down cycling losses are often not considered in lab testing

Shapiro and Aldrich (2008) discuss the "lack of maturity" within the GSHP industry as another potential issue which could lead to unfamiliarity with the installation and maintenance of the various types of systems[28]. These unfamiliarities can lead to suboptimal installation or maintenance which would ultimately lead to poorer efficiencies in comparison to a properly installed and maintained system. Similarly, Boait, P.J. (2011) discusses the issue of centralized systems and the need for accurate and constant settings of the radiator circulation temperature control for residents as suboptimal efficiencies arise when rooms or zones are individually controlled[29]. The issue of lower COPs due to excessive extraction of geothermal heat can be avoided in the new building sector by having building architects calculate the radiator heat transfer coefficient and heat loss rate, and apply a correction for appliance and metabolic inputs which would provide a good radiator circulation temperature estimate.

One of the most important aspects of calculating GSHP efficiencies is discussed by Puttagunta & Shapiro (2008). When calculating the COP or EER, according to ASHRAE/ISO 13256-1 standards, the power input includes the compressor, water pump, air handler fan, and all other controls[30]. However, when referring to the air handler fan, the flow resistance created from the ducts or the ground heat exchanger is not included by the manufacturer performance data which causes discrepancy between it and field data. Rated data does not always include or account for the ground loop, the desuperheater energy, or the duct system of a building when calculating efficiencies.

Farzin M. Rad, Alan S. Fung, Wey H. Leong (2009) concluded that hybrid ground source heat pump system with solar thermal collectors could be a feasible choice for space conditioning of heating-dominated houses. For the house used in this study, the seasonal solar thermal energy storage in the ground of the hybrid system was sufficient to offset large amount of ground loop heat exchanger (GLHE) length that would have been required in conventional ground source heat pump systems. The economic benefits of such system depend on climate, borehole drilling cost, in addition to the 15% reduction of GLHE length noted due to the three solar collectors. Comparing the solar combined system to a generic GSHP, there was not a significant increase in COP noted. Both systems performed with COPs around 2.7, underperforming compared to the manufactured solar assisted test results with COP published at 3.9[31].

Table 15: Performance Review of Ground Source Heat Pump Technology Types

Study Number	Study Source	Heat Pump Type	Location	Building Size (ft^2) and Type	Model	Heating Field Performance Data (COP and EST/EWT)	Performance Compared to Manufacturer Data	Manufactured Performance Data (COP and EST/EWT)
GSHP #1a	Canada Mortgage and Housing Corp. (2002)	Vertical Closed Loop	Toronto, CAN	MURB*	Carrier 50RWS036	3.49 (-1°C)	Not Achieved	5.22 (-1°C)
GSHP #1b		Vertical Closed Loop	Toronto, CAN	MURB*	Premier P034W	2.9 (-1°C)	Not Achieved	4.4 (-1°C)
GSHP #1c		Vertical Closed Loop	Toronto, CAN	MURB*	Trane WXWA026	2.14 (-3.8 °C)	Not Achieved	2.76 (-3.8 °C)
GSHP #2a	Shapiro, A. & Aldrich, R. (2008)	Horizontal Closed Loop	Connecticut & Vermont, US	House 1,800-2,800 ft^2	WaterFurnace Envision 038	3.5 (10°C)	Not Achieved	5.0 (20°C)
GSHP #2b		Open Loop, Water to Water	Connecticut & Vermont, US	House 1,800-2,800 ft^2	WaterFurnace (model unkown)	2.75 (N/A)	Not Achieved	4.1 (N/A)
GSHP #2c		Open Loop, Water to Water	Connecticut & Vermont, US	House 1,800-2,800 ft^2	Econar (model unkown)	2.75 (N/A)	Not Achieved	3.7 (N/A)
GSHP #3a	Stetcher, D. & Allison, K. (2012)	Vertical Closed Loop	Georgia, US	House 2,024 ft^2	House 1- N/A	2.4-5.3 (15.5 -21°C)	Matched	4.86-6.25 (15.5 -21°C)
GSHP #3b		Vertical Closed Loop	Georgia, US	House 2,946 ft^2	House 2- N/A	1.8-3.8 (15.5 -21°C)	Not Achieved	4.85-6.15 (15.5 -21°C)

Study Number	Study Source	Heat Pump Type	Location	Building Size (ft^2) and Type	Model	Heating Field Performance Data (COP and EST/EWT)	Performance Compared to Manufacturer Data	Manufactured Performance Data (COP and EST/EWT)
GSHP #4a	Puttagunta, S. & Shapiro, C. (2012)	Horizontal Closed Loop	Wisconsin, US	House 2,352 ft^2	WaterFurnace Synergy 3-D SDV038	3.1 (N/A)	Not Achieved	4.5 (0°C)
GSHP #4b		Horizontal Closed Loop	Wisconsin, US	House 4,638 ft^2	WaterFurnace Envision NDV038	2.7 (N/A)	Not Achieved	5.1 (0°C)
GSHP #5	Janssen, E. et al. (2015)	Direct Exchange with Closed Vertical Loops	Peel, CAN	House 1,750 ft^2	SCW-048-1B Earthlinked	2.8 (N/A)	Not Achieved	3.5 (N/A)
GSHP #6	Janssen, E. et al. (2015)	Direct Exchange with Closed Vertical Loops	Peel, CAN	House 5,360 ft^2	SCW-048-1B Earthlinked	3.5 (N/A)	Matched	3.5 (N/A)
GSHP #7	Janssen, E. et al. (2015)	Horizontal Closed Loop	Toronto, CAN	Commercial 12,000 ft^2	WaterFurnace EW060	3.5 (1 °C-20°C)	Exceeded	3 (0°C)
GSHP #8	Janssen, E. et al. (2015)	Vertical Closed Loop	Vaughan, CAN	Commercial N/A	Carrier 30HXC 086	2.4 (6°C)	N/A	N/A
GSHP #9	Luo, J. et al. (2014)	Vertical Closed Loop	Nuremburg, Germany	Commercial 16,468 ft^2	Uponor GmbH SWP 75 I	3.4 (N/A)	Not Achieved	3.9 (N/A)
GSHP #10	Ozyurt, O. & Ekinci, D.A. (2010)	Vertical Closed Loop	Erzurum, Turkey	N/A	N/A- laboratory study	3.0 (N/A)	N/A	N/A

Study Number	Study Source	Heat Pump Type	Location	Building Size (ft^2) and Type	Model	Heating Field Performance Data (COP and EST/EWT)	Performance Compared to Manufacturer Data	Manufactured Performance Data (COP and EST/EWT)
GSHP #11	Boait, P.J. et al. (2011)	Vertical Closed Loop	North Yorkshire, UK	House 646-861 ft^2	IVT Greenline HT Plus C6	2.4 (N/A)	Not Achieved	4.2 (N/A)
GSHP #12	Healy, P.F. & Ugursal, V.I (1997)	Horizontal Closed Loop	Halifax, CAN	House 2292 ft^2	N/A- computer modeling system	3.1 (-1°C)	Not Achieved	N/A
GSHP #13	Safa (2012)	Horizontal Loop	Vaughan, CAN	House 3767 ft^2	WaterFurnace EW 042 R12SSA	3.44 (0°C)	Exceeded	3.0 (N/A)
GSHP #14	Alzahrani (2009)	Vertical Loop, water to water	Vaughan, CAN	House 2497 ft^2	WaterFurnace EW042	4.5 (3-11 °C)	Exceeded	3.6-3.8 (12°C)
GSHP #15	Zhu et al. (2014)	Vertical Loop, Water to Air	Wuhan, China	Commercial 23680 ft^2	McQuay MWH-020	1.38-5.52 (N/A)	Matched	4.0 (20°C)
GSHP #16	Rad et al. (2009)	Vertical Closed Loop, Hybrid GSHP with solar thermal collectors, water to air	Milton, CAN	House 5360 ft^2	Atlas AT060	2.78 (10.04°C)	Not Achieved	3.9 (0°C)
GSHP #17a	Manitoba Hydro (2009)	Well to Well	Various locations in Manitoba	House ~2000 ft^2	N/A	2.8 (5.55°C)	Not Achieved	3.4 (0°C)
GSHP #17b		Lake Loop				2.7 (-1.55°C)	Not Achieved	3.6 (0°C)
GSHP #17c		Horizontal Loop				3.2 (-1.55°C)	Matched	3.2 (0°C)

Study Number	Study Source	Heat Pump Type	Location	Building Size (ft^2) and Type	Model	Heating Field Performance Data (COP and EST/EWT)**	Performance Compared to Manufacturer Data	Manufactured Performance Data (COP and EST/EWT)
GSHP #17d	Manitoba Hydro (2009)	Vertical Loop	Various locations in Manitoba	House ~2000 ft^2	N/A	2.3 (0°C)	Not Achieved	3.7 (0°C)
GSHP #17e		Horizontal Loop				2.9 (0.5°C)	Not Achieved	3.6 (0°C)
GSHP #17f		Horizontal Loop				3.3 (-0.8°C)	Not Achieved	3.8 (0°C)
GSHP #17g		Vertical Loop				2.8 (-2.66°C)	Not Achieved	3.2 (0°C)
GSHP #17h		Vertical Loop				1.9 (-4.38°C)	Not Achieved	3.8 (0°C)
GSHP #17i		Horizontal Loop				3.5 (0°C)	Not Achieved	3.9 (0°C)
GSHP #17j		Vertical Loop				3.0 (-2.5°C)	Not Achieved	3.7 (0°C)

*MURB- multi-unit residential building **Entering Source/Water Temperature
N/A = Information was not disclosed in the published study

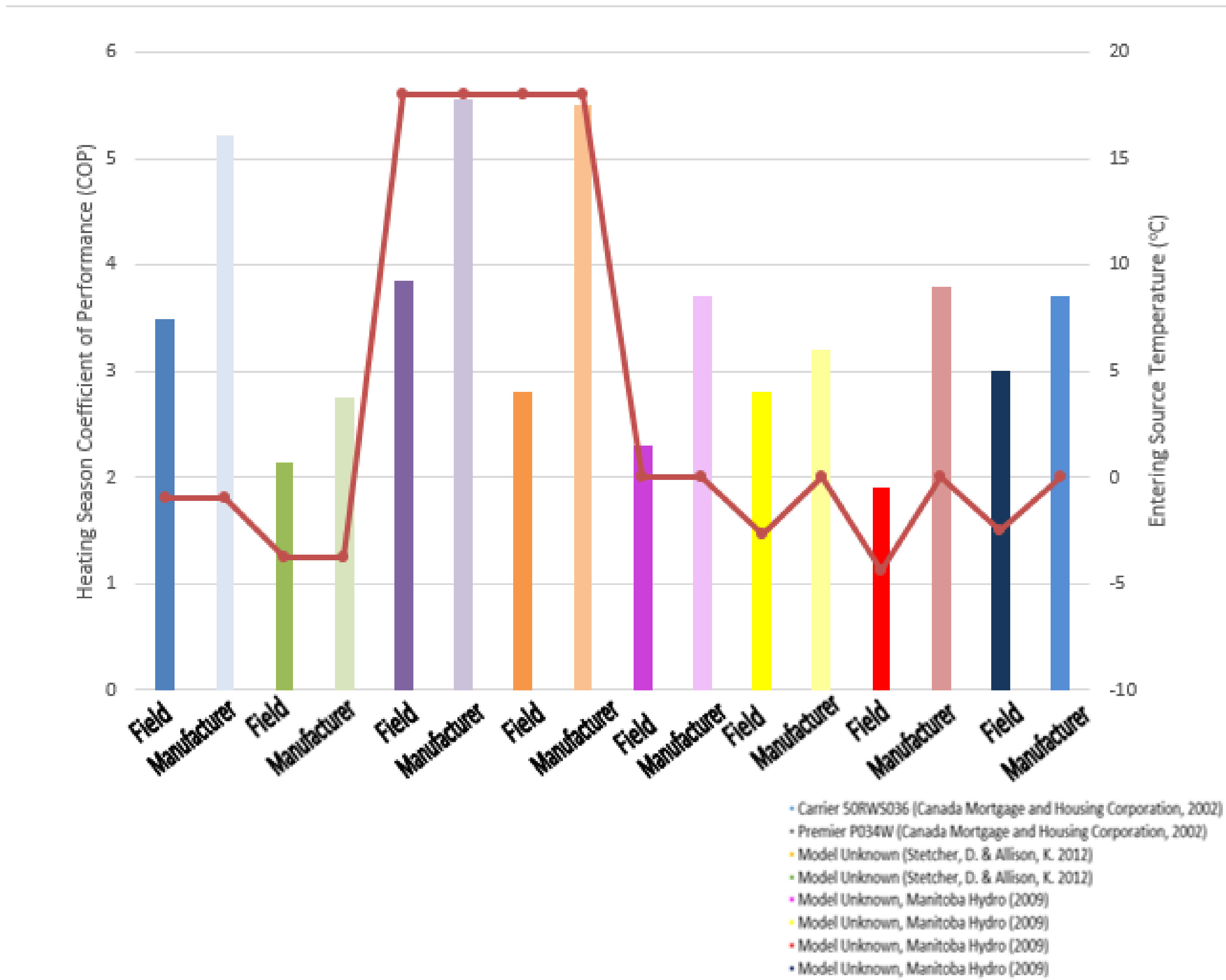


Figure 20: Comparing heating COP values for various vertical closed loop ground source heat pumps at various entering source temperatures

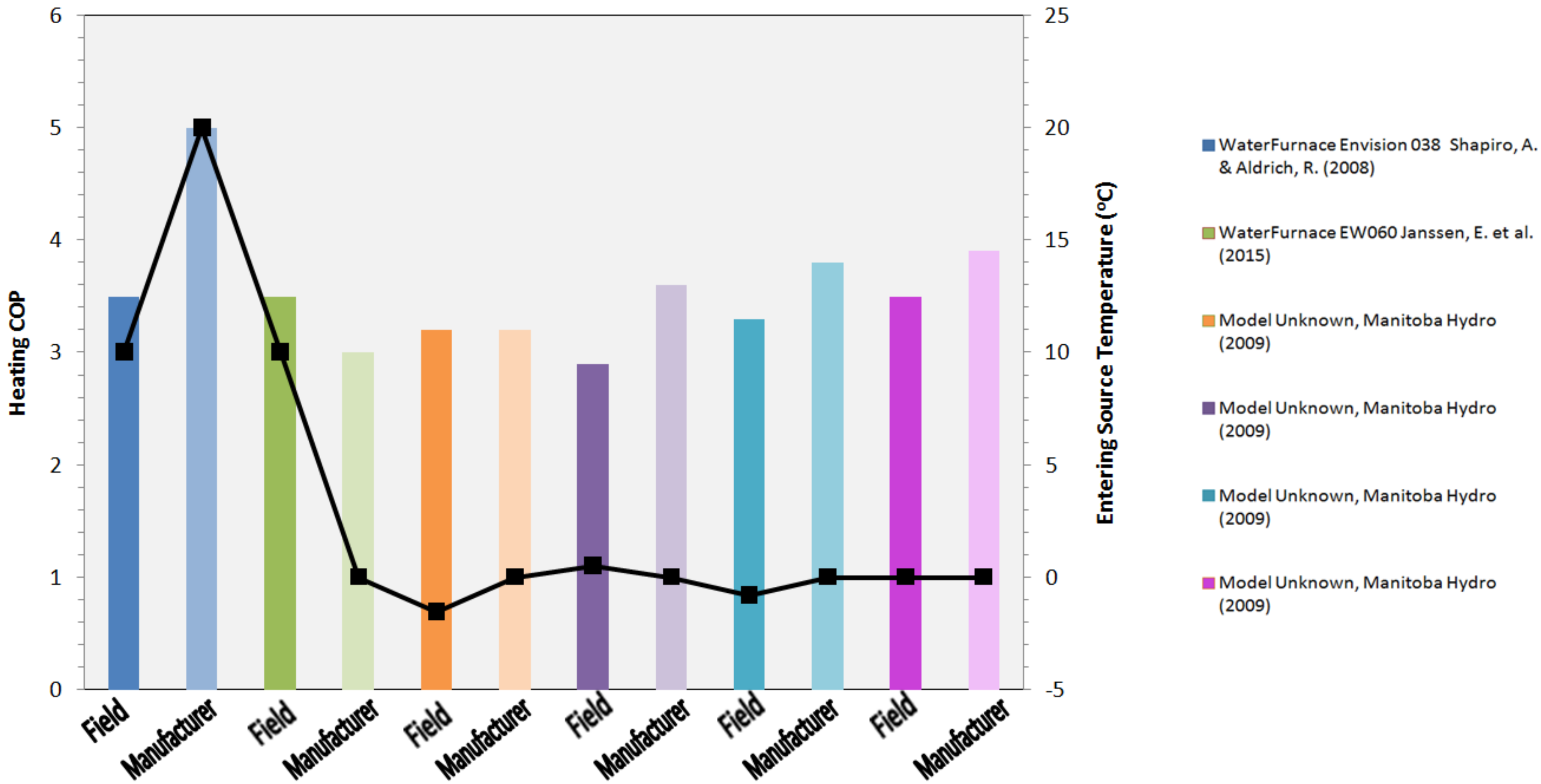


Figure 21: Comparing heating COP values for various horizontal closed loop ground source heat pumps at various entering source temperatures

Cost Evaluation

From the literature review, several studies confirmed the ability to achieve substantial operational savings through GSHP installations in Canada. Hanova, Dowlatabadi and Mueller (2007) concluded both energy pricing and COPs are the most significant parameters influencing total savings in addition to the type of fuel being replaced. The researchers found that homes in Newfoundland, Nova Scotia, New Brunswick, Ontario, and the Territories achieved annual savings in excess of $1,000 irrespective of which conventional fuel the GSHPs were compared to. Figure 22 below outlines these findings.

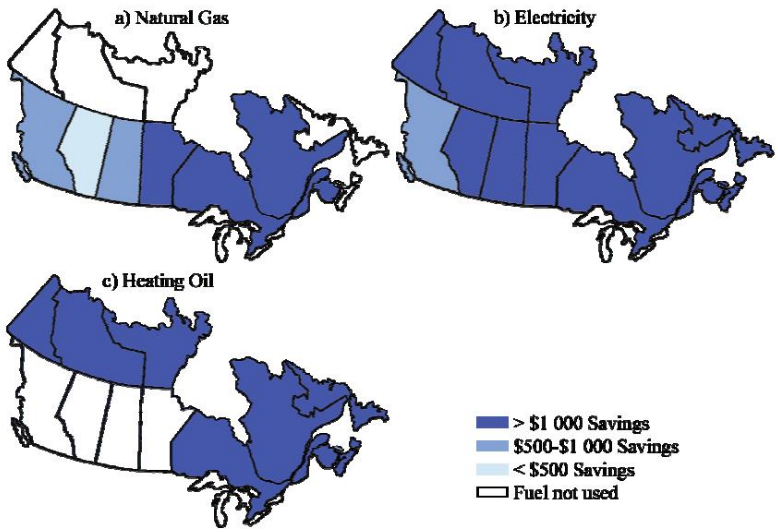


Figure 22: Annual Savings of GSHPs relative to conventional fuels including natural gas, electricity and heating oil[8]

Although costs can be saved when replacing conventional fuels, it was found that the initial investment cost associated with installing GSHP systems can often be the most prohibitive. Even with low maintenance and operational costs associated with the life cycle of the average system, to remain competitive the initial financial investment needs to be viable with realistic payback periods. The aim is to find a balance between investing in more efficient systems (higher COPs) versus the higher capital investment costs associated with these more efficient technology types. Hanova, Dowlatabadi and Mueller (2007) investigated this relationship looking at the tradeoffs between higher COPs (more operational savings) with the associated increased initial capital investment. The researchers concluded that investing in a system that operates at a COP of 5 in Ontario would make financial sense if the incremental cost of upgrading from COP 3 to COP 5 does not exceed ~$2,100 (20 year period, discount rate = 7.5 percent, 1507 ft^2). Figure 23 below includes a range of actual, incremental costs of a GSHP system designed for a 140m^2home in Ontario. With these specifications, the researchers found payback periods that can be expected to occur within 7 to 13 years[8].

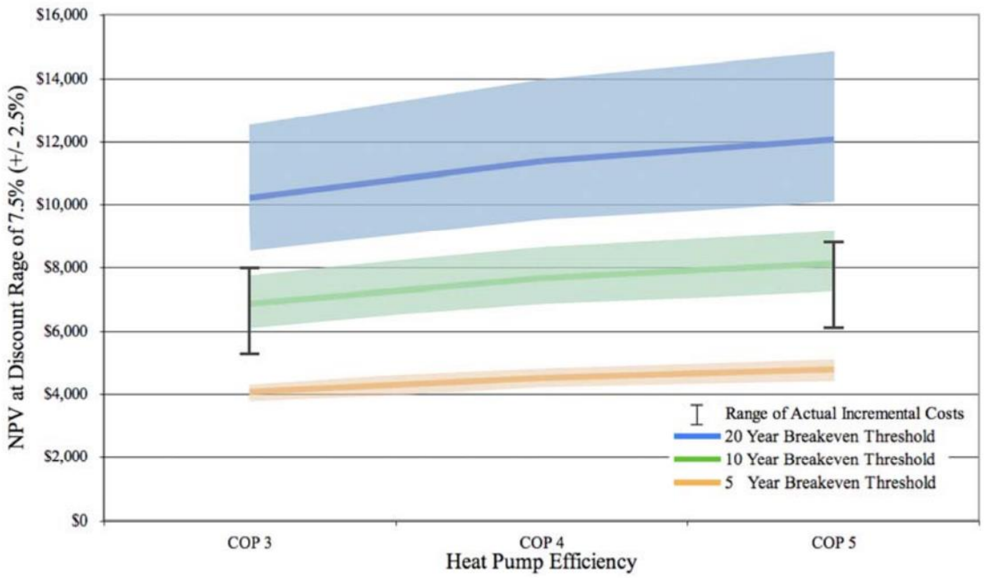


Figure 23: Comparing payback periods, heat pump efficiencies and net present value for Ontario[8]

In comparison, several of the studies completed in this review provided average costs of installation, capital costs, including material, labour, and taxes. Table 16 below provides these values. To normalize the findings, each total average cost was divided by the square footage of each of the homes investigated. A range of \$3.97/ft² - \$16.33/ft² was found from the ground source heat pump literature review. However, inflation over time was not taken into account as well as the additional costs associated with the life of the equipment once installed.

Table 16: Comparing Cost Data from the GSHP Review

Study Number	Heat Pump Type	Year of Study	Estimated Average Cost (CAN $)	Estimated Cost Per CAN $/ft²
GSHP #2a	Horizontal Closed Loop	2008	$22,536.90 to 37,561.50*	$9.80-16.33 $/ft²
GSHP #12	Horizontal Closed Loop	1997	$9100	$3.97 $/ft²
GSHP #13	Horizontal Loop	2012	$34,500	9.60 $/ft²
GSHP #14	Vertical Loop, Water to Water	2009	$28,462	11.4 $/ft²
GSHP #16	Vertical Closed Loop,Hybrid GSHP with solar thermal collectors, water to air	2009	40,278	7.5 $/ft²

*Converted to CAN $ using 1 US Dollar equals 1.25 Canadian Dollar exchange rate** 2,300 ft² used for calculation

Ease of Retrofit

For ground source heat pump designs, the size of the unit used is often based on the environmental conditions including climate, the level of the water table, subsurface material, as well as local thermodynamic conditions. Keeping this in mind, each ground source heat pump installed is site specific in addition to being designed with the building condition and predicted energy consumption required. One area with regards to retrofits that was consistently discussed in the literature was the economic benefits associated with retrofitting homes that currently have electric baseboard heating. In Canada, it is estimated that 27% of all buildings currently use electric baseboards as the main source of heating[32].

Looking at Ontario, approximately 7% of buildings currently use electric baseboard heating[32]. With the rising cost of electricity prices and increased demand for energy in Ontario, ground source heat pumps present a viable option. However, after reviewing several of the studies it does not appear that there is an optimal design or standard ground source heat pump type that consistently performed in a retrofit analysis. The literature review concluded that there are several challenges in retrofitting buildings with GSHPs. One challenge discussed was the issues associated with sizing the heat pump to meet the needs of the current buildings. The risk associated with this is oversizing the system resulting in longer payback periods as well as higher initial capital costs.

In regards to multi-unit residential buildings (MURBs), from 1960 to 1980 many of these buildings were installed with electric baseboard heaters based on the low capital costs at the time, ease of installation and low electricity costs at the time[9]. With current electricity prices and increased regulations on the efficiency requirements for new HVAC units, electric baseboard heating is becoming obsolete and undesirable. In recent years it has become much more economic to update and retrofit these types of buildings. Several research papers have investigated this type of retrofit including a 2002 retrofit of baseboard heaters with a water to water ground source heat pump conducted by the Canadian Mortgage and Housing Corporation[9]. A conceptual system was developed for a hypothetical 642 unit building. The design included pumping water from vertical bore holes containing closed loop heat exchange piping. The challenge associated with this investigation was not the sizing of the unit to meet heating requirements, but the demands for cooling capacity of the building. This resulted in significantly longer payback periods of generally over 20 years. The study showed that the retrofitting of buildings currently fitted with electric baseboard space heating with some form of ground source based heat pump system is possible but is not economically viable based on space heating energy savings alone. The study also showed that heat pump manufacturers could optimize the design of heat pumps and heat pump systems, to reduce system costs, improve efficiency and better meet the needs of MURBs. The authors recommended further research in the development of heat pumps that can meet both heating and cooling capacities for apartment-size loads[9]. Furthermore, there still appears to be a significant knowledge gap with regard to retrofitting electric baseboard heated buildings with GSHP, particularly taking into account space cooling requirements[33].

An additional study (GSHP Case #15 in Appendix B) discussed the retrofit of a hotel in Wuhan, China completed by Zhu et al. in 2014. The hotel was retrofitted with a ground water heat pump, replacing the building's splitting air-conditioner for cooling and coal fired boiler for heating. The authors found the retrofit to be economical and functional with system COPs ranging from 1.33-5.69 in the heating season (temperatures of -1 – 10 ^{o}C)[33]. This was one of the only studies where researchers found the design to be suitable for a retrofit of its size as well as meeting the hotel's cooling and heating needs.

Environmental Performance

In Toronto, approximately 40% of total city-wide emissions are due to providing heating and hot water to homes and buildings[1]. To change current energy production and to reduce emissions, significant deployment of alternative energy technologies is required. With respect to GSHP systems, Hanova, Dowlatabadi, and Mueller (2007) found that GSHPs can provide these essential energy services at emissions reductions of 60 percent relative to the conventional fuel options[8]. In relation to the potential GHG (greenhouse gas) emissions reductions associated with GSHP installations, the environmental success is often dependent on the fossil fuel system being replaced. Hanova, Dowlatabadi and Mueller conducted a study on the economics and GHG potential associated with installing ground source heat pumps in Canada. Taking into account the average size of a single family home (approximately 1507 ft^2) and an average COP of 4 for the GSHP unit installed, the researchers found that in all provinces where GSHP replaced natural gas systems, an observed GHG emissions reduction was observed.

Furthermore, as the implications of climate change continue to present in more urban environments like Toronto and summers become warmer, it is likely the city will see an increase in air conditioner installation. In addition, with more stringent environmental and emissions control policies, more environmentally beneficial HVAC systems will likely become more economic and desirable. Hypothetically, if all of Canada underwent a nation-wide transition to GHSP heating and cooling, the change would result in emissions reductions of 38 Mt of CO_2eq per year[8]. The retrofits would result in emissions reductions of approximately 62 percent with respect to current emissions associated with residential space conditioning and domestic hot water heating[8]. Figure 24 below outlines the annual reduction in tons of CO_2e through the use of installed GSHP systems. Furthermore, Table 17 provides the tons of CO_2 averted by use of GSHP, by region (1507 ft^2 home, COP of 4).

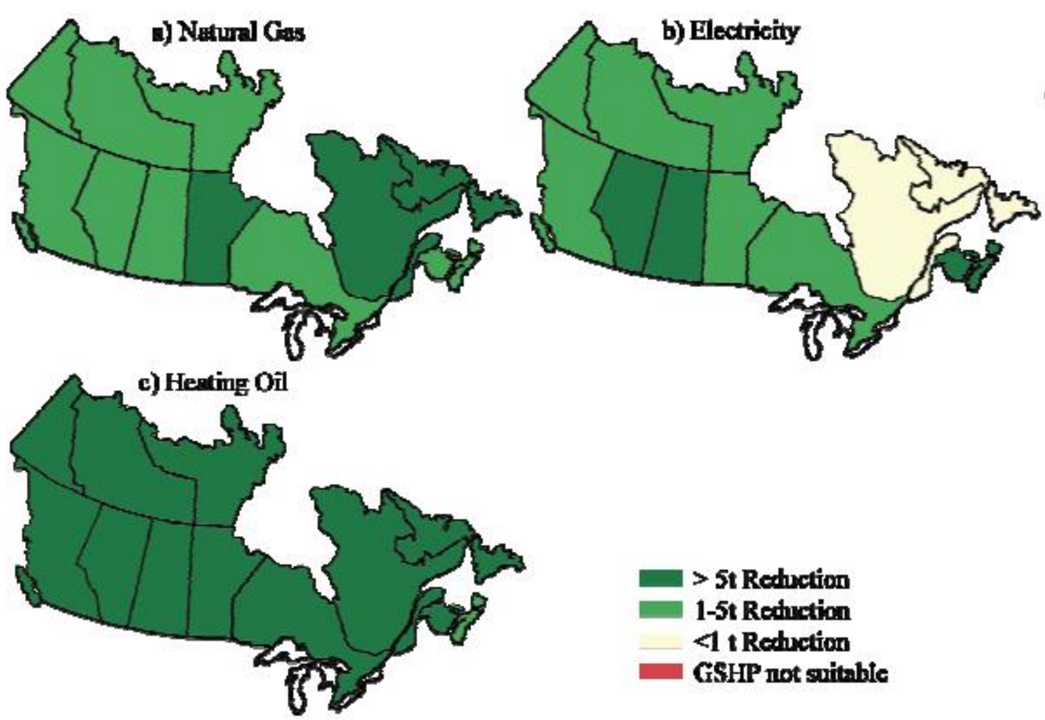


Figure 24: Annual Reduction in Tons of CO2e through the use of installed GSHP systems[8]

Table 17: Tons of CO_2 Averted by Use of GSHP, by Region (1507 ft^2 home, COP of 4)[8]

	GSHP Emissions Reductions Relative to		
	Natural Gas (t)	Electricity (t)	Heating Oil (t)
Newfoundland	5.0	0.3	8.1
Prince Edward Island	2.3	6.0	4.7
Nova Scotia	1.1	9.7	3.7
New Brunswick	2.9	7.6	6.5
Québec	6.1	0.6	9.8
Ontario	4.3	4.0	7.4
Manitoba	5.1	1.8	8.1
Saskatchewan	1.3	16.1	5.1
Alberta	1.6	22.3	5.2
British Columbia	3.9	1.1	6.4
Territories	2.8	3.1	5.5

In relation to studies examined in this report, only four of the GSHP studies reviewed included kg CO_2e data on emissions reductions associated with installment of a GSHP. Energy savings from the use of these more efficient heat pump systems translated into significant reductions in greenhouse gas emissions relative to conventional alternatives. In most cases, annual electricity savings relative to a conventional electric furnace and air conditioner were converted to the carbon dioxide equivalent based on electricity generation sources in Ontario to arrive at emission reductions. A study completed by Safa (2012) on the performance of a horizontal loop coupled ground source heat pump system in Vaughan, ON concluded that on average per capita emissions from private vehicles in Canada was 2149 kg eCO_2 in 2007[32]. Thus, the emissions savings from ground source heat pumps are greater than the savings achieved by a family that chooses to replace all annual car travel with zero emission alternatives such as walking or biking.

From the studies reviewed, estimated kg eCO_2 removed where applicable GSHP were installed ranged from 0.21-1.42 kg eCO_2/ ft^2. Furthermore, there is a significant difference (7:1 ratio between highest and lowest) for estimated kg eCO_2 removed but whether or not this is due to system type is difficult to say without a much larger sample size. For specific details, refer to Table 18 below.

Table 18: Comparing GSHP installation kg eCO_2removed where applicable data was available

Study Number	Heat Pump Type	Kg eCO_2 Reduction*	Estimated kg eCO_2 per ft^2
GSHP #5	Direct Exchange with Closed Vertical Loops	990	0.57 kg eCO_2/ ft^2
GSHP #6	Direct Exchange with Closed Vertical Loops	1,100	0.21kg eCO_2/ ft^2
GSHP #13	Closed Horizontal Loop	2,449	0.65 kg eCO_2/ ft^2
GSHP #14	Closed Vertical	3,549	1.42kg eCO_2/ ft^2

* Compared to Conventional Systems

Applicability to Toronto

As previously mentioned, in the air source section, Toronto is located in AHRI Region V, so all studies performed in Region V are extremely relevant[25]. 88% of the data collected referenced cold climate data, having a maximum external temperature of 0°C for testing during the heating season. The regional classification for AHRI is based on the heating load hours values for a given location.

Table 19: Study Locations and AHRI Regions

Study #	Location	AHRI Region
GSHP #1	Toronto, Canada	V
GSHP #2	Connecticut & Vermont, U.S.	IV & V (respectively)
GSHP #3	Georgia, U.S.	III
GSHP #4	Wisconsin, U.S.	V
GSHP #5	Peel, Canada	V
GSHP #6	Peel, Canada	V
GSHP #7	Toronto, Canada	V
GSHP #8	Vaughan, Canada	V
GSHP #9	Nuremburg, Germany	--
GSHP #10	Erzurum, Turkey	--
GSHP #11	North Yorkshire, UK	--
GSHP #12	Halifax, Canada	V
GSHP #13	Vaughan, Canada	V
GSHP #14	Vaughan, Canada	V
GSHP #15	Wuhan, China	--
GSHP #16	Milton, Canada	V
GSHP #17	Manitoba, Canada	V

As seen in Table 19, 70% of the studies chosen for analysis of performance metrics reside in the same region as the City of Toronto; Region V. In comparing the heating performance for each study, having a similar heating load and general climate for each studied region makes for more uniform testing parameters resulting in fairer comparisons of performance. AHRI states that the heating load hours for Region V are 2,750 hours which is the highest among the six regions in North America[25]. In contrast, Regions I to IV range between 750 and 2250[25]. GSHP 9 to 11 did not have heating load hours available due to the different standards in their given regions. The heating season in Toronto falls into Region V of the AHRI Standard[25].

Figure 17: AHRI Climate Zones in the US with Heating Load Hours

4.3 Gas Absorption Source Heat Pumps

Data Availability

To complete the gas absorption heat pump review, six studies were referenced. It should be noted that because GAHP is a newer technology compared to electric heat pumps, information was limited. In some cases the exact model of the heat pump was omitted from the available studies. The available literature in online databases for GAHP was also limited. As more stakeholders become aware of the option of using natural gas in heat pumps instead of electricity, it is expected that the number of studies available overtime will increase.

Table 20 outlines the availability of data based on the five criteria used for the analysis: the availability of *Field Data, Manufactured Data, Cold Climate Data, Cost, Environmental Performance* and information on the *Ease of Retrofit*. The data areas with the least information available included cost, and cold climate data. Furthermore, most studies provided limited information about retrofits and used no quantitative values in their discussion for this topic. For some models of heat pumps, the manufacturer provided basic retrofit information. All six studies included information on field based data and manufactured information for direct comparisons. Furthermore, five of the six studies referenced for gas absorption heat pump feasibility and performance were completed in Europe, and one was completed in North America. Study details for gas absorption heat pumps can be found in Appendix D.

Figure 25: Outdoor Gas Absorption Heat Pump[20]

Table 20: Comparing Data Availability for the Gas Absorption Heat Pump Review

Study Number	Study Source	Location	Field Data	Manufactured Data	Cool Climate Data	Cost	Environmental Performance	Retrofit
GAHP #1	Robur, (2013)	Karlsruhe, Germany	✓	✓	✗	✗	✓	✓
GAHP #2	FAU GI and SGC, (2013)	Limhamn, Sweden	✓	✓	✗	✓	✓	✓
GAHP #3	International Gas Union Research Conference, (2012)	Boucherville, Quebec, Canada	✓	✓	✓	✗	✓	✓
GAHP #4	R.E., Critoph (2013); Tiemeier, H. (2011); Erdgas Die FreundlicheEnergie. (2012)	Germany (various locations)	✓	✓	✓	✓	✓	✓
GAHP #5	Buderus Bosh Groups. (2013).	North Hull, UK	✓	✓	✓	✗	✓	✗
GAHP #6	Modern Building Services. (2015), Remeha Commercial (2014 and 2015)	Limhamn, Sweden	✓	✓	✓	✗	✓	✓

Performance

Gas absorption heat pump performance is measured in gas utilization efficiency (GUE).GUE is the ratio between the useful heat delivered by the heat pump and the amount of gas (converted into an amount of energy based on the lower heating value of the gas) the heat pump uses . The GUE does not take into account the usually nominal amount of electric energy for the pumps and the control[20]. For the purpose of this report, GUE values were reported as coefficient of performance (COP).

Table 21: Performance Review of Gas Absorption Heat Pump Technology Types

Study Number	Study Source	Heat Pump Type	Building Type	Model	Field Performance Data (COP)	Field Temperature Ranges	Manufactured Performance Data (COP)	Manufactured Performance Temperature	Performance Compared to Manufacture Data
GAHP #1	Robur (2013)	Ground Source	N/A	Robur GAHP-GS Model: N/A	1.41	45°C-55°C	1.47	Max: 45 °C Min: -15°C	Matched
GAHP #2	FAU GI & SGC (2013)	Air Source	Commercial	Robur, GAHP-AS Model: Robur E³	1.07	Input Source: 2°C -8°C Output Source: 45°C-55°C	1.65	Max: 40 °C Min: -20°C	Not Achieved
GAHP #3	International Gas Union (2012)	Geothermal /Water Source	MURB*	Robur GAHP-W Model: N/A	1.25	Space heating system at 45°C for heating season	1.74	Max: 45 °C Min: -15°C	Not Achieved
GAHP #4	Critoph (2013), Tiemeier (2011), Erdgas Die Freundliche Energie. (2012), Wienen et al. (2013)	Zeolite	N/A	VaillantzeroT HERM VAS 106/4 zeolite gas absorption heat pump; solar add on	1.33 at 45°C-55°C 1.44 at 28°C-35°C	28°C-55°C output range	1.36	Solar circuit, temperature range: -20 to 80 °C Primary circuit, temperate range: 5 to 127 °C	Matched
GAHP #5	Buderus Bosh Groups. (2013).Buderus Commercial GWPL 38. (2012).	Air	Commercial	Buderus Model: GWPL 38 Air	1.60 at 7°C 1.25 at -7°C	7°C to -7°C	1.64 at 7°C 1.25 at -7°C	Output temperatures: 35 °C - 50 °C, permissible ambient temperature: -20°C - 45°C	Matched

Study Number	Study Source	Heat Pump Type	Building Type	Model	Field Performance Data (COP)	Field Temperature Ranges	Manufactured Performance Data (COP)	Manufactured Performance Temperature	Performance Compared to Manufacture Data
GAHP #5	Buderus Bosh Groups (2012, 2013)	Air	Commercial	Buderus Model: GWPL 38 Air	1.60 at 7°C 1.25 at -7°C	7°C to -7°C	1.64 at 7°C 1.25 at -7°C	Output temperatures: 35 °C - 50 °C, permissible ambient temperature: -20°C - 45°C	Matched
GAHP #6	Modern Building Services (2015), Remeha Commercial (2014, 2015).	Hybrid	Commercial	Remeha Fusion Hybrid and Remeha Quinta Pro gas condensing boiler	1.40	N/A	1.44	Output Max: 55°C Outdoor Temperate Permissible Min: -20°C	Matched

*MURB- multi-unit residential building
N/A = Data was either unavailable or outside of the study's scope

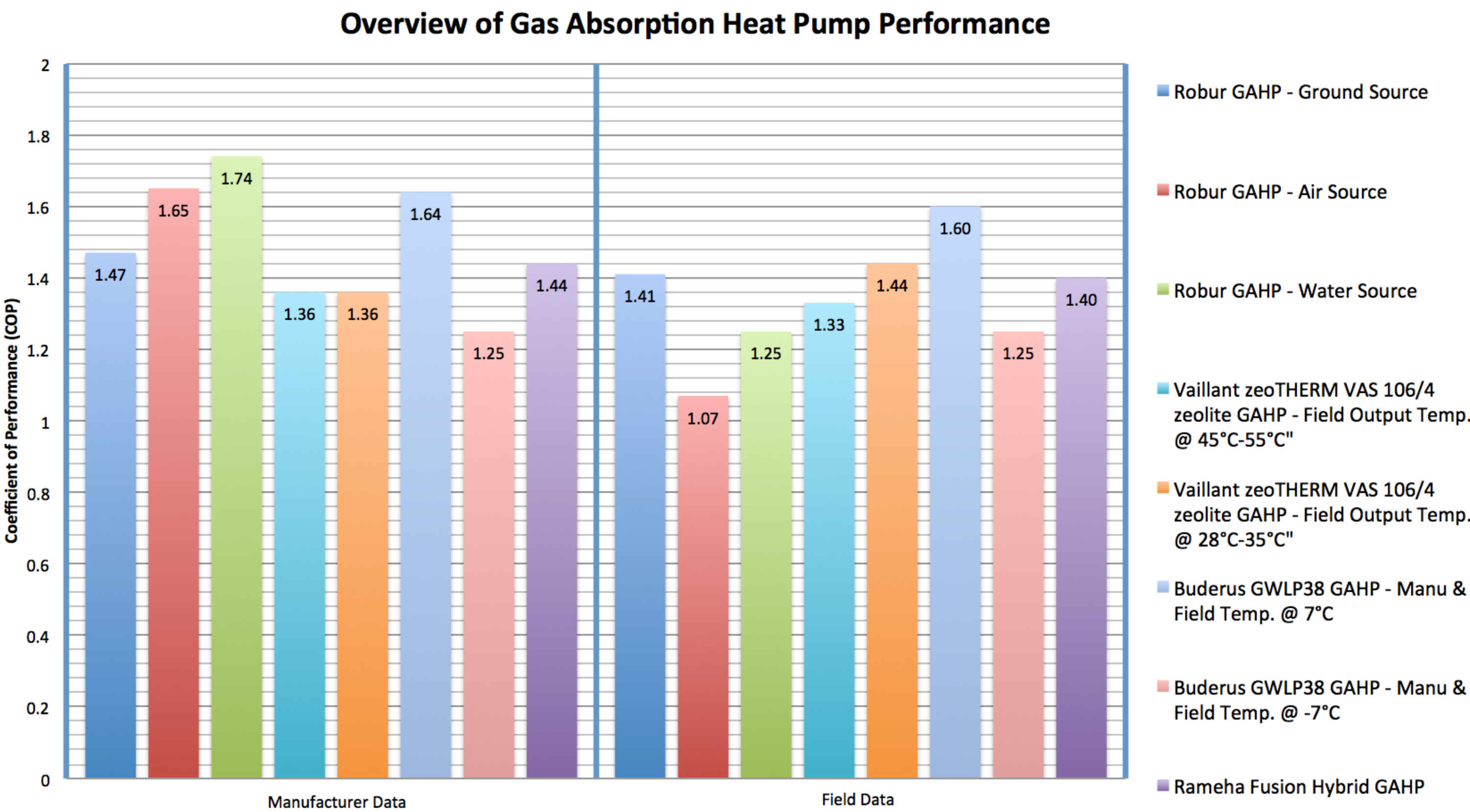


Figure 26: Manufacturer data and field data compared for gas absorption heat pump models

As shown in Figure 26, ground, air, and water Robur heat pumps were analyzed. All heating systems using heat pumps use less primary energy compared to heating system consisting of only gas boilers[34]. For the three different source types, GAHP-ground from Robur had the best performance with a field COP of 1.41[37] followed by geothermal/water with a field COP of 1.25[35] and lastly air with a field study COP of 1.07[36] with a space heating system temperature of approximately 45°C. The field study data was reasonably aligned to the manufacturer data for GAHP-ground source. For air source GAHP there was a clear variance in field performance and manufactured rated COPs. It was concluded that Robur GAHP air source performed poorly compared to other Robur GAHP source types. This finding was also concluded by manufacturer Vellema[34]. This may be because of parasitic defrost cycles and the fact that the model types do not generally perform well during extended periods of sub-freezing temperatures.

The Vaillant zeroTHERM with a solar add-on is a hybrid gas absorption heat pump that also performed satisfactorily and exceeded the manufacturer's performance values. The solar collectors on this heat pump significantly increased the efficiency of performance. The manufacturer data rated the COP of this heat pump with solar domestic hot water (DHW) as 1.36[31] at an output temperature of 40°C. As depicted by Figure 26, the output temperature demand as stated by the manufacturer was 40°C. When the output demanded was in the range of 45°C-55°C, the heat pump resulted in a COP of 1.3, in line with the manufacturer data. When the output required was in the range of 28°C-35°C, the heat pump performed better due to less demand on the machine and therefore resulted in a COP of 1.44[30], which exceeds the manufacturer data. Based on the manufacturer, in sunny cold weather conditions solar direct heating with only three solar collectors were found to be sufficient in terms of overall performance[31].

The Buderus GWPL 38 heat pump that uses air as the heat source also met manufacturer ratings and customer expectations. There was a minor performance variance observed at 7°C between the field study and manufacturer data but performance did match at -7°C. The decrease in performance as temperatures dropped below zero was expected and common of all heat pumps. More information on Buderus can be found in Appendix D.

The Remeha Fusion Hybrid consists of a gas absorption heat pump and a Quinta Pro gas condensing boiler. The efficiency is enhanced due to their compatibility. The manufacturer advertised COP value is 1.44 for the Remeha Fusion Hybrid with a maximum return temperature of up to 55°C. The case study revealed the hybrid system's performance to be 1.40, which matches what the manufacturer reported. The variance is minor and it performs better than some of the previously mentioned heat pumps, such as the Robur GAHP air source. At temperatures of -7°C the efficiency of this system was reported by Modern Building Services to be 1.20. The manufacturer states that the system can perform well at -20°C[33], however the COP at that temperature is not stated by the manufacturer.

Cost

Many of the referenced studies did not include quantitative numbers for cost analysis. The Robur GAHP-ground source study found in Appendix C did not include any cost analysis data. For the Robur GAHP – air source study, the manufacturer noted the cost per kWh is less than the electric heat pumps by 0.98 cents per kWh[93]. According to the manufacturer the heating cost for air source GAHP is 5.33 e/kWh whereas the heating cost for electric heat pumps is 6.31e/kWh[93]. Due to the comparison of models and their use of different fuel sources such as electricity and natural gas, e/kWh refers to the equivalent of energy used. Although, exact costs for installing a GAHP air source is not mentioned, the payback time for a well operating installation with 1.3 annual efficiency is estimated to be 6 years. The Robur GAHP-water source mentioned all criteria of interest except cost analysis.

The GAHP zeolite and solar system is sold as a complete package which includes solar panels, solar water storage and solar pump ground at a price of €16,000, roughly CDN$21,734[39]. For Buderus GWPL it was mentioned that operating costs would be reduced since gas is typically only a third of the price of electricity, however no other information on cost is given. For the Remeha Hybrid Fusion, the payback period was reported to be 4-5 years without any evidence of actual cost[41]. In summary, there was a lack of cost information in GAHP studies. As evident from the study details in Appendix D, some studies have no mention of the cost at all, whereas some provide the cost, but not the payback period and vice versa.

Cold Climate Data

Cold climate data was emphasized in this report. The Robur GAPH manufacturer data states that all three heat pumps will function in conditions below freezing. The lowest temperature at which the GAHP ground source is rated is -15°C[97]. For Robur's GAHP-air source and water source the lowest is -20°C and -15°C respectively[96] however, no COPs are given at temperatures 0°C and below. For the Robur GAHP air source the input supply in the study was in the range of 2 to 8°C[35], which is similar to temperature conditions at the beginning of the winter season in Toronto. This study would have been more applicable if the input supply had a sub-zero range. It should be noted that although Robur GAHP's have a minimum value of -15°C and -20°C, there are days during Toronto's winter where the temperature is even lower. Therefore, depending on the lowest expected ambient temperature for Toronto, a back-up heating system may be required. The back-up heating system will be used only for brief periods with a Robur heat pump as compared to an electric heat pump.

For the Vaillant zeroTherm VAS 106/4 zeolite gas absorption heat pump with the solar addition, the temperature range for the solar circuit is -20 to 80°C. This heat pump is only intended for use with under floor heating systems with maximum output temperature of 40°C.

For the Buderus GWPL 38 heat pump, the lowest temperature at which it will perform efficiently, based on the manufactured data is -20°C. Based on common winter temperatures in Toronto, this should be sufficient. In the study based in Netherlands; the heating season hits a low of -7°C. This value is likely to be lower for Toronto's heating season. The COP at -7°C was reported to be 1.25, therefore a much lower COP can be expected for temperatures around -20°C[41].

The Remeha manufacturers state that the Fusion Hybrid will perform efficiently up to -20°C at a COP of 1.44[33]; however at -7°C another source reported the COP to be significantly lower at a COP of 1.20[35]. It is common and expected that the COP of all heat pumps will decrease as the temperature gets lower, so the ideal heat pump for Toronto will have to be decided strategically giving perspective to the other assessed criteria, mentioned in the study details in Appendix D.

Environmental Performance

Another way in which gas absorption heat pumps differ from electric ground, water, and air heat pumps is that they use an ammonia water mixture as a refrigerant[20]. Unlike the refrigerants that electric ground, water and air heat pumps use, ammonia water does not have any ozone-depleting compounds. However, if there is a defect and ammonia leaks from heat pumps, it can prove to be a human health hazard. Ammonia is corrosive to human skin, eyes and lungs. However, risk from ammonia leaks from GAHP is not significant. Installation is the most likely time for any refrigerant leakage. GAHPs are generally pre-charged and hermetically sealed at the factory, so the installer does not typically have to handle the ammonia. Usually, GAHPs are installed away from end-users which dramatically reduces the chance of leakage occurring inside a building in the proximity of customers. Furthermore, unlike carbon monoxide, ammonia can be detected before it turns into a health hazard. In the very unlikely case of an ammonia leak, ammonia can be detected through smell[20].

With regards to emissions, the Robur GAPH geothermal/water source study reinforces that the amount of CO_2 emissions reductions from switching to a heat pump depends on the energy production profile (coal, nuclear, etc) of the province[29]. In Canada, only provinces whose main electricity source is hydropower or nuclear power can claim that electrically driven heat pumps produce less GHG than natural gas absorption heat pumps in heating mode[29]. Indeed, the GHG emissions of electrically driven heat pumps in coal-dominated provinces are far greater than that of natural gas heat pumps.

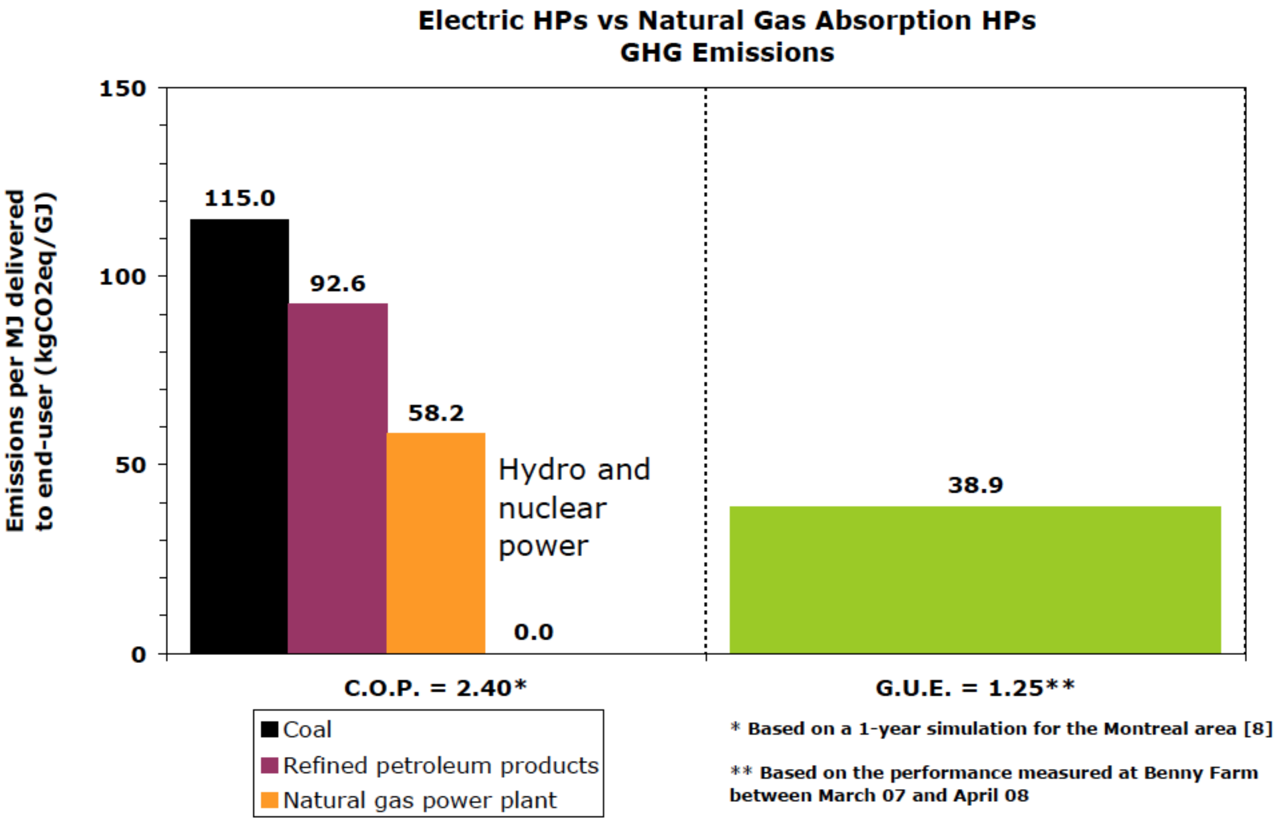


Figure 27: GHG emissions of electric heat pumps vs. natural gas absorption heat pumps[36]

Comparing Robur's GAHP ground source model to a gas boiler, the GAHP energy savings and CO_2 reductions are up to 27%[37]. Greater reductions are possible using greener fuel sources such as biogas, which can replace natural gas in these heat pump systems. A condensing gas boiler using 20% biogas was shown to produce 9.88 kg CO_2/a, while a ground source heat pump using 20% biogas will produce 8.23 kg CO_2/a to produce the same amount of heat[37]. For Robur's GAHP air source, there are numerical values for CO_2 reductions from the manufacturer. A Robur air source gas heat pumps emits 7.7488kg CO_2/a, less than a condensing gas boiler using the same fuel mix[37].

The Vaillant heat pump is a hybrid, which consists of solar collectors. Solar energy is renewable therefore using this heat pump will help decrease CO_2 emissions that are involved in heating the house. However the study does not mention the approximate percentage of CO_2 emissions reduced.

The Buderus GWPL heat pump draws energy from the air using advanced heat pump technology and a highly efficient yet low-NO_x emitting heat generator[40]. As a renewable technology with low NO_x emissions it can be used for buildings that are trying to qualify for LEED Certification in Canada. Although it does not give a quantitative number, the Buderus GWPL heat pump is stated to reduce carbon emissions dramatically.

When it comes to the environmental performance of the Remeha Fusion Hybrid, the manufacturer stated that the system has good efficiencies. After an extensive search, no other objective reports on the Remeha

Fusion Hybrid were found. A low noise brushless fan is fitted in the outdoor air source GAHP, which keeps the environmental noise down to a minimum[33]. Anti-vibration pads are available to reduce the transmission noises throughout the building[14]. Remeha reports that after renovations and the installation of the Fusion Hybrid, CO_2 emissions will decrease around 20% per year and NO_x emissions will decrease approximately 80% per year[33].

Ease of Retrofit

Most of the studies reviewed did not disclose information about retrofits. In some cases, the manufacturer briefly mentioned retrofits and in other cases common knowledge in terms of retrofits was applied. The three Robur GAHPs analyzed do not have any specific information on retrofits. Generally, ground and water source gas absorption heat pumps are expensive to install because boreholes need to be drilled so that the heat exchanger piping can be placed vertically or trenches need to be dug out so that the piping can be placed horizontally. Considering this, it was concluded that ground and water gas absorption heat pumps make for more difficult retrofits. Generally, retrofitting air source gas absorption heat pumps is feasible since it requires only outdoor installation and minimal number of pipes for transporting the heat inside to the house.

For the Vaillant heat pump, it is recommended to install the zeroTHERM model with other components that come in the package: bivalent solar storage tank for domestic hot water preparation, solar station, and solar thermal collectors (flat or tubular)[37]. However it can also be integrated in an existing solar thermal system[37]. Due to the compact design of the collectors, only three to five collectors are needed in a cold climate for good performance[38]. The flexible solar mounting systems for on-roof installations make it easy to install the zeroTHERM in both new construction and retrofits. As seen in Appendix D, the study on the Buderus heat pump also did not give specific information about the ease or difficulty of retrofits. Although no detailed information was given, the Remeha Fusion heat pump uses outside air as a heat source instead of an expensive ground source, therefore it may be more feasibility when it comes to retrofits.

4.4 Gas Engine Driven Heat Pump

Data Availability

To complete the gas engine driven heat pump review four studies were referenced. It should be noted that GEDHP is a newer technology compared to electric heat pumps and gas absorption heat pumps, thus less information was available. In some cases the exact model of the heat pump tested was omitted from the studies. To complete an analysis on one model type, several sources were used because a singular study did not include all required data. As adoption of natural gas engine driven heat pumps increases, the number of studies available overtime should also increase. Table 23 outlines the availability of data based on the five criteria that has been used throughout the study. The data areas with the least information available included cost, environmental performance and retrofits. Two of the studies included information on field-based data and manufactured information for direct comparisons. Furthermore, 75% of the studies referenced for these types of heat pump were completed in Europe, and one was completed in USA. Extreme efforts went into trying to find more EDGHP studies in an attempt to widen the sample size however these efforts were unsuccessful as there is minimal literature available on this type of heat pump.

Figure 28: Gas Engine Driven Heat Pump

Table 22: Comparing Data Availability for the Gas Engine Driven Heat Pump Review

Study Number	Study Source	Location	Field Data	Manufactured Data	Cool Climate Data	Cost	Environmental Performance	Retrofit
GEDHP #1	Van Dijk & Lemmens (2001)	Groningen, Netherlands	✓	✓	✓	✗	✓	✓
GEDHP #2	Hissel (2012).	Son, Netherlands	✓	✓	✗	✗	✗	✗
GEDHP #3	Traversari & Wagener (2013), Sanyo (2011)	Schagen, Netherlands	✗	✓	✓	✗	✗	✗
GEDHP #4	Matson (2011, January), York (2014)	York, Penn Chicago, Ill Wheaton, Ill Girard, Ohio Baltimore, Md Maplewood, N.J. Brooklyn, N.Y. Phoenix, Ariz Atlanta, Ga. Salt Lake City, Utah)	✓	✗	✓	✓	✗	✗

Performance

Table 23: Performance Review of Gas Engine Drive Heat Pump Technology Types

Study Number	Study Source	Heat Pump Type	Building Type and Size	Model	Field Performance Data (COP)	Field Temperature Ranges	Manufactured Performance Data (COP)	Manufactured Performance Temperature	Performance Compared to Manufacture Data
GEDHP #1	Van Dijk & Lemmens (2001)	Commercial Engine	N/A	Yanmar gas-driven heat pumps (GHP) – Eco Compact H1 Series - ANZP450H1	1.16	N/A	1.6	Outdoor Temperature: Cooling: -10°C-43°C, Heating: -20°C - 35°C Indoor Temperature: Cooling: 20°C - 30°C, Heating: 15°C - 30°C	Not Achieved
GEDHP #2	Hissel (2012)	Commercial Engine	7 Floors of office space Heating Area = 400 kg/m²	Aisin Toyota Group Gas Engine Driven Heat Pump Model: not specified	Heating: 1.5 Cooling: 1.95	Heating temperature range is 35°C < total supply < 45°C.	Heating: 1.63 Cooling: 1.76	N/A	Matched
GEDHP #3	E.,Bakker, et al. (2013) Sanyo (2011)	Commercial Engine 3 Pipe VRF	Size = 18298 ft²	Sanyo Engine Driven Heat Pump, three-pipe VRF	N/A	The design temperature at -7°C is 20°C	Heating: 1.34 Cooling: 1.14	Performs at full heating capacity up to min: -21°C	N/A

Study Number	Study Source	Heat Pump Type	Building Type	Model	Field Performance Data (COP)	Field Temperature Ranges	Manufactured Performance Data (COP)	Manufactured Performance Temperature	Performance Compared to Manufacture Data
GEDHP #4	Matson (2011, January) York (2014)	Outdoor split system	MURB	York outdoor split-system Model: E2GE036N06 401C	Heating: 1.35 Cooling: 1.05	Heating supply air temperature: 38 °C - 46 °C	N/A	Indoor Coil Temperature: Heating: 10°C min, 27°C max Cooling: 14°C min, 22°C max Outdoor Coil Temperature: Heating: -23°C min, 24°C max Cooling: 10°C min, 46°C max	N/A

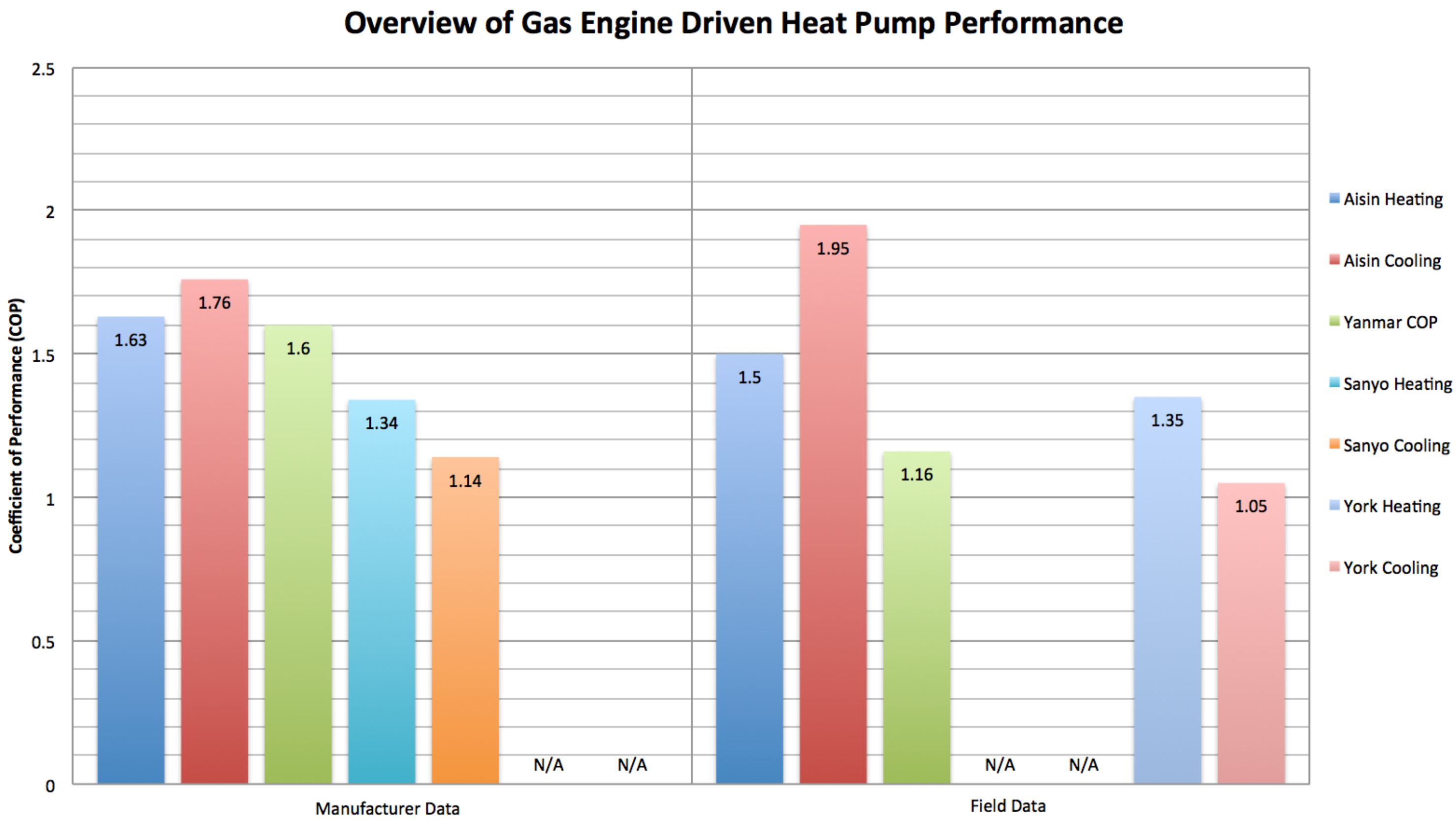


Figure 29: Manufacturer data and field data compared for gas absorption heat pump models

In the field study the Yanmar gas driven heat pump performed at a COP of 1.16[38], whereas based on the calculations the COP from the manufacturer data is 1.6[39]. The study does not mention the temperature at which the COP was measured, but the manufacture data mentions that it can perform at an outdoor temperature of -10 to 43°C for cooling and -20 to 35°C for heating. The variance is 0.44, which is similar to other variances with natural gas as the fuel source. Therefore, this heat pump is still sufficient, but if chosen, other factors must be considered. The study assessed a 5 horse-power (HP) heat pump, which is suitable for small offices or large single rooms. For larger settings, the same heat pump is available with greater HP.

The field study on Aisin's GEDHP did not include a specific model and neither did the manufacturer data therefore the performance results of this study should be interpreted with caution. The manufacturer data reported may have been on one type of model while the case study utilized another model of Aisin's. Nevertheless, in the study it was found that the heat pump exceeded the manufacturer's and customer's expectations in terms of cooling performance, with a COP of 1.95[40] which is 0.19 greater than what was expected. This system's performance was labelled as being optimal in the case study and was used as a baseline for comparing other HVAC systems. The study regarding the Sanyo Engine Driven Heat Pump, three-pipe VRF provided a lot of applicable information other than COP values. As seen in Figure 29, the manufacturer COP values for expected heating and cooling were 1.34 and 1.14, respectively[41]. The York outdoor split system gas engine driven study has COPs calculated from 10 different cities in the USA. As seen above, the field study COP mean for heating was 1.35 and 1.05 for cooling[42]. Although installation manuals are available online, the manufacturer stated COPs or efficiencies of performance were not found. Attempts to talk to the manufacturer (York) and the research partner (the Gas Research Institute) were unsuccessful. In the York Technical Guide to Split System Heat Pumps, model E2GE036N06401C was not found. This study's performance data remains inconclusive.

Cost

For the GEDHP studies, information on the cost of installation was not provided. For the York outdoor split system gas engine driven study, the Gas Research Institute estimated energy cost savings to range from 20%-80% when compared to conventional electric heat pump and furnace/air conditioners.

Cold Climate Data

For the Yanmar GEDHP, manufacturer information stated that outdoor temperatures for heating can go as low as-20°C[39]. For the Aisin GEDHP there is no mention in the study or manufacturer information on what the minimum effective performance temperature is. According to the manufacturer of the Sanyo Engine Driven Heat Pump, the heat pump can perform at full heating capacity down to temperatures as low as -21 °C[41]. The minimum outdoor coil heating temperature for the York GEDHP is -23°C[43]. These conditions are sufficient for Toronto's winter climate. There was no third party field data for sub-zero conditions.

Environmental Performance

Gas engine driven heat pumps, like electric heat pumps, often use R-22 as a refrigerant, which has ozone-depleting chlorofluorocarbons. Currently, R-22 is being phased out in Canada and the US and is being replaced with non-ozone depleting refrigerants such as R-410a and R-407C, but those refrigerants but those refrigerants still have some negative environmental characteristics[5]. R-22 can only be used in equipment installed prior to January 1, 2010 or for equipment that has been imported by businesses that have prescribed allowances from U.S. EPA through 2020[7]. Only 25% of the GEDHP studies had information on environmental performance. Unfortunately, the information that was present was vague, no quantitative values were available. It was found that engine driven heat pump technology had lower primary energy consumption and lower CO_2 emissions compared to average emissions produced with electrically driven technologies (air and ground sourced heat pumps).

Ease of Retrofit

For the studies referenced for GEDHPs, only 25% of the studies had information on retrofits. The Yanmar study mentioned that investment and maintenance costs are barriers for large-scale adoption for the technology, as such further performance improvement by the manufacturer and smart implementation is required for more favorable economics. However, due to the fact that Yanmar 5HP heat pumps are small units, they are easily installed as part of a building retrofit.

5.0 Conclusion and Recommendations

Air Source Heat Pump

The literature on air source heat pumps suggests that new, cold climate mini-split heat pumps (CC-MSHPs) are a viable and potentially energy saving option for retrofits in the GTA. MSHPs were by far the simplest to install of the heat pump technologies reviewed in the study. They were also considerably less expensive compared to alternative such as ground source heat pumps. The literature showed values of ~CDN$3.90 to $7.83 to heat a single ft^2 using a MSHP compared to CDN$3.97 (a value from 1997) to $16.33 for GSHPs. MSHPs are an ideal fit for multi-unit resident buildings (MURBs) as they are the most compact, perform both heating and cooling, do not require ducts, can be wall mounted, and are available in smaller capacities to better suit apartments and individual rooms. Technological advances, such as inverter-driven, variable speed compressors allow CC-MSHPs to operate in conditions similar to Toronto winters. Independent research in the same and similar AHRI Climate Regions as Toronto has demonstrated that these heat pumps can perform to manufacturer ratings in even -20°C weather[59]. Furthermore, energy costs and consumption savings have been realized in other MSHP retrofits of MURBs when converting from electric baseboard heaters. Switching from fuel oil boilers to MSHPs will also likely generate substantial savings. Decreases in energy consumption will obviously facilitate reductions in CO_2 emissions.

While the performance of CC-MSHPs has shown to be very intriguing, many other factors such as compressor placement, sizing, increased maintenance, tenant education, and ice formation must be considered when complementing the switch. Despite the increased operational and maintenance-related complexity, feedback from major MSHP retrofit projects has mostly positive.

Findings for central split systems are less concrete, as there is a lack of third party performance trials for newer central split models. More research on cold climate central split system, especially ones with variable speed compressors, is needed.

Overall Recommendations

1. MSHPs need to be sized properly to ensure optimum performance. For heating dominated climates such as the GTA, MSHPs should be should be sized using heat capacity. For bigger apartments the tradeoff between comfort, installing more than one indoor fan unit so heat is more evenly distributed, and costs needs to be evaluated.
2. Switching from electric baseboard heaters to MSHPs is a learning curve for tenants and property managers. Heat pumps are more complex to operate than electric resistance heat, tenants should receive kickoff training. If the old electric resistance heaters are not removed, tenants should also be encouraged to not use them at the same time as heat pumps to maximize energy savings. Property managers should be prepared for the more frequent need of maintenance (mostly in the form of filter cleaning/changing) and to weatherize the outdoor compressor to protect them from excessive ice formation (probably with metal covers). MSHPs are more fragile than electric baseboard heaters due to the outdoor compressor and should be treated as such.
3. MSHPs deserve a strong consideration when planning MURB retrofits in Toronto due to their relatively low cost, small size, lack of need for duct work, and their verified performance in climates similar to the GTA.

Ground Source Heat Pump

The results of the literature review indicates that there are many nuances associated with maximizing the efficiency and cost savings of GSHPs. Proper installation of the entire system is needed in order to ensure satisfaction from the system as many issues from refrigerant leaks to insufficient depth of trenches for horizontal looped systems can arise. Installation costs also vary considerably based on the geographic location of the building, geological makeup of the surface, proximity to open water and overall water quality, depending on the type of GSHP.

There are potentially significant energy savings in Canada when utilizing a ground source heat pump compared to electric resistance heat. Studies found that annual electricity savings relative to a conventional electric furnace and air conditioner were converted to the equivalent carbon dioxide based on electricity generation sources in Ontario. Emissions reductions were found to be 2,449 kg eCO_2 for the average GSHP. If the heat pump displaced natural gas during the heating season instead, the annual emissions reductions would rise to 3,549 kg eCO_2[44]. The savings made in the cooling season do not appear to be significant when compared to a new central air conditioner with the major benefit being the fact that the unit is indoors and not exposed to the outdoor conditions.

Given the spatial restrictions of an urban center such as Toronto, vertical GSHP systems are the most feasible ground option for a MURB retrofit. Despite the main deterrent being costs associated with the installation of the vertical loops, the process could be substantially reduced if several adjacent systems are constructed at the same time. This is often the case for new subdivisions designed to condition homes by geoexchange which applies to certain regions of the Greater Toronto Area (GTA). However, speaking to the areas needing MURB retrofits, smaller capacity water-to-air heat pumps would be a more suitable fit. Furthermore, in order to add to the overall savings of the system, time of use controls for geoexchange systems should be developed and included in more heat pump systems with the potential for some units to save between 20 to 25% in electricity fuel costs[47].

A hybrid ground source heat pump system with solar thermal collectors could also be a feasible choice for heating-dominated houses in the GTA however a multi-unit building would not have the solar capacity. The seasonal solar thermal energy storage in the ground of the hybrid system was sufficient enough to offset large amounts of ground loop heat exchanger length that would have been required in conventional ground source heat pump systems. However, like most ground source heat pump installations the economic benefits of such systems depend on climate, borehole drilling cost, current energy prices as well as interest rates[45].

Overall Recommendations

1. Systems should be commissioned after the original installation and checked periodically to ensure proper operation. Installation of basic, permanently mounted metering equipment such as a flow meter and temperature probes on the ground loop and a run hour meter on the heat pump itself could be of significant benefit to both customers and geothermal contractors in diagnosing and troubleshooting problems and maintain proper operation. They could also be used for collecting further research on GSHP[46].
2. GSHP owners should be provided with energy usage and savings based on an estimated Seasonal Coefficient of Performance (SCOP) that can be achieved and sustained over the

expected operating life of the system. This will ensure all components including additional fans, pumps, and auxiliary heater electricity requirements are accounted for. These components are not included in AHRI/CSA certified test standards steady state COP[46].

3. Short cycles should be avoided when possible as there is a possibility that they have a negative effect on performance due to the starting of the compressor[47]. Methods of avoiding short cycles include properly sized buffer tanks and turning certain heat pump units off during low-load times when multiple units exist in a system.
4. Installers, engineers, and certified electricians should be aware of the efficient cooling potential of free-exchange. Determining the suitability of a particular site should be included in more installation plans[47].
5. It is important to interlock the circulator pumps within a heat pump system. Constant flow as a result of the circular pumps dramatically decreases the performance of the system as a whole as well as increasing the operating costs. Such errors could be avoided through the implementation of a standardized installation template for all professional technicians or electricians[47].

Gas Absorption Heat Pump

Gas absorption heat pumps are a low-carbon and energy efficient option for heating and cooling. Gas absorption heat pumps do not rely on electricity, reducing demand on the electric grid. The above analyzed GAHPs reveal that for the majority of the models, the performance of these heat pumps were in proximity of the manufacturer ratings. In some cases, heat pumps exceeded manufacturer and consumer expectations. The cost for GAHPs varied significantly. GAHP air source models were less expensive to install than ground or water, however it does not always perform the most efficiently.

The COP of GAHPs was found to be lower compared to its electric ground, water and air counterparts. However GAHPs put less stress on electric energy infrastructure, furthermore:

1. GAHPs allow for the use of natural gas or biogas which reduces electricity demands.
2. They perform in par with manufacturer stated performance, with the exception of air source.
3. They can be used for multiunit housing, commercial property and private property.
4. GAHPs can use ammonia-water as a refrigerant, which has no ozone-depleting compounds.

Overall Recommendations

1. Air source gas absorption heat pumps do not meet manufacturer or consumer expectations. They should be tested further before being considered.
2. Solar hybrid models for gas absorption heat pumps deserve extra consideration, as their performance can exceed manufacturer rated COP.
3. If environmental performance is the key criteria, then gas absorption heat pumps are a good option because they use ammonia-water, a non-ozone depleting refrigerant.
4. Natural gas fuelled heat pumps should be used to reduce peak demand on the electric grid, especially in summer.

Gas Engine Driven Heat Pump

It was found that several studies did not include manufacturer and field study COP values, thus the performance values of GEDHPs remains inconclusive. Although the COPs of an engine driven heat pump are not as high as electric heat pumps, the main advantage of a GEDHP is its ability to reduce infrastructure strain during peak electricity demand. In the summer, many electric utilities experience peak summer loads which sometimes surpass the utility's peak capacity. These peaks are temporary, but utilities face high costs in trying to meet these loads. A considerable solution would be to utilize natural gas fueled gas engine driven heat pumps instead of electricity during the summer months[5]. Consequently, this type of heat pump deserves further investigation. The engine recovery process of GEDHP is quite noteworthy and brings advantages such as reducing or eliminating the need for extra heaters and increasing cost savings due to powering the compressor with an engine fueled by natural gas instead of electricity.

Overall Recommendations

1. Quantitative CO_2 reduction values to be reported in manufacturer catalogue.
2. Retrofit opportunities and challenges to be clearly described to potential customers.
3. Studies on negative performing models of GEDHPs by academic institutions or non-for-profit institutions should be openly available to the public.
4. Use natural gas fuelled heat pumps to reduce the peak demand on the electric grid.
5. Since gas absorption hybrid models are usually successful, consider hybrid models of GEDHPs.

Final Recommendations

To outline the overall conclusions on each heat pump type, a summary of each is provided in the table below. Based on the number of models reviewed, ground and air source sections are provided as general summaries and the natural gas source models are reviewed based per model type. For more detailed information on each model type reviewed please refer to the Appendix Section.

Table 24: Research Findings & Conclusions

Research Findings & Conclusions		
ASHP (General Summary)	Mini-Split (Ductless)	- Smallest outdoor unit, easiest system to install, can be wall mounted - They are a good option when there is no ducting, or when the ducting is in disrepair - Relatively low capital costs, especially compared to ground source - New, cold climate systems using inverter-driven, variable speed compressors perform well and are viable for the GTA and similar climates - Things to consider when planning a mini-split heat pump retrofit include the placement of the outdoor unit, choosing a unit with the correct heating capacity, increased maintenance over conventional systems, tenant education, and ice formation prevention
	Central-Split	- Performance for central-split using single speed compressors was shown to be generally disappointing - New systems, especially those with inverter-driven, variable speed compressors could potentially work well in climates like the GTA but testing from third parties is lacking - Older homes may have smaller ducting which can be a bottleneck for higher capacity central-split systems - The air handler unit and return duct should be placed in a part of the home that does not become significantly hotter and/or colder than the rest of the house to improve efficiency
GSHP (General Summary)	Vertical Closed Loop	- Capital cost of vertical borehole installation can be prohibitive - Important to find a balance between high efficient technologies (more operational savings) and higher capital investment costs - Installations are site specific: ease of retrofit is based on subsurface material, climate, level of water table - Important to properly size the heat pump system as over sizing systems have longer payback periods and/or higher initial capital costs
	Horizontal Closed Loop	- Efficiencies heavily depend on the depth of horizontal trenches
	Open Loop Water-to-Water	- Strict regulations such as local bylaws can exist for water discharge based on geographic location of installation - Water quality directly effects the efficiencies of the system and has the potential to damage the unit
	Direct Exchange	- No defrost cycle needed - Unit is located indoors - Less looping than traditional GSHP which results in lower installation costs
	Hybrid Systems	- With solar thermal collectors, system could be a choice for space conditioning for heating-dominated houses in GTA

Research Findings & Conclusions		
GAHP (Summary of Models)	Robur Ground	- Manufacturer COP: 1.47, Field COP: 1.41 COP - High installation and retrofitting cost for ground source gas absorption heat pump - Ammonia-solution (non-ozone depleting compounds) used as a refrigerant
	Robur Air	- Manufacturer: 1.65, Field: 1.07 - Lowest level of performance from other Robur gas absorption models - Performance is low if integrated with pre-existing gas boilers - Low/decent installation and retrofitting costs - Uses non-ozone depleting compound as a refrigerant
	Robur Water	- Manufacturer COP: 1.74, Field COP: 1.25. - Performance did not consider hot water, only space heating - The 1.25 COP was stable despite the changes in ground temperature variation - High installation and retrofitting cost for water source gas absorption heat pump - Non-ozone depleting compounds used as a refrigerant
	Zeolite Vaillant	- Manufacturer COP (including solar thermal DHW): 1.36 - Field COP at 45°C-55°C output temperature = 1.33 - Field COP at 28°C-35°C output temperature = 1.44 - Performs well due to hybrid nature of technology - Cost of technology was approximated at $25,000 CA - Non-ozone depleting compounds used as a refrigerant
	Buderus	- Manufacturer COP at 7°C is 1.6; -7°C is 1.25 - Field COP at 7°C is 1.60; -7°C is 1.25 - COP decreases as temperature decreases - Cost of installation and retrofitting is low/decent, since the source type is air - Non-ozone depleting compounds used as a refrigerant
	Remeha Hybrid	- Manufacturer COP: 1.44. Field COP: 1.40 - Low air pollution, due to low noise brushless fan - System effectively lowers CO_2 and NOx - Non-ozone depleting compounds used as a refrigerant
GEHP (summary of models)	Yanmar	- Manufacturer COP: 1.6 - Field COP (averaged): 1.16 - Uses same refrigerant as electric heat pumps
	Aisin Toyota	- Manufacturer COP for heating: 1.63; Cooling: 1.76 - Field COP for heating: 1.5; cooling: 1.95
	Sanyo	- Manufacturer COP Heating: 1.34 - Manufacturer COP Cooling: 1.14
	York	- Field COP for heating: 1.35 - Field COP for cooling: 1.05 - York Triathlon Gas engine driven heat pump is now off the market

Appendix

Within each appendix the literature review of the various cases compiled for each technology are displayed, outlined with a case number, title, date and study details. Each study also has pertinent conclusions and data (both manufactured and field) as well as important figures from the reviewed studies.

Appendix A - Air Source Heat Pump (ASHP) Review

Ductless Mini-Split Heat Pumps

ASHP Case #1: Performance Assessment of a Variable Capacity Air Source Heat Pump and a Horizontal Loop Coupled Ground Source Heat Pump System (2012)[32]

Study Details	
Purpose	This study evaluates the performance of air source heat pump (ASHP) and ground source heat pump (GSHP) systems individually and as part of their associated heating and cooling distribution systems in two semi-attached houses. In this analysis, the performance of the new-two stage variable capacity air source heat pump will be considered.
Location	Toronto, ON; Halifax, NS; Vancouver, BC; Edmonton, AB; Montreal, QC, Canada
Model	Mitsubishi PUZ-HA36NHA
Specifications[48]	Ductless Mini-Split Indoor Unit: PKA-A36KA HSPF 9.3 SEER 14.0 Heating Capacity: 12,000 – 38,000 Btu/h Cooling Capacity: 12,000 – 34,200 Btu/h Compressor: Variable Speed Refrigerant: R-410a
Parameters	The study was performed at the Archetype Sustainable Twin Houses in Toronto. The ASHP was tested in House A of the semi-detached homes, which was designed to demonstrate current best practice sustainable technologies. The ASHP was tested in cooling conditions and extreme winter heating conditions.

The Archetype Sustainable Twin Houses are built to high sustainability and energy efficiency standards such as LEED Platinum and ASHRAE 90.1 (air-tight building envelope). House A has a floor area of 345 m^2 (3,708 ft^2). Using calibrated sensors data on “outdoor temperature and relative humidity, supply/return temperature and relative humidity to the zones, supply/return air flow rate, and the power consumption of the system” were collected over a period from August 23 through September 15th, 2010 and from December 24, 2010 to January 12, 2011.

Power draw for the 23-day test period ranged from 1.05 to 1.25 kW while cooling output ranged from 5.6 to 6.3 kW, leading to COP values ranging from 4.7 to 5.7. These results are displayed in Figure 30, the ASHP performed very efficiently. COP at this range was approximately 20% higher than the rated capacity COP. The COP values did not include the energy draw of the indoor fan unit, the author was only interested in the performance of the heat pump alone.

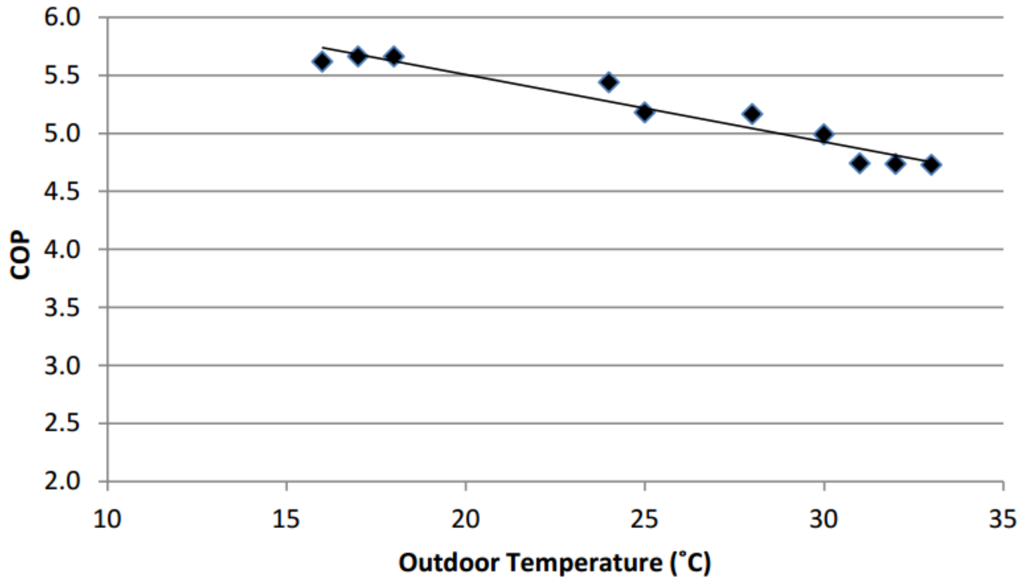


Figure 30: ASHP Cooling COP

Efficiency degrades when ASHPs perform at part load, under their designed load capacities. ASHPs designed for extreme conditions often operate at part load, thus the author decided to compare tested and manufacturer data in terms of part load performance. Figure 31 illustrates this comparison, where the total input/COP ratio refers to input/COP at a certain capacity divided by the rated input/COP at that corresponding outdoor temperature. Since the data was obtain at a capacity of 52% to 57%, all the data points are within this range. The experimental COP and input data (COP Expr. and Input Expr.), falls well within the manufacturer's part load performance curve (COP Manu. and Input Manu.).

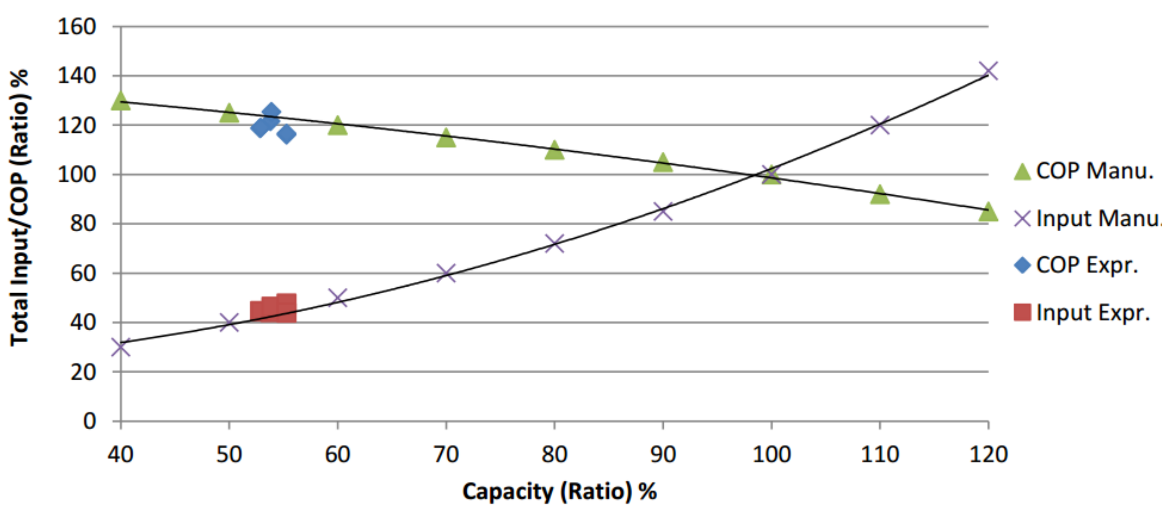


Figure 31: ASHP Part Load Experimental and Manufacturer Cooling Performance

The tested ASHP has a two stage compressor setup. In lower demand heating conditions only the first stage compressor will operate, in higher demand conditions the second stage compressor will also operate. Figure 32 shows the relationship between COP and outdoor temperature. When the heat pump was operating at 54% capacity, COP was 40% higher than rated, at 100% capacity it was close to the rated capacity COP.

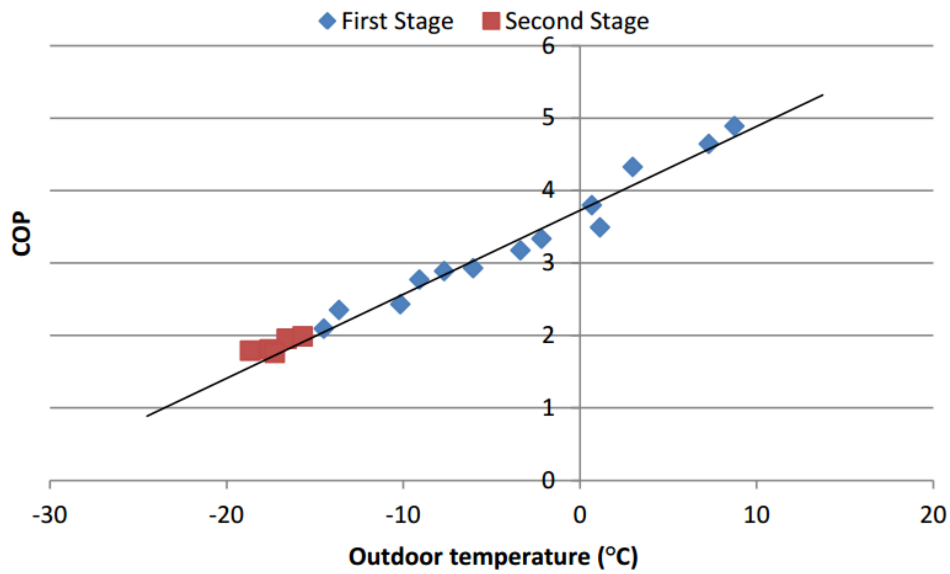


Figure 32: ASHP Heating COP (Dec 1, 2010 – Feb 9, 2011)

With these results, the author simulated performance over an heating and entire cooling season in Toronto using detailed termperature and metrological data.

Table 25: ASHP Heating and Cooling Simulation Results for Selected Canadian Regions

Location	Heating Output (kWh)	Cooling Output (kWh)	Heating Consumption (kWh)	Cooling Consumption (kWh)	Heating SCOP	Cooling SCOP
Metro-Toronto	17,579	2,289	5,442	434	3.23	5.27
Halifax	21,689	1,133	6,009	203	3.61	5.58
Vancouver	18,916	1,404	4,236	245	4.47	5.73
Edmonton	26,644	1,830	10,141	337	2.63	5.43
Montreal	23,888	2,934	8,031	540	2.97	5.42

The study found ASHP to be slightly less efficient than the GSHP in this study. However, when we considering the comparative initial investments and payback periods, there is a compelling argument to be made for an ASHP vs. a GSHP.It should be noted that with the ASHP, no heat transfer will occur below -24˚C due to the outdoor temperature being lower than the evaporator heat exchange temperature.

Table 16: Cost Analysis of ASHP and GSHP Systems Relative to Conventional Electrical Energy Systems

	Annual Energy Cost	Annual Cost of Conventional Energy	Initial Investment	Simple Payback Period
ASHP	$664	$2,074	$14,500	10.3
GSHP	$725	$2,205	$34,500	23.3

Energy savings from the use of these more efficient heat pump systems translated into significant greenhouse gas emission reductions. Emission reductions are outlined in table 3 for the ASHP.

Table 27: ASHP Annual CO_2 Emissions Reductions

	Electric Baseboard Heating + Air Conditioner	Natural Gas Furnace + Conditioner
Reduction in CO_2 (kg eCO_2)	2,330	3,329
Reduction per m^2 (kg eCO_2)	6.76	9.37

Conclusions

The ASHP performed very well, often exceeding manufacturer rated performance. However, performance was less constant compared to the GSHP in colder weather due to the relative constant ground temperature compared to air temperature. In the cooling season the ASHP was able to operate for longer period and delivered better thermal comfort by closely meeting thermostat settings, mainly due to the variable speed compressor (the GSHP has a constant capacity compressor).

ASHP Case #2: Laboratory Test Report for Fujitsu 12RLS and Mitsubishi FE12NA Mini-split Heat Pumps (2011)[49]

Study Details		
Purpose	To expand on data reported by manufacturers to be able to better compare mini-split system performance and cost to conventional systems	
Location	Lafayette, IN, USA	
Model	Fujitsu 12RLS	Mitsubishi FE12NA
Specifications[50,51]	Ductless Mini-Split Indoor Unit: AOU12RLS HSPF 12.0 SEER 25.0 Heating Capacity: 16,000 Btu/h Cooling Capacity: 12,000 Btu/h Compressor: Variable Speed Refrigerant: R-410a	Ductless Mini-Split Indoor Unit: MSZ-FE12NA HSPF 10.6 SEER 23.0 Heating Capacity: 13,600 Btu/h Cooling Capacity: 12,000 Btu/h Compressor: Variable Speed Refrigerant: R-410a
Parameters	The heat pumps were tested at the Herrick Laboratories ASHRAE standard psychometric chambers. The chambers consisted of two highly insulated rooms capable of simulating indoor and outdoor conditions. Steady-state, cyclic, and defrost performance was tested.	

Fujitsu's and Mitsubishi's reported performance data were tested under "intermediate" compressor speed running conditions. Since both ASHPs uses variable speed compressors, intermediate compressor speed is an arbitrary term, it could be referring to any speed between maximum and minimum load. Without knowledge of the exact compressor speed and the external special controller that is typical used by manufacturer to achieve a steady intermediate compressor state, the exact conditions under which the manufacturers collected their performance data could not be replicated. Therefore, the authors of this report decide to use maximum compressor speeds.

Figure 33 compares Fujitsu's reported heating capacity to laboratory test data. Heating capacities were higher in the test results; this was anticipated since the authors tested the ASHP at full load as discussed previously. Therefore, it is difficult to directly compare the two data sets. However the laboratory data does display a similar linear decline in performance with decreasing temperatures.

Figure 34 compares Fujitsu's reported COPs with the COPs derived from the laboratory results. The manufacturer COPS are slightly higher but that was expected by the authors since Fujitsu had tested the unit at an intermediate compressor load, which requires less electricity and thus greater efficiency.

Due to the differences in testing parameters, intermediate compressor load vs. maximum compressor load, these laboratory results cannot completely prove or disprove Fujitsu's performance claims. The comparisons do show that performance degradation in response to colder temperatures is similar for the reported and laboratory data.

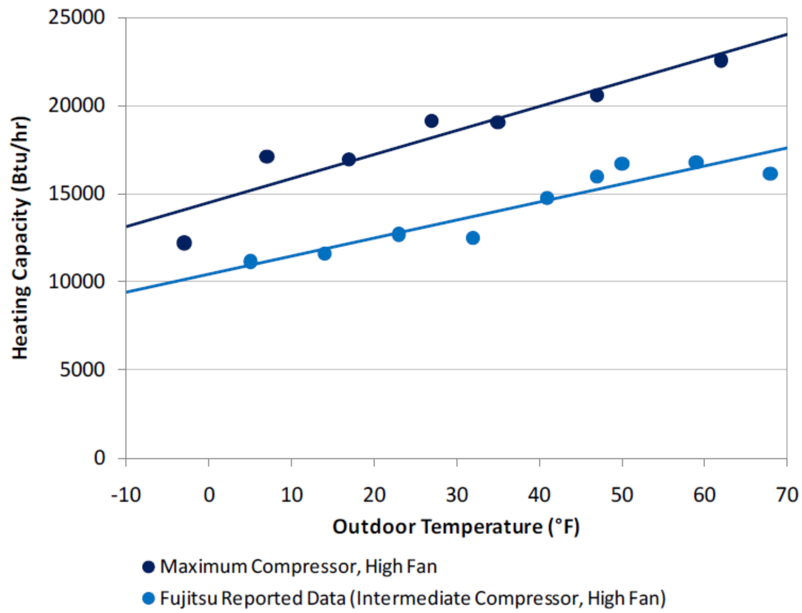


Figure 33: Fujitsu 12RLS Maximum Steady-State Heating Capacity Compared to Manufacturer-Reported Data (70°F Return Temperature)

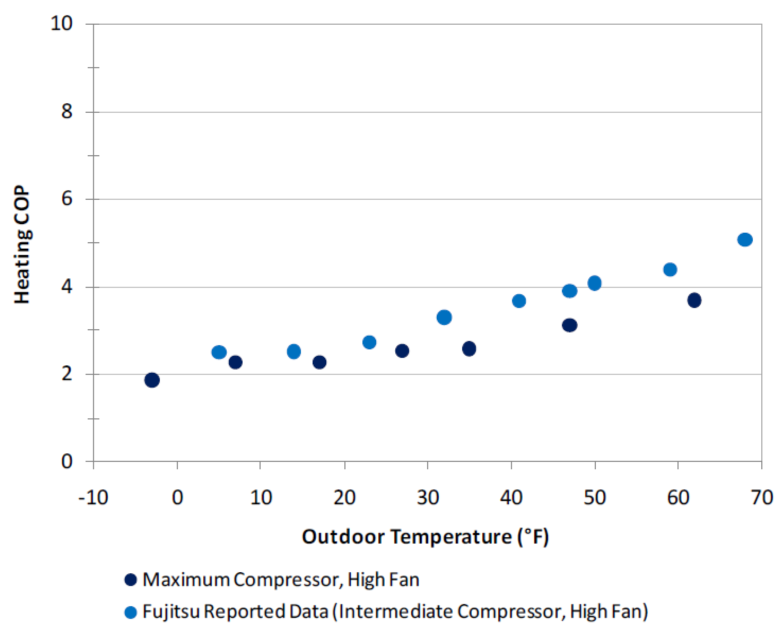


Figure 34: Fujitsu 12RLS Heating COP Compared to Manufacturer-Reported Data (70°F Return Temperature)

Cooling performace as tested are shown in Figure 35 and 36. Simiarly to the heating results, differences in absolute performace were atrributed mostly to differences in compressor load, while overall performance trends between tested and maufacturer data seemed to correlate well.

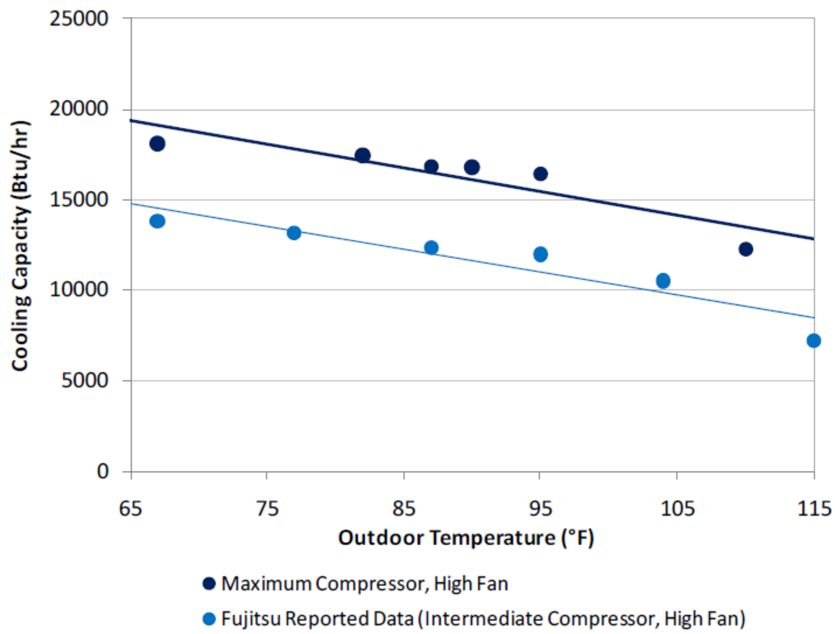


Figure 35: Fujitsu 12RLS Maximum Steady-State Total Cooling Capacity Compared to Manufacturer-Reported Data (80°F DB, 67°F WB Return Condition)

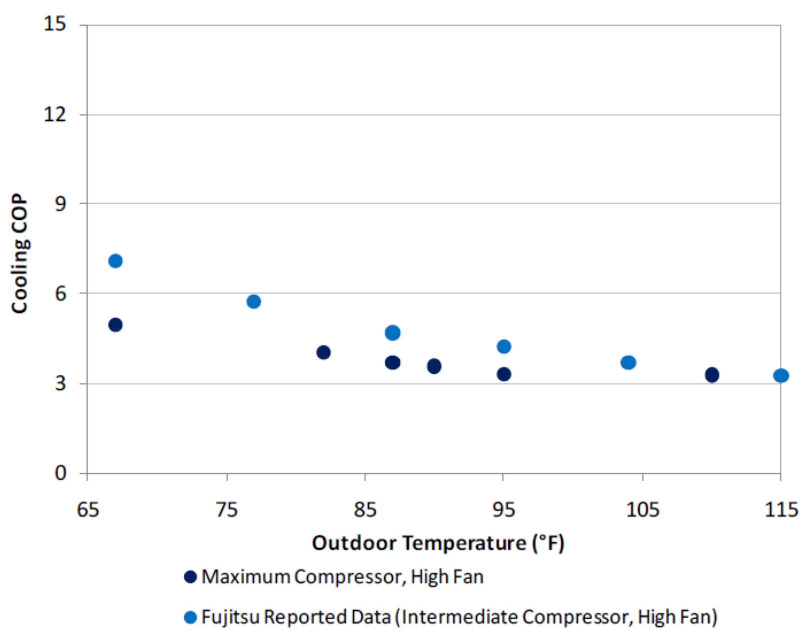


Figure 36: Fujitsu 12RLS Steady-State Cooling COP Compared to Manufacturer-Reported Data (80°F DB, 67°F WB Return Condition)

Figure 37 compares Mitsubishi's reported heating capacity to laboratory test data. Once again, due to the higher load the authors ran the unit at, the higher capacity compared to the reported data was expected. Like the Fujitsu 12RLS, there was similar linear decline in performance with decreasing temperatures between the two data sets.

Figure 38 compares Mitsubishi's reported COPs with the COPs derived from the laboratory results. Due to the laboratory unit running at higher load the drop in tested COP was expected. The laboratory results do suggests that under full load, less efficiency degradation occurs at lower temperatures.

Like with the Fujitsu model, these laboratory results can neither prove nor disprove Fujitsu's performance claims due to difference in testing parameters. The comparisons do show that performance degradation is similar in response to colder temperatures.

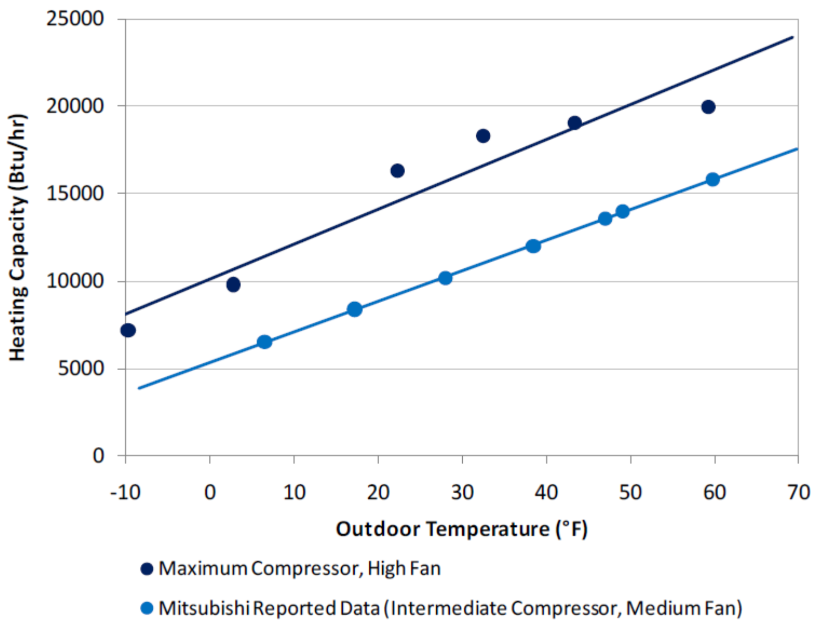


Figure 37: Mitsubishi FE12NA Maximum Steady-State Heating Capacity Compared to Manufacturer-Reported Data (70°F Return Temperature)

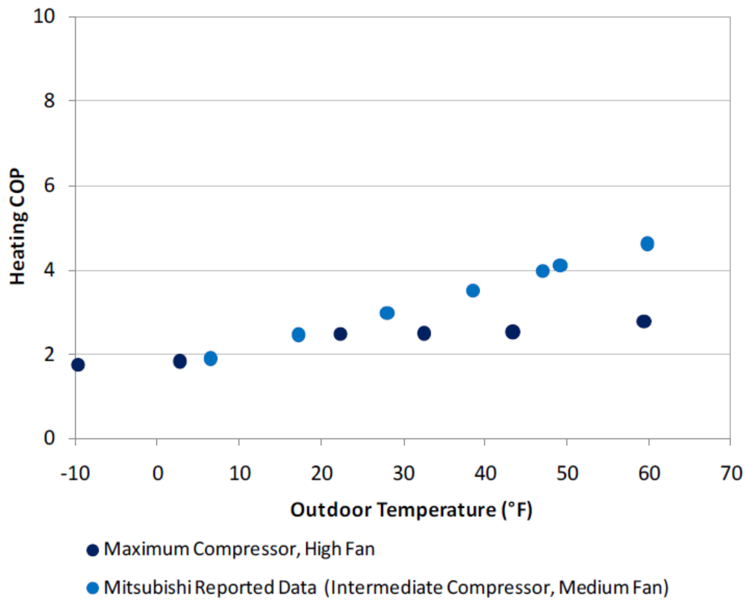


Figure 38: Mitsubishi FE12NA Heating COP Compared to Manufacturer-Reported Data (70°F Return Temperature)

Cooling testing results are shown in Figure 39 and 40. In this case manufacturer rated data were available in the maximum compressor and high fan configuration so we can directly compare tested and rated data. The experimental data for cooling capacity and COP was very much in line with Mitsubishi's reported performance.

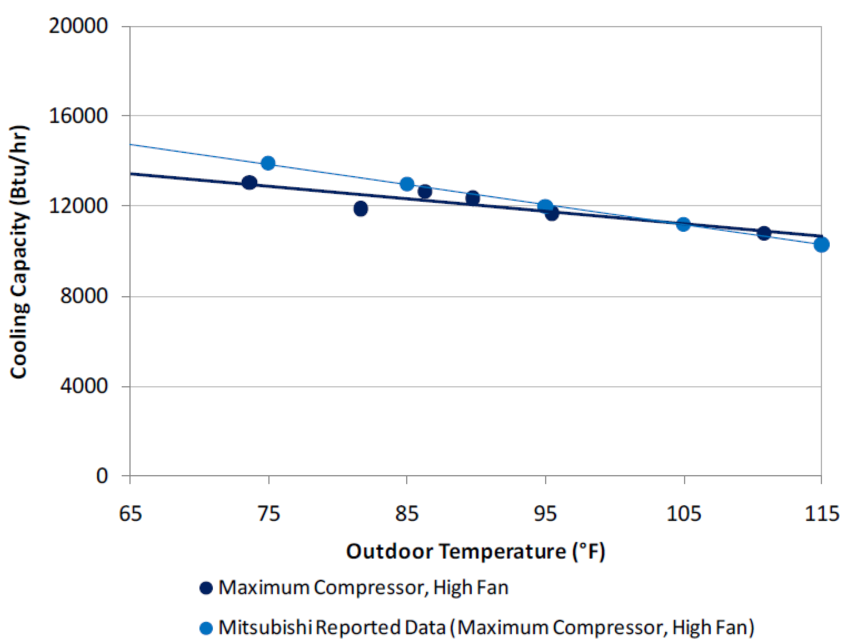


Figure 39: Mitsubishi FE12NA Maximum Steady-State Total Cooling Capacity Compared to Manufacturer-Reported Data (80°F DB, 67°F WB Return Condition)

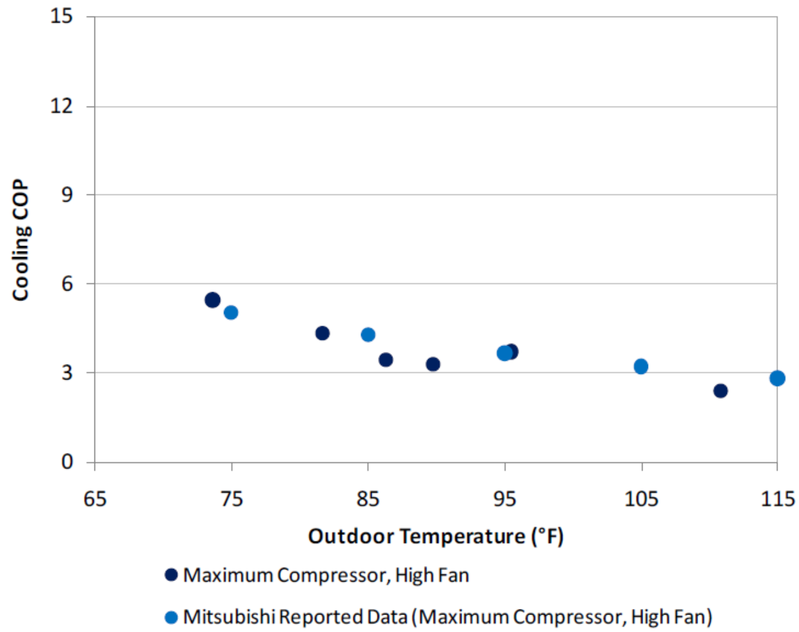


Figure 40: Mitsubishi FE12NA Steady-State Cooling COP Compared to Manufacturer-Reported Data (80°F DB, 67°F WB Return Condition)

Table 28 lists the results for defrost testing for both models. Defrost times were much shorter for the Mitsubishi unit and for the most performance penalties for both were minimal. For the Mitsubishi unit, defrosting took much longer when tested at the coldest tempeature during this defrost trial, -3°F (-19°C).

Table 28: Defrost Test Results

MSHP	Test Code	Total Cycle Time (min)	Defrost Time (min)	Integrated Cycle COP	Integrated Heating COP	Defrost COP Penalty
12RLS	H-DF-35-M-MX	117	10.3	3.26	3.38	3.5%
	H-DF-17-M-MX	142	14.9	2.90	3.06	5.0%
FE12NA	H-DF-35-M-MX	90	3.3	1.76	1.78	1.4%
	H-SS-27-H-MX	79	2.0	1.72	1.74	1.3%
	H-SS-17-H-MX	91	3.8	2.24	2.28	1.8%
	H-SS-17-M-MX	90	3.3	0.88	0.89	1.4%
	H-SS-7-H-MX	31	2.2	1.08	1.13	4.7%
	H-SS-7-L-MX	23	2.5	1.53	1.60	3.9%
	H-SS-n3-H-MX*	47	10.2	1.35	1.52	11.5%

* "n" denotes negative (n3 = –3)

Conclusions

Winkler concluded that the Fujitsu 12RLS and Mitsubishi FE12NA tested over a broad range of operating conditions in the laboratory achieved performance that matched manufacturer data quite well.

ASHP Case #3: Cold Climate Ductless Heat Pump Performance (2013)[52]

Study Details	
Purpose	To examine the viability of ductless mini-split heat pumps by testing the real-world performance of a ductless mini-split heat pump in Connecticut winter conditions.
Location	Middletown, CT, USA
Model	Fujitsu AOU9RLQ
Specifications[53]	Ductless Mini-Split Indoor Unit: ASU9RLQ HSPF 11.0 SEER 21.0 Heating Capacity: 3,000 – 18,000 Btu/h Cooling Capacity: 3,600 – 12,000 Btu/h Compressor: Variable Speed Refrigerant: R-410A
Parameters	The heat pump was installed in a 550-sq ft apartment built over an unconditioned garage in Middletown, Connecticut. The apartment was constructed in 2009 with energy efficiency features such as low-e argon-filled windows, blown-in insulation (in the walls, floors, and ceiling), and advanced air sealing.

Figure 41 illustrates the layout of the apartment during this field trial. DHP performance over two winter heating season was collected and compared to: Zone A Baseboard (running alternatively) and the Zone C Baseboard (running simultaneously). COP was estimated using the relative energy consumption of the DHP compared to the energy consumption of the baseboard heaters. Watts per temperature difference (ΔT) were used to normalize due to differences in capacity between the DHP and resistance heaters. Net installed cost of the unit was under $2,000 after local energy efficiency program rebates and federal tax credits.

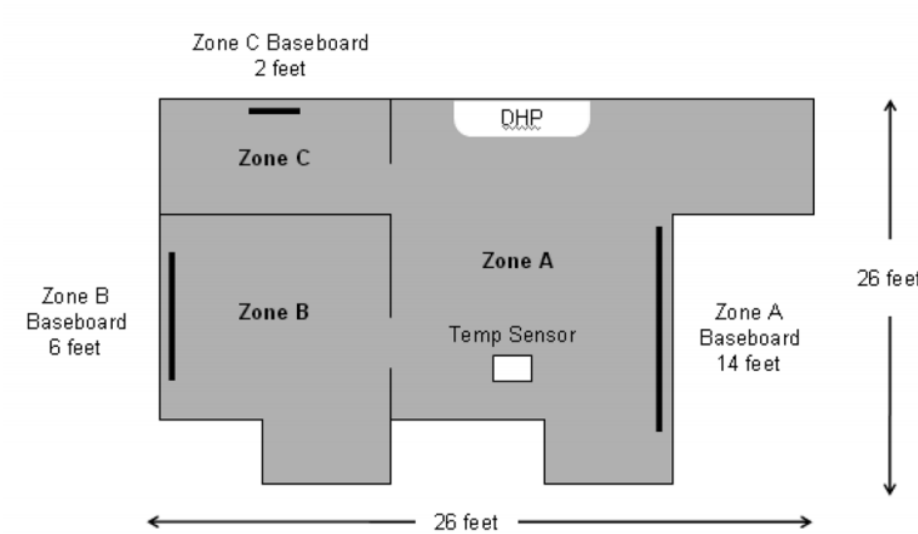


Figure 41: Apartment Schematic and Heating Equipment Location

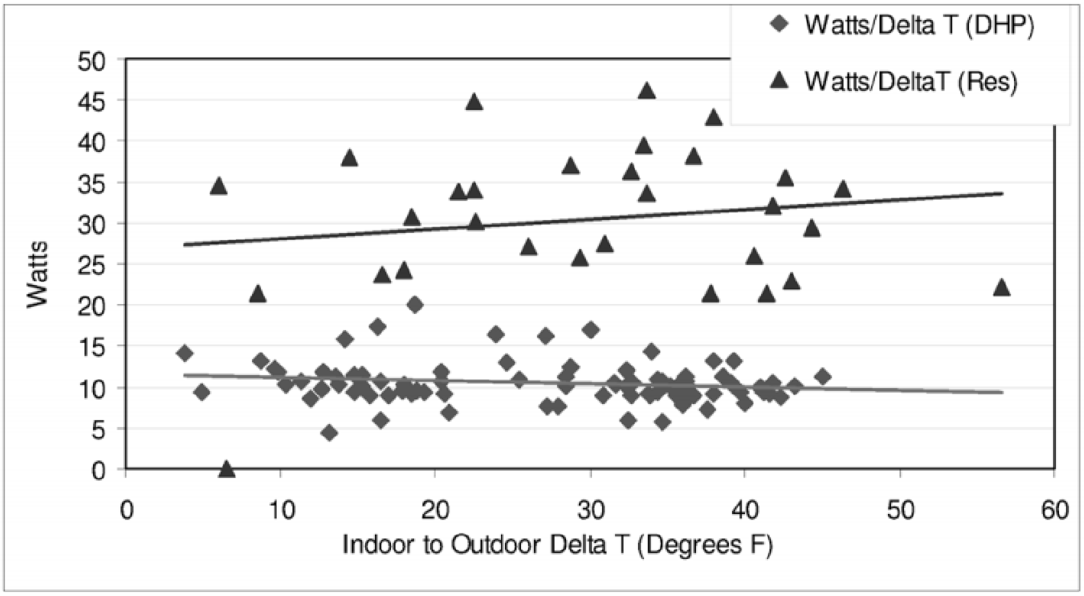


Figure 42: Power Consumption per Temperature Differential (ΔT)

From these results displayed in Figure 42, the authors estimated the DHP's seasonal COP for the winter heating month to be 2.9, which was respectable considering temperatures dipped under 5°F (-15°C). However, the DHP heating capacity was unable to match expected output from manufacturer data at very cold outdoor temperatures, Figure 43, suggesting the need for a secondary heating source when a DHP is the primary heater. The authors did note that the DHP was undersized for the apartment and that better results could have been seen with a larger, multi-zoned heat pump or one more optimized for cold climates.

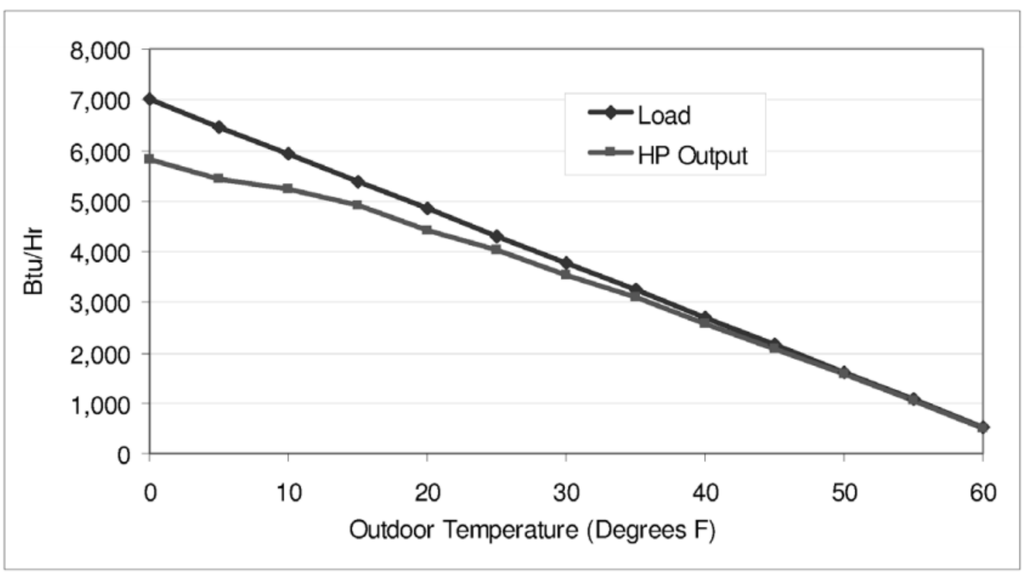


Figure 43: Estimated Heat Pump Output vs. Outdoor Temperature

Lastly, the authors compared energy consumption of the DHP and the Zone C baseboard heater separately and concurrently. Running them concurrently simulates the situation in which backup heat is needed due to decreased DHP performance in extreme cold weather.

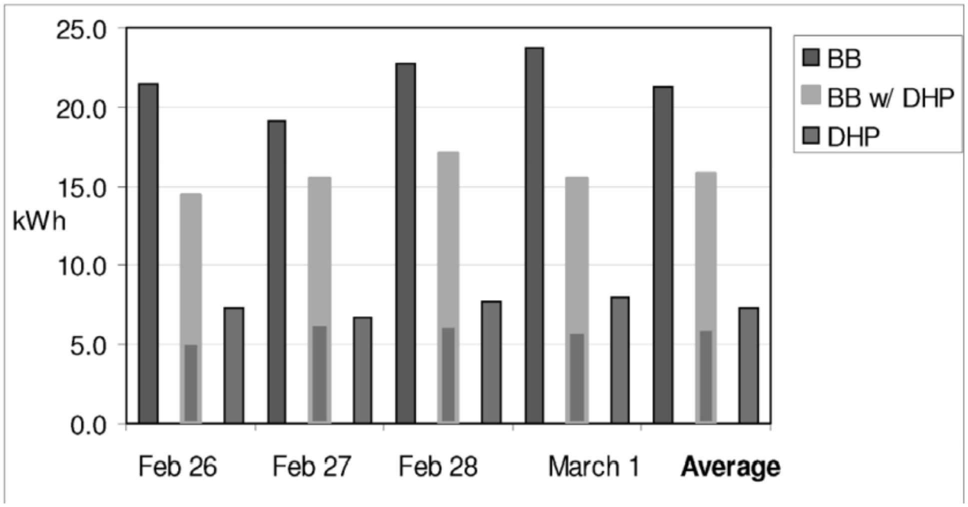


Figure 44: Combined Zone C Baseboard and DHP Results

The results (Figure 44) showed that when running separately, the DHP realized energy savings of 70%. The introduction of a concurrently running secondary heat source, the baseboard heating, reduced energy savings by 40%. This highlights the need for proper heat pump operation strategies, such as setbacks and proper controls, when DHP systems are installed with a secondary backup source of heat.

Conclusions

Based on their tests, the authors concluded that DHPs have the capability to deliver efficiencies of much more expensive GSHPs. This study compared DHPs to electric baseboard heaters but that data suggested that they would make a good replacement for fuel oil and propane as well. DHPs could be a good heating option for newer homes with low heating loads that are built to high performance standards, already a number of builders in the US Northeast have been incorporating DHPs as primary heat sources. The authors also warned about the large impact that even small secondary sources on heat can have on energy savings.

ASHP Case #4:Mini-Split Ductless Heat Pump Bench Test Results (2009)[54]

Study Details	
Purpose	This study reported on the key aspects of a Fujitsu mini-split heat pump's performance. These key aspects were heating season performance, midsummer cooling performance, and defrost cycles.
Location	Goldendale, WA, USA
Model	Fujitsu 12RLQ
Specifications[55]	Ductless Mini-Split HSPF 10 SEER 20 Heating Capacity: 1,700 – 15,000 Btu/h Cooling Capacity: 1,700 – 10,900 Btu/h Compressor: Variable Speed Refrigerant: R-410a
Parameters	The indoor unit was enclosed in a wooden box for the purpose of measuring system airflow. Heating performance in terms of COP was measured during a cold snap where outdoor temperatures ranged from 0°F and 20°F (-18°C to -7°C). Defrost cycle behavior was also monitored. Cooling performance was measured in early July.

Figure 45 displays the testing setup for the indoor unit employed by Davis. The enclosure included depressurized fan to measure system airflow from the unit.

Figure 45: Head-on View of Indoor Unit Test Enclosure

Heating performance at temperatures from 20°F to 60°F (-7°C to 16°C) are show in Figure 46. The system was ran on AUTO mode, running under part load for the majority of the trial, drawing around 350 – 450 Watts of energy to maintain a 25°F – 35°F temperature rise from outdoor temperatures. COP was calculated to range from 3.8 at 38°F (0°C) to 5.6 at 55°F (13°), which the author considered to be remarkable performance. Performance fell to around 2.5 after defrost cycles but that was expected as the system must recover from running a reverse cycle. Davis described heat performance as "quite remarkable".

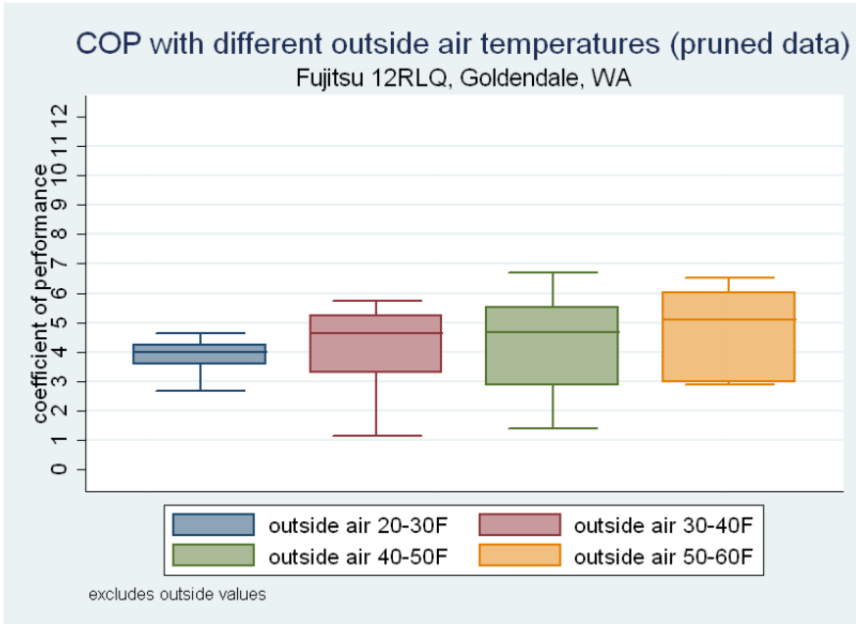
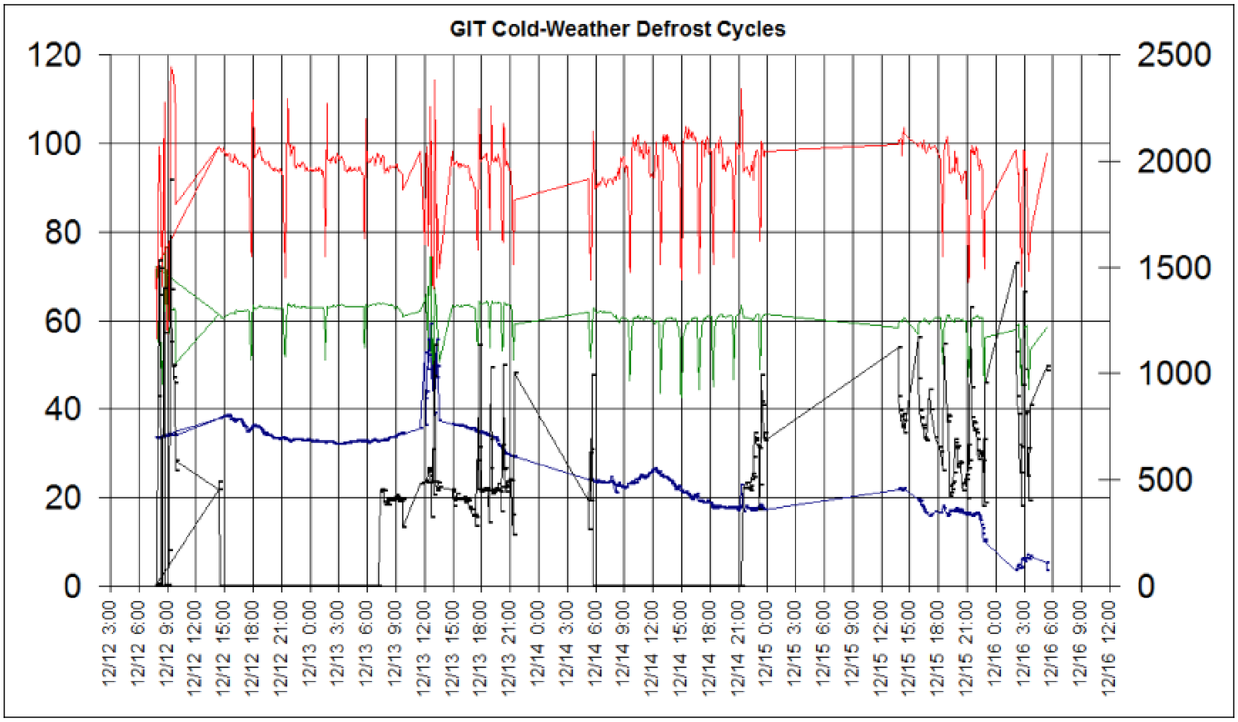


Figure 46: Summary of Heating COP at Different Outdoor Temperature Bins

When examining defrost cycle behaviour, Davis found that the system ran several defrost cycles over the course of a day when the ambient temperature dropped below freezing. The cycles lasted an avearge of four minutes and supply air temperatures would drop during the defrost cycle. Immediately after the defrost cycle the supply air temperature would rapidly increase to compensate. This compensationary "boost" used 600 – 1000 Watts more of electricty over two to four minutes. The supply air temperature never dropped under set return air temperature so comfort was not negatively impacted. In terms of energy consumption the effects of defrosting were negliable, the extra power used during boost periods were offset by the lower power consumption of the defrost cycle and there was no backup resistance heat to consume more elctricity. Furthermore, defrost cycles were found to increase COP by roughly 25% compared to just performance just prior to defrost. Figure 47 illustrates defrost cycle events and their affects on supply temperatue and energy consumption.



Note left y-axis label is degrees F and right y-axis label is system power (Watts).
Red line is supply air temperature; green line is return air temperature.
Blue line is outdoor temperature; black line is DHP power.

Figure 47: December 2008 System Behavior (Emphasis on Defrost Cycles)

Cooling performance (Figure 48) was monitored in early July with the unit running mostly in part load. The system was set to AUTO and the fan was set to LO. Outdoor temperatures ranged from 78°F to 90°F (26°C to 32°C). This is considered a typical summer afternoon in western Washington or Oregon. These parameters lead to an average cooling output of 4,500 Btu/hr and an average COP of 5.6. An average COP of 5.6 roughly translates to a SEER value of 19 (average COP x 3.413). From these results the author concluded that there was a rough agreement between rated SEER and test COP. At maximum settings on a hot day (mid 90°s F) with the fan on HI efficiency was less impressive. Calculated COP averaged around 2.9 over the course of that afternoon.

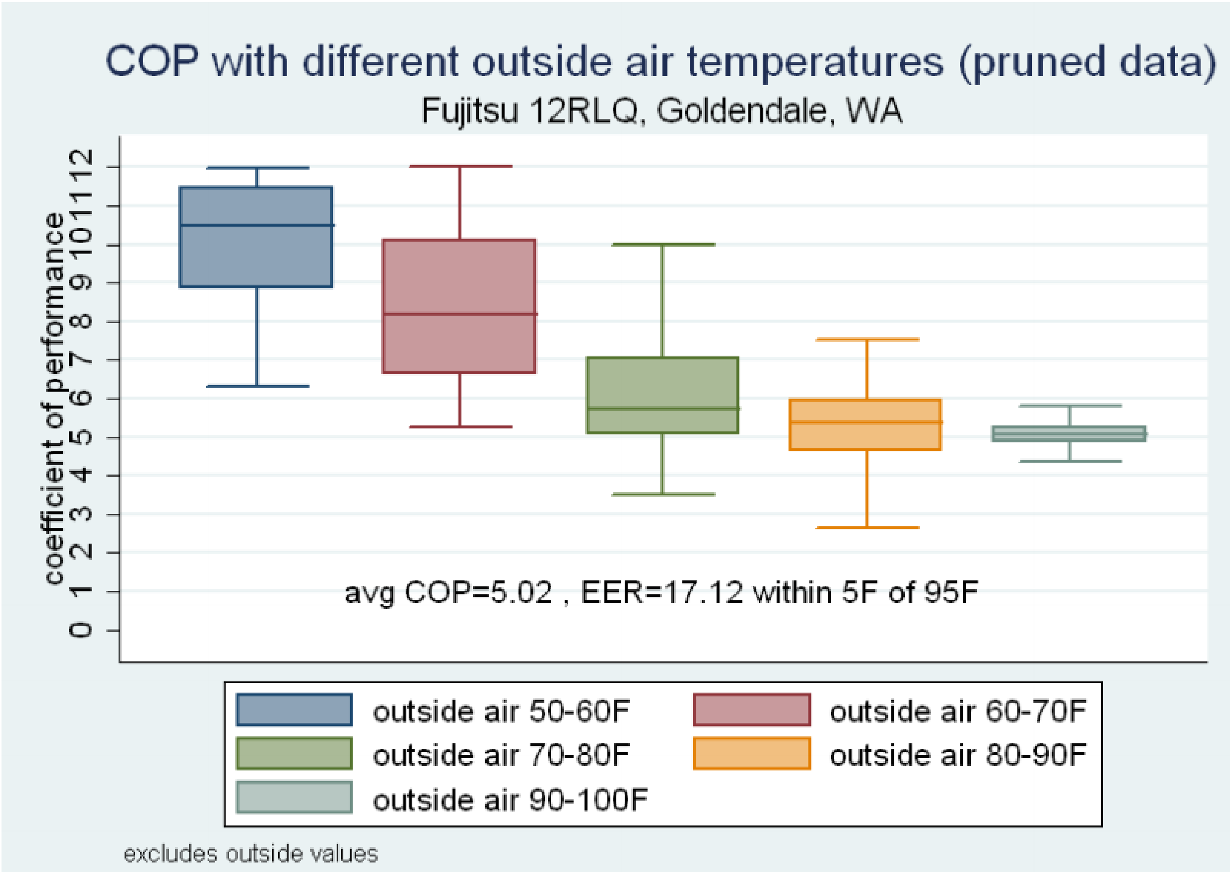


Figure 48: Summary of Cooling COP at Different Outdoor Temperature Bins Performance on a Very Hot Afternoon (Full-Capacity Forcing)

During a checkup before the summer data collection the author discovered an issue with the airflow. On HI the unit had previously been measured to deliver 320 CFM but it was only delivering 265 CFM. Disassembling the indoor unit, Davis found that the filter had become filled with dust and hair. This particular unit did not have an ECM motor to compensate for the increased resistance to flow; the author noted that it is common for inverter-driven DHPs to not have ECM motors. Prior to cleaning out the filter, performance suffered by about 22% with COP averaging around 2.5.

Conclusions

Heating performance was excellent, even surpassing Fujitsu's ratings. Defrost cycles which have been described as parasitic in terms of their impact on energy consumption were found to not have negative effects on system performance and energy use. Cooling performance was also very good, roughly matching advertised values when set to AUTO. However, efficiency dropped when running on maximum settings, highlighting the need to properly size heat pumps. Lastly, the study reinforced the need for regular maintenance.

ASHP Case #5: Mini-Split Heat Pumps Multifamily Retrofit Feasibility Study (2014)[56]

Study Details	
Purpose	This study aimed to fill in information gaps regarding mini-split heat pumps by analyzing the mini-split heat pump retrofit feasibility for low to mid-rise multifamily buildings.
Location	New York, NY; Boston, MA; Maine; Centralia, IL; USA
Model	N/A
Specifications	A theoretical MSHP with a HSPF of 10 and SEER of 22 was used in the modeling software in this study.
Parameters	To evaluate MSHP retrofit feasibility the following aspects were discussed: technical barriers to installation, cost relative to alternatives, impacts and benefits, and market potential. Energy consumption modeling, literature review, and interviews were used to gather information.

MSHPs have many attributes that make them a promising option for new construction where several units can be placed strategically and retrofit of old, inefficient HVAC systems where space is often limited. They are a compact, complete solution, do not require ducts, can be mounted outside, are available in smaller capacities for apartments and individual rooms, have been demonstrated to work at high efficiencies, and require only electricity as fuel. Dentz et al. have attempted to answer some remaining questions about the actual feasibility of the technology.

The total annual energy costs for heating and cooling an insulated midsize apartment in New York was estimated for a MSHP with a COP of 2.5 (a value the authors deemed moderate) and alternative systems with a window or sleeve air conditioner. The apartment annual heating demand was set at 30 MMBtu. Table 29 shows the estimated savings for the MSHP from the authors' calculations.

Table 29: Space Conditioning Site Energy Savings Using MSHP Compared to Alternatives

Heating Fuel	MSHP Savings ($)	MSHP Savings (%)
#2 Heating Oil-Fired Boiler	$424	39%
Natural Gas-Fired Boiler	$25	4%
Electric Resistance Baseboard	$1003	60%
LPG-Fired Boiler	$832	55%

The authors then used BEopt version 2.0 software to predict energy costs and consumption for an existing three-story, 11 unit apartment building that uses a centralized oil burning furnace. A graphical model of the simulated building is shown in Figure 49. BEopt was not intended to be used for multi-unit buildings, so the model was treated as a large single family home with an increased amount of bedrooms, bathroom, and appliances. The software also did not model MSHPs, so central variable speed heat pump without ducts were used in their place. Other assumptions for the simulation are as listed in Table 30 and 31.

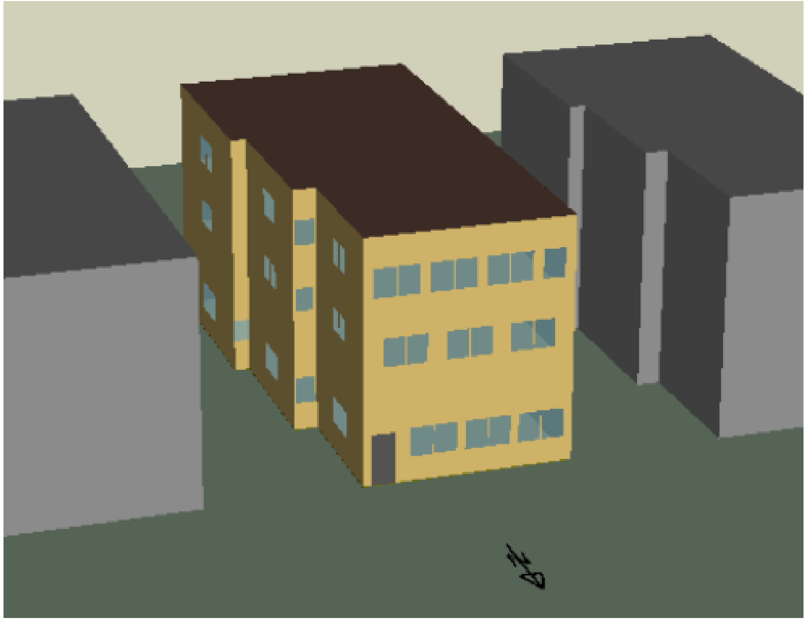


Figure 49: BEopt Model Geometry

Table 30: BEopt Assumptions

	#2 Heating Oil	Natural Gas	Electricity (Resistance)	Electricity (Through-the-Wall Heat Pump)	Electricity (MSHP)
Fuel Unit	Gallon	1000 ft^3	kWh	kWh	kWh
Cost per Fuel Unit NY (BEopt NYS Average)	$2.89	$13.32	$0.17	$0.17	$0.17
Cost per Fuel Unit MA (BEopt MA Average)	$2.85	$12.32	$.017	$0.17	$0.17
Heating Equipment Cost	$16.32/kBtu $1,934 installation $1,150 removal	$21.19/kBtu $1,934 installation $1,150 removal	$16.24/kBtu $21.96/kBtu installation $8.09/kBtu removal	$800 × 11 units	$3,500 × 11 units (installed cost)
Heating Equipment Lifetime	25 years	25 years	20 years	10 years	16 years
Efficiency Heating Plant	80%	85%	100%	7.7 HSPF % to 40°F), resistance below 40°F	10 HSPF to 0°F, resistance below 0°F
Efficiency Heating Distribution	85%	90%	100%	100%	100%
Efficiency Cooling	13 SEER	13 SEER	13 SEER	13 SEER	22 SEER
Cooling Equipment Cost	$400 × 11 units	$400 × 11 units	$400 × 11 units	n/a	n/a
Cooling Equipment Lifetime	10 years	10 years	10 years	n/a	16 years

Table 31: BEopt Default Economic Modeling Inputs

Economic Variable	Modeling Input
Project Analysis Period	30 years
Inflation Rate	3%
Discount Rate (Real)	3%
Loan Period	5 years
Loan Interest Rate	7%
Fuel Escalation Rate	0%

The simulation was run for the New York and the Boston climate. The authors noted that the software runs heat pumps as a central system with forced air distribution so energy consumption ended up a bit higher than the decentralized point source systems that they wanted to simulate.

Figure 50 and 51 show the modeled energy-related savings converting to a MSHP in New York and Boston respectively from a baseboard heater. The MSHP produced a 41% energy savings in both cities, greater than the 33% savings from the older through the wall heat pumps units. The Boston site consumed more energy in total compared to New York.

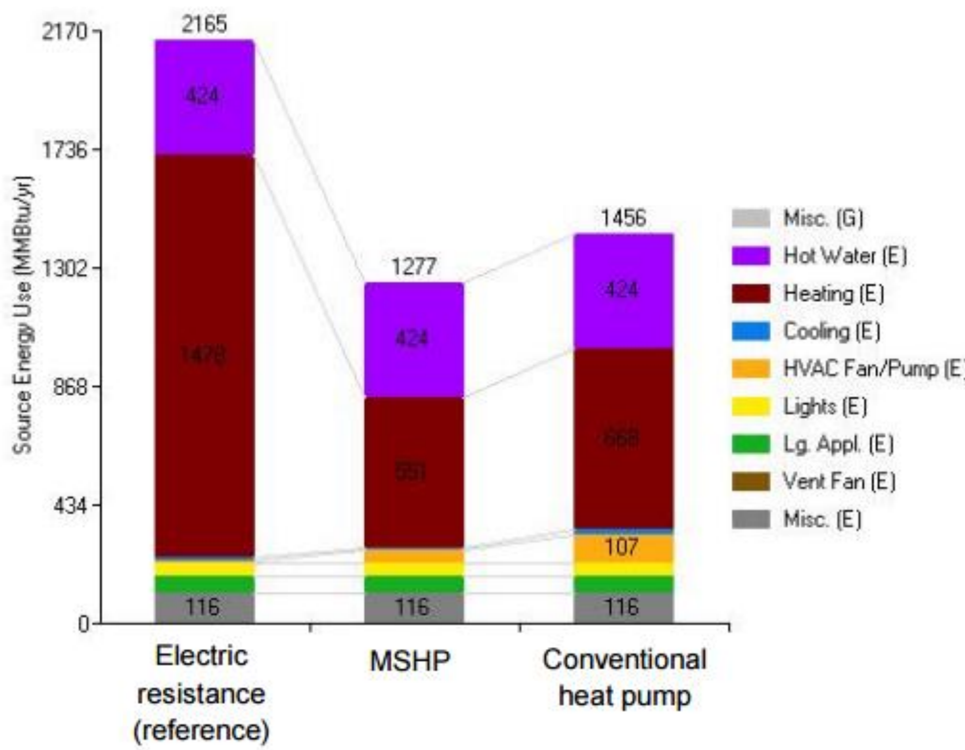


Figure 50: BEopt Output Comparing Electric Resistance, MSHPs, and Conventional Heat Pump—New York

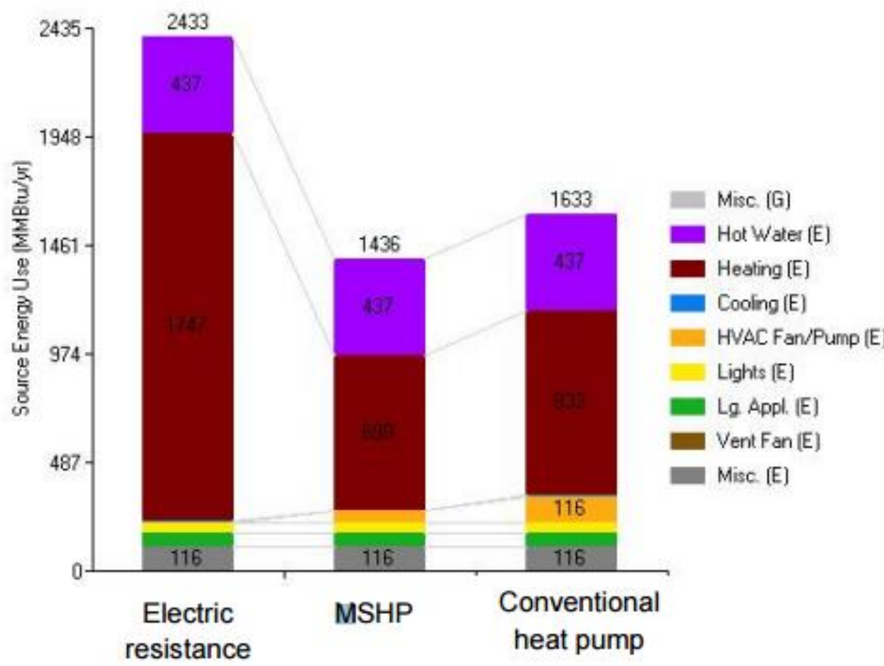


Figure 51: BEopt Output Comparing Electric Resistance, MSHPs, and Conventional Heat Pumps—Boston

When converting from heating oil, New York saw a 6% reduction in energy-related costs using MSHPs while Boston saw a 2% reduction. These results are visualized in Figure 52 and 53.

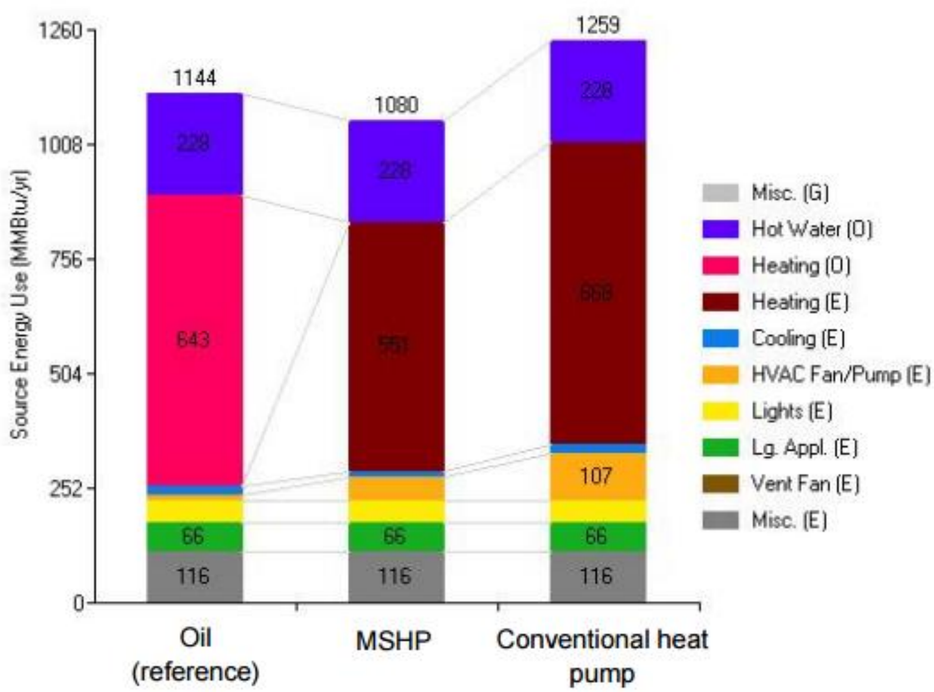


Figure 52: BEopt Output Comparing Oil, MSHPs, and Conventional Heat Pump—New York

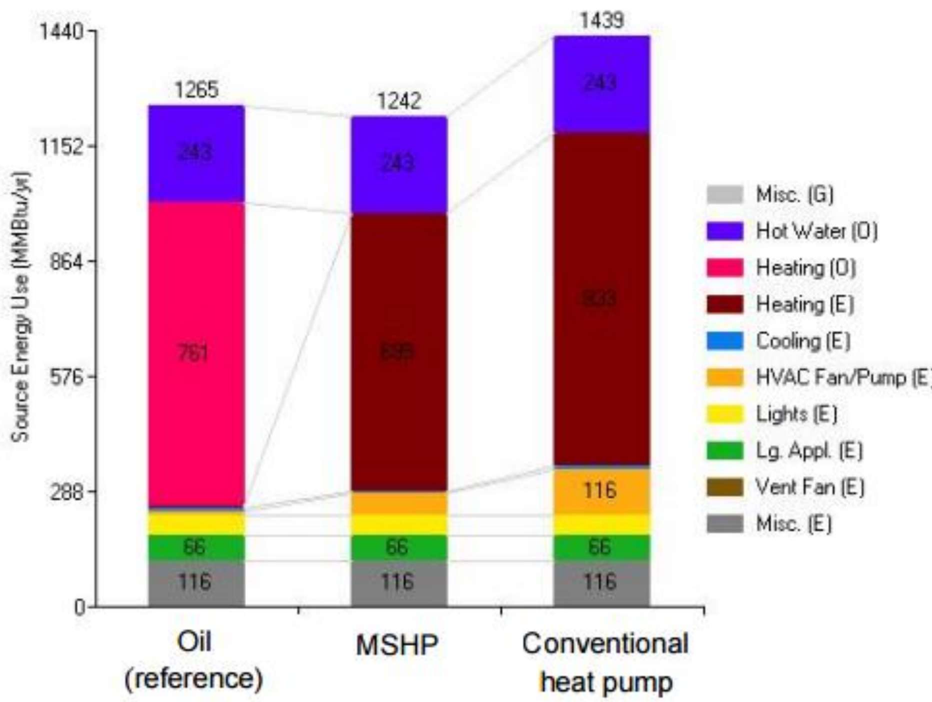


Figure 53: BEopt Output Comparing Oil, MSHPs, and Conventional Heat Pump—Boston

In the case of switching from natural gas, the lowest cost option, New York only saw a 2% energy-related costs savings using MSHPs (Figure 54). Boston saw a 2% increase in energy consumption (Figure 55).

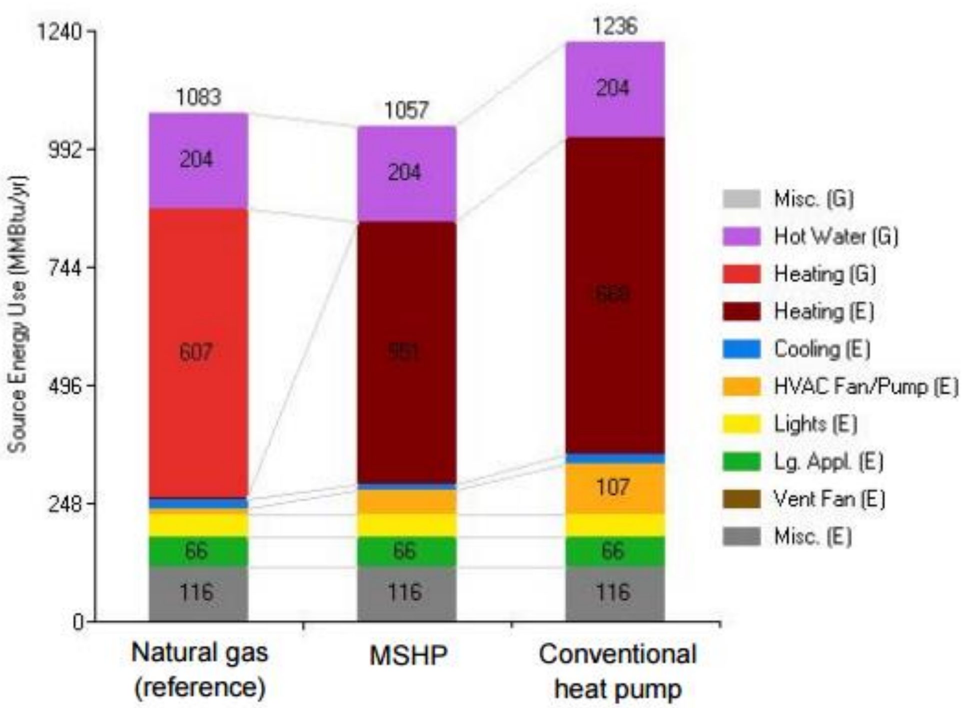


Figure 54: BEopt Output Comparing Natural Gas, MSHPs, and Conventional Heat Pump—New York

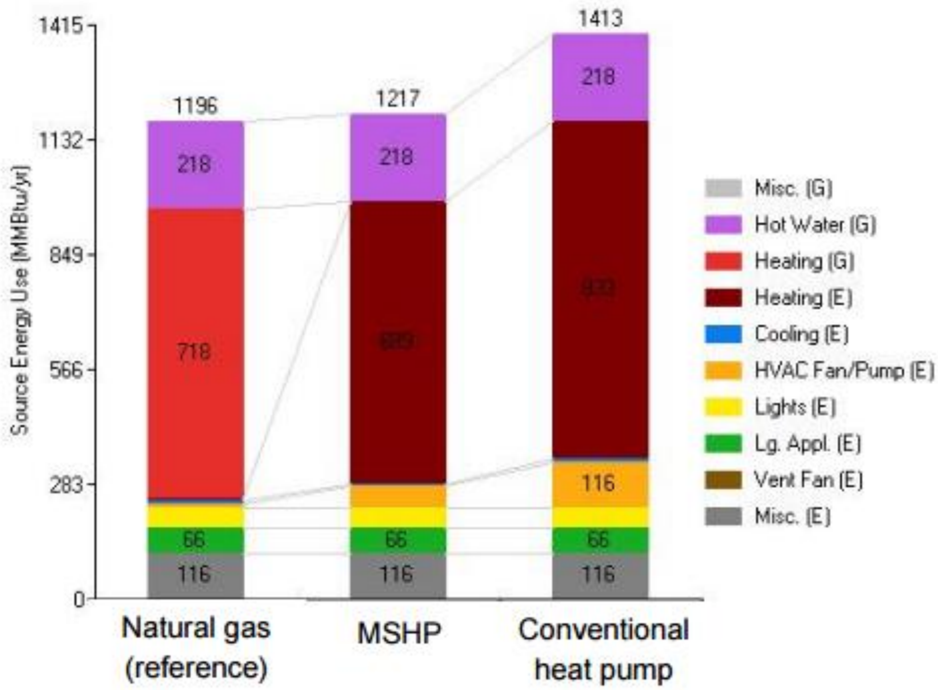


Figure 55: BEopt Output Comparing Natural Gas, MSHPs, and Conventional Heat Pump—Boston

Furthermore, the authors decided to model the effects of envelope improvements on energy-related costs. Table 32 lists the different tiers of improvements while Figure 56 illustrates the resulting simulated savings.

Table 32: Envelope Improvements for BEopt Modeling

Envelope leakage	Baseline	Add 4 in. EIFS	Add 4 in. EIFS and New Windows	Add 8 in. EIFS and New Windows
14 ACH50	✓			
10 ACH50	✓	✓	✓	✓
6 ACH50	✓	✓	✓	✓
3 ACH50	✓	✓	✓	✓

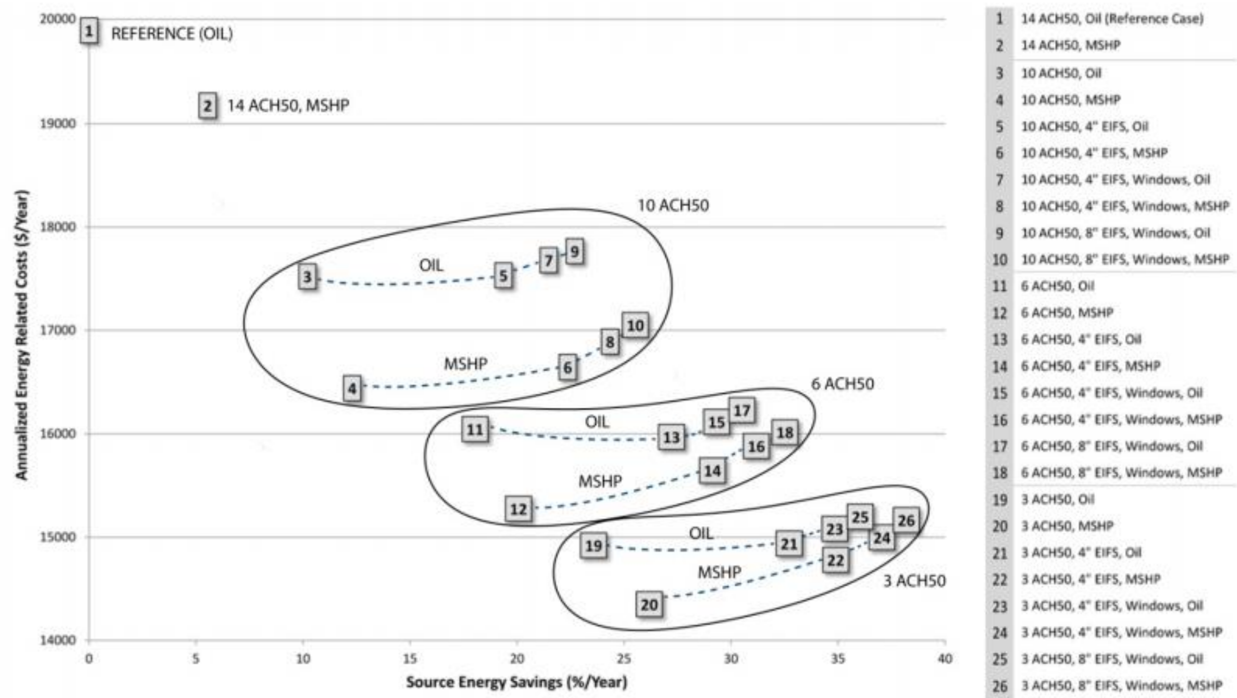


Figure 56: BEopt Output Comparing Envelope Improvements—Air Sealing

After modelling for energy savings, Dentz et al. performed a literature review and interviewed various stakeholders to discuss various issues and questions regarding MSHP retrofits. They investigated technical barriers, building code compliance, utility billing, peak electricity demand, occupant comfort, general satisfaction, and distribution. Their findings were mostly positive and workarounds for potential hurdles were presented. The authors were able to interview program managers and contractors from organizations who have participated in MSHP multi-unit retrofit projects, these organizations were: Efficiency Maine, Connecticut Energy Efficiency Fund, and B.C.M.W. Community Services. Key findings from these interviews are summarized below.

Efficiency Maine

Efficiency Maine's Low Income Multifamily Weatherization Program has been providing cash incentives for MSHP installations since 2012. Approximately 600 MSHPs have been installed so far. Apartment units have been mostly one bedroom apartments. All the apartments were part of either a one floor or two floor complex. Prior to the MSHPs all the units use electrical resistance heating, some used window air conditioner units as well. The MSHP units being installed have a capacity of 9,000 BTU/h, an HSPF of 12, a single fan unit, and are wall-mounted. Cost for installation has decreased from the initial budgeted $4,500 per unit to $2,229 ($1,041 for equipment and $1,188 for labour). Only three broken units have been reported so far (two to abuse and one to failure).

The major lessons learned over the duration of the program have been that: metal covers are needed to protect the outdoor compressor from roof melt water and rain to prevent excessive ice formation, extra care is need when installing the fragile plastic fan cover, education is needed to teach the more complex control scheme of the MSHPs (one page starter guides have shown to be useful).

So far feedback from the residents has been positive. The fact that seasonally installation and storage of window air conditioners is no longer needed offsets the need to clean filters. The removal of window A/C units has also improved aesthetics.

Connecticut Energy Efficiency Fund

3,576 MSHP units were installed at 51 sites in 2011 under the Connecticut Energy Efficiency Fund Home Energy Solutions—Income-Eligible program. The most common dwelling in the program were one bedroom apartments in a single story public housing property. The MSHPs replaced electric baseboard heaters and window A/C units. Installation price per apartment ranged from $3,000 to $4,000. Residents were educated with kickoff meetings and feedback has been reported to be positive.

The Wethersfield Housing Authority has had some complaints regarding the MSHPs, regular filter cleaning, annual weatherization of outdoor units, and repairs of complicated equipment has added to their costs. A housing agency in Sharon, CT is expecting heating energy savings of 25 to 50% for its residents.

B.C.M.W. Community Services

B.C.M.W. Community Services is a weatherization agency in Centralia, IL. It has installed MSHPs in a three-story apartment complex that contains studio, one bedroom, and two bedroom units. HSPF 8.0, SEER 16 MSHPs replaced baseboard heaters. The units cost $1,300 for a single fan and $1,500 for a two fan setup (without installation). Several efficiency retrofits were made to the apartments, vinyl, argon-filled windows, ENERGY STAR exterior doors, and R-49 insulation was installed. Feedback from a handful of residents has been very positive, utility bills have been reduced $150-$275 per month.

Conclusions

Dentz et al. concluded that MSHPs are a viable retrofit option for low to midsize multifamily buildings. MSHP retrofits were shown to be highly cost effective compared to baseboard heating and moderately cost effective compared to fuel oil heat (even in buildings with poor thermal envelopes). Costs savings were shown to be minimal or even increased when compared to natural gas. Installation is easiest when the building is nine floors or less and outdoor units can be installed relatively close to indoor units. Previous retrofits have all been from electrical resistance heating so case studies on conversions from other heating fuel types does not current exist. Lastly, property managers should be prepared for slight increases in maintenance costs when switching to MSHPs.

ASHP Case #6: Mini-Split Heat Pumps Multifamily Retrofit Feasibility Study Ductless Heat Pump Retrofits in Multifamily and Small Commercial Buildings (2012)[57]

Study Details		
Purpose	This report evaluated the energy savings from ductless heat pumps retrofitted in multifamily and small commercial buildings.	
Location	Richland, WA, USA	Eugene, OR, USA
Model	Mitsubishi FE12NA	Mitsubishi FE09NA
Specifications[5]	Ductless Mini-Split Indoor Unit: MSZ-FE12NA HSPF 10.6 SEER 23.0 Heating Capacity: 13,600 Btu/h Cooling Capacity: 12,000 Btu/h Compressor: Variable Speed Refrigerant: R-410a	Ductless Mini-Split HSPF 10.0 SEER 26.0 Heating Capacity: 10,900 Btu/h Cooling Capacity: 9,000 Btu/h Compressor: Variable Speed Refrigerant: R-410a
Parameters	Four units in Jadwin Village, Richland and eight units in Oakwood Manor, Eugene were selected for this study. A variable-base degree day method was applied to billing data to estimate heating and cooling use. Sensors were used calculate DHP performance in terms of COP and output. These data sets were used to calculate the energy savings that were a result of the DHP retrofits.	

The multifamily sites were selected from the Northwest Energy Efficiency Alliance's database of approved installations from the NW Ductless Heat Pump Project. 12 units in two apartment complexes were chosen from an initial list of 500 units in nine buildings. Selection was based on a combination of factors that included: unit size, heating signature, and solar exposure diversity. Four units from Jadwin Village, an apartment complex in Richland, WA and eight units from Oakwood Manor in Eugene, OR were chosen for the study.

Jadwin Village was built in 1975 is comprised of 155 units (28 one-bedroom, 56 two-bedroom, and 32 three-bedroom). The site is bordered by deciduous trees and two major freeways. The units were originally heated using electric baseboards and cooled using packaged terminal air conditioners. The apartments were converted to DHPS in 2009. All units were outfitted with the same DHP, a Mitsubishi MUZ FE12NA (outdoor) + Mitsubishi MSZ FE12NA (indoor). All apartments selected for the study were on the ground level, a description of the characteristics is listed in Table 33.

Table 33: Description of Jadwin Units

Building C Site	Occupancy	ft^2	Solar Exposure	Building UA = 956 (8 units)
				UA
18264	1 adult from March-Sept and 2 adults since October 2011	479	West & North	130
18247	1 adult	479	East & North	130

Building S Site	Occupancy	ft^2	Solar Exposure	Building UA = 1317 (8 units)
				UA
18235	1 adult	759	West & South	175
18232	2 adults and 1 child	759	West & North	175

Oakwood Manor was built in 1966 in a grove of large oak trees. The complex has 72 units (one bedroom, two bedroom, and three bedroom. Due to the mild cooling season, no cooling appliances were installed at this complex prior to the retrofit. All units were retrofitted with the Mitsubishi FE09NA. The selected units were all located on the ground level. A description of the selected units is available in Table 34.

Table 34: Description of Oakwood Units

Site	Occupancy	ft^2	UA
99471	1 adult	576	158
99469	1 adult	732	215
99461	1 adult, 1 child	900	240
99460	2 adults	900	238
99465	2 adults, 2 children	900	238
99464	3 adults, 1 child	900	238
99447	1 adult	600	150
99446	1 adult	600	150

The authors used a variable-base degree day (VBDD) methodology described by Geraghty et al.[58] and in Appendix A of this study to estimate heating or cooling use from billing data. This data was used to estimate the energy savings there were attributable to the DHPs. Larson et al. also calculated DHP output and COP sensors that collected data in 5 minute intervals were deployed. From the field data COP performance curves were generated. Outside temperature, and vapour line temperatures and the performance curves were used to calculate output heat. Cooling COP was assumed to be 4 due to a lack of cooling performance data.

Table 35 and Table 36 show the estimated energy heating and cooling savings respectively normalized by long-term average weather. The authors noted that the heating energy savings were surprisingly low. No cooling results were available for Oakwood as no cooling units were installed before the DHP retrofit.

Table 35: Estimated Per-Unit Heating Savings Using Bills Aggregated Across Units (kWh/yr Input Energy)

Site	# units	Avg. unit size	Pre-install heat (nrm)	Post-install heat (nrm)	kWh change (nrm)
Jadwin	116	865	2980	2244	-736
Oakwood	72	750	2181	1269	-912

# units	number of units used in estimate
Avg. unit size	average unit size (ft^2)
Pre-install heat (nrm)	weather-normalized pre-installation heat, VBDD billing data estimate
Post-install heat (nrm)	weather-normalized post-installation heat, VBDD billing data estimate
kWh change (nrm)	weather-normalized pre-to-post heat change, VBDD billing data estimate

Table 36: Estimated Per-Unit Cooling Savings Aggregated Across Units (kWh/yr Input Energy)

Site	# units	Pre-install cooling (nrm)	Post-install cooling (nrm)	kWh change (nrm)
Jadwin	116	690	157	-386

# units	number of units (apartments) used in estimate
Pre-install cooling (nrm)	weather-normalized pre-DHP-installation cooling, VBDD billing data estimate
Post-install cooling (nrm)	weather-normalized post-DHP-installation cooling, VBDD billing data estimate
kWh change (nrm)	weather-normalized pre-to post cooling change, VBDD billing data estimate

Larson et al. explored several possible reasons for the low realized savings, the investigated the realized COP, degree of continued use of electric resistance heat, and possible increases in aggregate output heat after DHP installation. Average COPs were calculated to be above 3 at both sites (Table 37). After installation of the DHPs heat output was calculated to be 78% higher in the Jadwin units and 39% higher at the Oakwood units. After calculating takebacks (input energy required to generate the change in output heat), the results implied that the occupants were heating their units to a higher average temperature following the installation of the DHPs. Furthermore, resistance heating still made up 57% and 25% of input heat at Jadwin and Oakwood post-installation. The concurrent use of resistance heat has been shown to greatly decrease DHP energy savings[6].

Table 37: Post-Installation COPs and Per-Unit Heat Disaggregations for Metered Sites (kWh/yr)

Site	# units	COP (heat)	DHPH	ER	Resid. heat	DHPH out	Resist. fraction (input)	Resist. fraction (output)
Jadwin	4	3.3	1302	900	820	4234	57%	29%
Oakwood	8	3.4	1363	448	0	4616	25%	9%

# units	number of units used in estimate
COP (heat)	energy-weighted COP for DHP in heating mode
DHPH	per-unit DHP heating mode input energy
ER	per-unit 220V electric resistance heat
Resid. heat	per-unit 110V electric resistance heat inferred from the heating signature in the residual load
DHPH out	per-unit DHP heating mode output energy
Resist. fraction (input)	per-unit electric resistance heat (both 110V and 220V) as a percentage of total input heat
Resist. fraction (output)	per-unit electric resistance heat (both 110V and 220V) as a percentage of total output heat

Conclusions

Realized per-unit heating and cooling savings at Jadwin Village after the installation of DHPs were estimated to be 736 kWh/yr and 386 kWh/yr respectively. Realized per-unit heating savings for Oakwood Manor was estimated to be 912 kWh/yr, cooling increased by 143 kWh/yr from 0 as no cooling equipment was installed previously. Cooling savings were expected to be low due to the mild cooling season in the Pacific Northwest. Heating savings were significantly below anticipated values, payback schedule was calculated to be unfavourable with an assumed installation cost of $3,000. The authors attributed low heating savings to three main reasons. Firstly, it was likely after looking at takeback values that the occupants were heating their apartments to a higher average temperature post DHP installation. Secondly, resistance heating was still being used regularly post-installation, greatly reducing realized energy savings. Lastly, the units did not consume that much electricity to begin with, therefore potential savings were already lower to begin with.

ASHP Case #7: Ductless Heat Pump Meta Study (2014)[59]

Study Details	
Purpose	This meta-study attempted to address the question of ductless heat pumps in colder climates by reviewing the literature and interviewing those in the industry.
Location	Pacific Northwest; mid-Atlantic; New England, USA
Model	Various
Specifications	N/A
Parameters	40 DHP studies relevant to the US Northeast were gathered. The studies were synopsized into a series of spreadsheets for easy comparison. Information was classified as either performance or market analysis. In addition to the 40 studies, 16 interviews with manufacturer representatives, DHP contractors, and energy efficiency program administrators were conducted.

This research reviewed the literature to examine the performance new cold climate heat pump technology and conventional heat pump technology. Most of the reports examined were focused on single head units. The studies included in this meta-study are listed below.

Table 38: NEEP Meta Study – Studies Examined

NEEP Meta Study – Studies Examined	
• BHE-EMT Heat Pump Interim Report 2013 • BPA- ACEEE Performance of DHP in the Pacific NW 2010 • BPA DHP Engineering Analysis (Res) 2012 • BPA DHP Retrofits Commercial Buildings 2012 • BPA Variable Capacity Heat Pump Testing 2013 • Cadmus DMSHP Survey Results 2014 • CCHRC ASHP Report 2013 • CSG DHP Performance in the NE 2014 • CSG Mini-split HP Efficiency Analysis 2012 • DOE DHP Expert Meeting Report 2013 • DOE DHP Fujitsu and Mitsubishi Test Report 2011 • DOER Renewable Heating & Cooling Impact Study 2012 • DOER Renewable Thermal Strategy Report 2014 • Ductless Mini-Split Heat Pump Customer Survey Results • Eliakim's Way 3 Year Energy Use Report 2013 • Efficiency Maine Case Study (Andy Meyer) 2014 • Efficiency Maine EE Heating Options Study 2013 • Efficiency Maine LIWx Program Checkup 2014	• Emera Maine Ductless Heat Pump Pilot Program 2014 • KEMA Ductless Mini Pilot Study & Update 2009-2011 • Mitsubishi Heat Pump Market Data 2011 • Mitsubishi Indoor Unit Brochure 2011 • Mitsubishi M-series Features & Benefits 2011 • NEEA DHP Billing Analysis Report 2013 • NEEA DHP Evaluation Field Metering Report 2012 • NEEA DHP Final Summary Report 2014 • NEEA DHP Impact Process Evaluation Lab Testing Report 2011 • NEEA DHP Market Progress Evaluation 2 2012 • NEEA DHP Market Progress Evaluation 3 2014 • NEEP DHP Report Final 2014 • NEEP Incremental Cost study • NEEP Strategy Report 2013 • NREL Improved Residential AC & Heat Pumps 2013 • Rocky Mountain Institute DHP Paper 2013 • SCEC DHP Work Paper 2012 • Synapse Paper 2013 Heat-Pump-Performance • VEIC Mini Split Heat Pump Trends 2014 • VELCO Load Forecast with Heat Pumps 2014

Performance

The authors noted that extracting key information on the performance of DHPs from the 40 studies was difficult due to lack of consistency in the methods or approach between the studies. From the 40 studies Faesy et al. concluded that DHPs, especially the Mitsubishi and Fujitsu models, had been demonstrated in the lab and field to perform at manufacturer specifications. Energy penalties during defrost cycles (usually less than 10%) were a common finding in these studies. The energy penalty was seen in drain pan heaters as well. The authors concluded that more isolated research is needed on the subject to better understand and mitigate the issue.

Faesy et al. found that laboratory testing results were generally in line with manufacturer rated performance, albeit usually a little lower. Trying to match manufacturer data in the field proved to be difficult as standard COP testing protocol is for steady state performance in a laboratory. Heat pumps in the field are constantly modulating compressor and fan speeds, making data collecting and calculations more difficult. Results from the field were comparable to the lab results with a wider range of results. The ranges of COPs at different temperatures are listed in Table 39.

Table 39: COP at Various Outdoor Temperatures

Outdoor Temperature	COP
≥40°F	≥ 3.5
10°F to 20°F	≈ 2.5 to 3.5
-10°F to -20°F	≈ 1.4
Average Seasonal	2.4 – 3.0

Sizing heat pumps appropriately can have large impacts on efficiency. Since multi-zone cold climate DHPs are a relatively new addition to the market, it is not uncommon to see a single-zone heat pump be oversized for its installed room to provide heat for multiple rooms. The authors saw only small efficiency penalties for oversized units with variable speed compressors.

Throughout the literature, customers have been reported to be generally happy with their heat pumps. Owners of more conventional heat pumps found cooling to be more satisfactory than heating, especially at colder temperatures. Owners of cold climate DHPs were significantly happier with heating performance. Many participants even reported increased comfort using DHPs.

Cost

Installed costs of DHPs ranged from $2,500 to $5,000. One ton (12,000 Btu) models average $3,500 to $4,000. 0.75 ton (9,000 Btu) models cost approximately 10-20% less while 1.5 ton (18,000 Btu) models costs about 10-20% more. The observed incremental costs of buying a high efficiency cold climate over a standard model are outlined in Table 40.

Table 40: DHP Incremental Costs

HSPF Base	HSPF Improvement	Incremental Cost
8.2 HSPF standard	11.0 HSPF high efficiency	$400 - $600
11.0 HSPF high efficiency	12.0+ HSPF Cold Climate	≈ $300
8.2 HSPF standard	12.0+ HSPF Cold Climate	$700-$900

Energy usage and savings for DHPs were found to be highly dependent on local climate and what they were replacing. A common theme among studies that took into account customer feedback was that DHP systems were more difficult to understand and control. Heating energy savings ranged from 1,200 to 4,500 kWh/ton compared to electric baseboard heating. Savings were less prominent in the Northeast. Increased cooling loads were found to increase savings. The authors are expecting the savings to increase as more multi-head systems reach the market. Savings were also realized when DHPs were retrofitted to be part of a larger central system to heat just a section of a home or as the primary source except during extremely cold temperatures.

Knowledge Gaps

The authors felt that the information in these areas were lacking: performance improvements through control optimization and customer education, life of the equipment, parasitic performance losses, effects of different control schemes, demand response suitability, disposal of replaced units, price analysis when replacing natural gas, GHG effects of replacing various heating fuels, accuracy of rated data by climate zone, performance at sub -15°C temperatures, more energy consumption data, more field performance data (instead of laboratory), how performance and savings differ by climate zone, and how applicable a cold climate specification would be.

Conclusions

Faesy et al. concluded that high oil prices, reliability, cold climate technology, satisfied customers, and upcoming multi-head units should drive DHP growth in the US Northeast. They produced an extensive list of recommended follow-up research areas for various stakeholders which should be reviewed in the report itself.

Ducted Central Split Systems

ASHP Case #8: Without Strip Heat: In-Situ Monitoring of a Multi-Stage Air Source Heat Pump in the Pacific Northwest (2006)[60]

Study Details	
Purpose	To examine if the performance of a heat pump with staged capacity is adequate in cold climates, in this case the Pacific Northwest.
Location	Chiloquin, OR; Paul, ID; Burley, ID; Rigby, ID; Ashton, ID, USA
Model	Nyle Cold Climate Heat Pump
Specifications	The only specifications available from Nyle were for the geyser CCHP, an air-source heat pump water heater. The specifications listed in this summary are from the study itself. Central Split System Compressor: Twin Cylinder Reciprocating Piston Refrigerant: R-410A
Parameters	The Cold Climate Heat Pump (CCHP) was installed in several single-family homes in the US Pacific Northwest. Two Micro Data Loggers and associated sensors were installed at each house to take 1-minute average temperature and current measurements every 3 seconds. The sensors were installed inside as well as outside.

Table 41 provides more information about the installation at each site.

Table 41: House Characteristics

	Chiloquin, OR	Paul, ID	Burley, ID	Rigby, ID	Ashton, ID
Monitoring Installation Date	11/15/2004	2/15/2005	2/16/2005	12/1/2005	11/30/2005
Avg. Heating Degree Days	6300	6877	6704	7995	8777
Winter Design Temperature	4 °F	-5 °F	-5 °F	-12 °F	-12 °F
CCHP Nominal Size	4 ton	2.5 ton	3.5 ton	3.5 ton	3.5 ton
Indoor Airflow	1652 CFM	1101 CFM	1108 CFM	1425 CFM	1400 CFM
Strip Heat Toggle Control	yes	yes	no	yes	no

Table 42 summarizes the heat pumps four distinct operating modes. The booster compressor works in conjunction with the primary compressor to increase capacity at low temperatures. The economizer is a plate type heat exchanger that helps to recover waste heat.

Table 42: CCHP Modes of Operation

Mode	D	C	B	A
Outdoor Temperature	Below 10°F	10°F to 20°F	20°F to 34°F	Above 34°F
Stage 1 Heating	Primary & Booster Compressors, Economizer.	Primary & Booster Compressors.	Primary Compressor.	Primary Compressor.
Stage 2 Heating	Add Supplemental Heat.	Add Economizer.	Add Booster Compressor.	Add Supplemental Heat.

Table 43 provides the manufacturer claimed COP while Table 44 displays COP derived from the collected field data from the five sites. It is clear that that COP values gathered from the field fall well short of the advertised values. The manufacturer tested their unit in an independent laboratory at steady state so decreased efficiencies from units in real-world conditions (part-load and defrost cycles) were expected. However, the authors remarked that the drop-off was much more drastic than results from similarly run trials. It was also concluded that the poor COP at higher temperatures were likely due to short compressor runtimes.

Table 43: Manufacturer Claimed COP

Outdoor Air Temp.	-20°F	-10°F	0°F	10°F	20°F	30°F	40°F	50°F
CCHP	1.9	2.0	2.2	2.2	2.5	2.8	3.1	3.3
Std. ASHP	na	na	2.0	2.3	2.5	2.8	3.1	3.6

Table 44: Measured Coefficient of Performance

Outdoor Temperature Bin	-15°F to -10°F	-10°F to -5°F	-5°F to 0°F	0°F to 5°F	5°F to 10°F	10°F to 15°F	15°F to 20°F	20°F to 25°F	25°F to 30°F	30°F to 35°F	35°F to 40°F	40°F to 45°F	45°F to 50°F	50°F to 55°F
Chiloquin	-	-	-	-	-	1.3	1.5	1.6	1.6	1.7	1.9	1.9	1.8	2.0
Burley	-	-	1.7	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.6	1.7	1.7	1.6
Paul	1.5	1.5	1.6	1.6	1.6	1.6	1.6	1.7	1.8	1.9	2.0	2.1	2.1	1.9
Rigby	1.3	1.2	1.2	1.3	1.3	1.3	1.4	1.4	1.5	1.6	1.6	1.6	1.5	1.4
Ashton	-	1.0	1.4	1.3	1.2	1.2	1.2	1.3	1.3	1.3	1.4	1.4	2.0	1.7
Average	**1.4**	**1.2**	**1.5**	**1.3**	**1.3**	**1.4**	**1.4**	**1.5**	**1.6**	**1.6**	**1.7**	**1.7**	**1.8**	**1.7**

Table 45 shows more details of each testing site. Much of the resistance heating at Burley and Ashton occurred during defrost cycles.

Table 45: Monitoring Period Results

	Average COP	Heating System Energy Use (kWh)	Resistance Element Energy Use (kWh)	% Resistance Element Energy Use	Number of Monitoring Days
Chiloquin	1.7	3811	0	0%	77
Burley	1.5	4632	860	19%	163
Paul	1.8	4135	0	0%	159
Rigby	1.5	5527	4	0%	124
Ashton	1.3	4152	541	13%	124

Other finding of interest from this study included the fact that the primary compressor in Chiloquin heat pump unit failed six months after installation (reason unknown) and that the heat pump at Burley never activated the booster compressor, even at low outdoor temperatures. These incidents do raise some concerns regarding the reliability of Nyle heat pump products.

Conclusions

In terms of comfort the homeowners found the CCHP to be adequate enough to maintain reasonable average temperatures even in colder weather. However, the CCHP did not perform as efficiently as it could have which was cited by the authors as a major concern. This could have been due to the manufacturer being a low volume producer with little experience in manufacturing residential heat pumps. Hadley et al. suggested that defrost cycle performance and duct locations need to be further improved for backup resistance heat to be no longer needed in colder climates.

ASHP Case #9: Field Monitoring of High-Efficiency Residential Heat Pumps (2006)[61]

Study Details	
Purpose	This study monitored performance of residential high-efficiency heat pumps and one older unit installed in the US Pacific Northwest over a year.
Location	The Dalles; Sunriver; Ashland; Eugene; Manzanita, OR, USA
Model	Trane, Carrier, York (Models Unspecified)
Specifications	Central Split System HSPF <6 (1), >8(3), Unspecified (1) Compressor: Single and Multi Stage
Parameters	Four high-efficiency ducted heat pumps and one older unit installed in typical family homes were observed over the course of one year starting on August 2004. Energy use and outside temperature, thermostat temperature, return air and supply air were monitored over the observation period.

Table 46 displays the key characteristics of each site and each installed heat pump.

Table 46: Monitored Site Characteristics

Site Location	Climate	Compressor	Fan/ducts
The Dalles, Oregon existing stock reference unit	Low elevation hot dry summer with cold winter	Single-stage piston, 15 yr old unit, HSPF<6	Standard fan basement location and under floor distribution
Sunriver, Oregon	4000 ft elev. mountain/ high desert cold winter mild summer	Single-stage scroll, new unit HSPF>8	Standard fan interior location with attic return and under floor distribution
Ashland, Oregon	2000 ft elev. dry mountain warm summer cool dry winter	Two-stage scroll, new unit HSPF>8	VSD fan in attic with attic distribution
Eugene, Oregon	Mild interior valley mild moist winter and summer	Two-stage piston	VSD fan basement location underfloor distribution
Manzanita, Oregon	Oregon Coastal cool moist summer and mild moist winter	Single-stage scroll, new unit HSPF>8	Standard fan interior location under floor distribution

The COP values at each site shown in Figure 57 do not include the downstream system losses through ducts or air handlers. The unit at Ashland performed more efficiently at colder temperatures because it was operating at its more efficient 2nd stage. The performance of the Sunriver unit was quite disappointing; it was less efficient than even the 15 year old model. The authors summarized heating performance with the statement that none of the units did all things right at all times, therefore none of them reached their full potential as shown by the red line at all the temperature bins. It is unclear how these full potential values were arrived at.

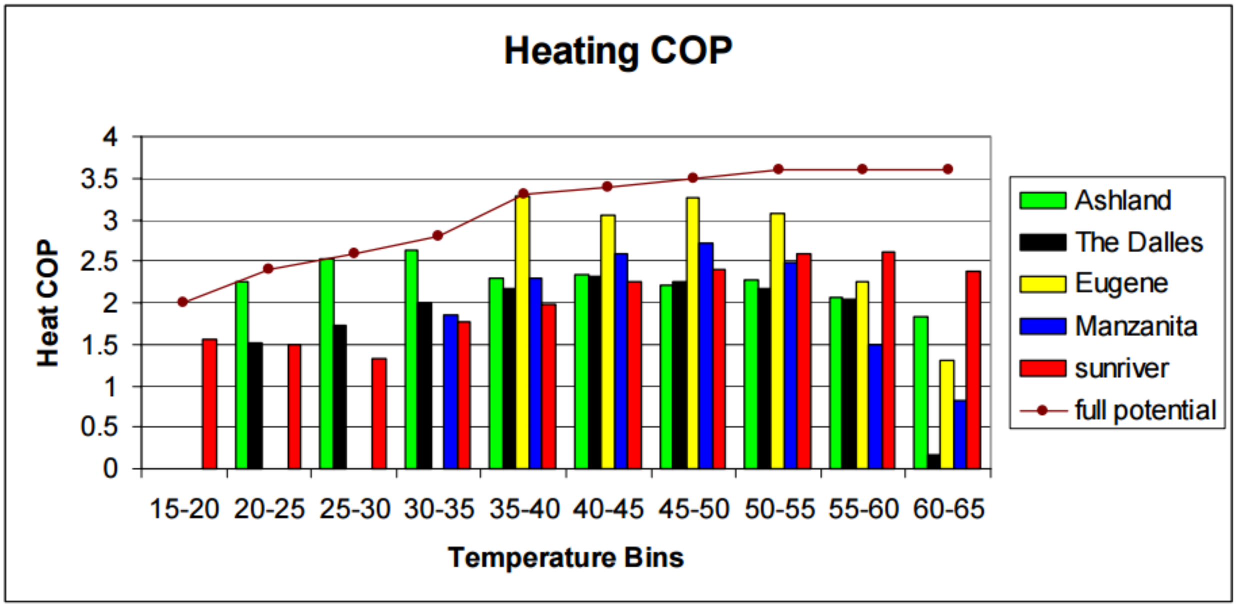


Figure 57: Heating COP by Temperature Bins

Overall COP values for cooling in Table 47 were based on weighted average COP. For each temperature bin, as seen in Figure 58, the COP was weighted by the thermal output. The target EER is calculated from manufacturer label specs using US Northwest specific planning correction factors. All units besides the one at Eugene underperformed.

Table 47: Summary of Estimated Cooling Performance

Site	COP	Quasi EER	Target EER	Comments
Ashland	2.5	8.5	11.5	Inefficient first Stage
The Dalles	1.2	4.1	N/A	15 year old unit
Eugene	3.1	10.6	11.1	Efficient first stage
Manzanita	2.6	8.9	10.89	Short cycling
Sunriver	2.6	8.90	11.81	

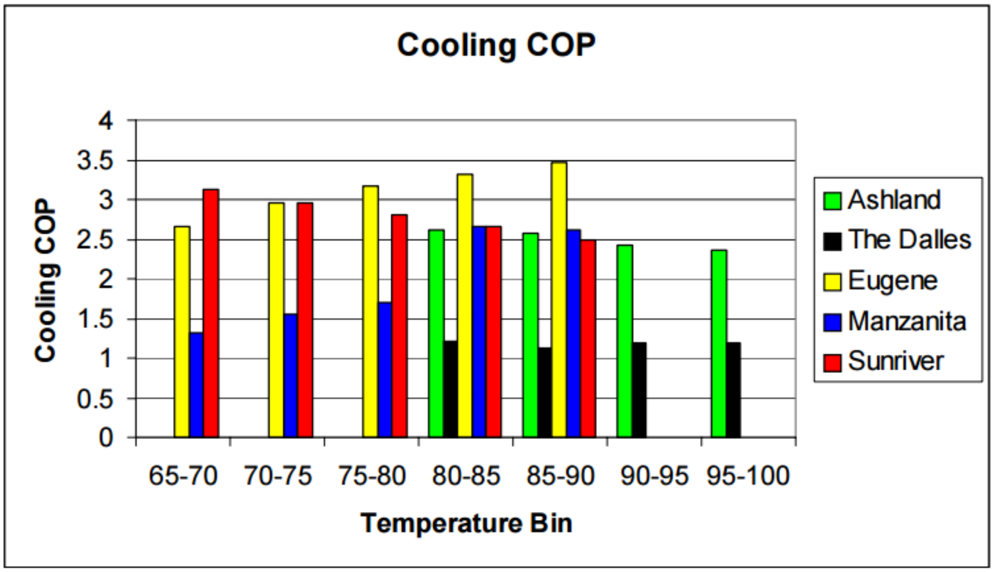


Figure 58: Cooling COP by Temperature Bins

There were many factors that contributed to the heat pumps underperforming. The return duct and air handling unit at the Sunriver and Ashland sites were in the attic. This lead to these components being subjected to temperature extremes that were 30°F cooler during heating season and 30°F warmer during cooling season, thus severely affecting system performance. Another issue that appeared was short-cycling; the unit at Manzanita was never able to reach higher efficiency, steady-state performance due to too short heating cycles. This was blamed on the thermostat being too close to supply airflows. The Asland unit worked in two-stages but the airflow in stage one was cut too drastically, causing efficiencies to drop. Defrost cycles were overly active at the Eugene site, it was discovered that the metering device was overly restrictive in heating mode, leading to excess ice formation.

Conclusions

For the most part the heat pumps in this study did not perform as expected. From the lessons learned in this study the authors had many recommendations. They included avoid attic placement of return ducts and air handler units in colder climates and carefully planning the placement of the thermostat. The full list is quite extensive and can be read in the paper itself.

ASHP #10: Field Monitoring of High Efficiency Residential Heat Pumps (2008)[62]

Study Details	
Purpose	This study monitored energy consumption and performance of heat pumps installed in the US Pacific Northwest over a year.
Location	Bend, OR; Boise, ID; Ashton, ID; Moses Lake, WA; Deer Island, OR; Shelton, WA; Roseburg, OR, USA
Model	Not Specified
Specifications	Central Split System HSPF 8.6 – 10.9 ARI EER 11.7 – 12.5 Capacity: 2.5 – 4 tons Compressor: Mostly variable speed Refrigerant: all but one R-410a (R-22)
Parameters	Test sites (single-family homes) were located in a variety of areas in the Pacific Northwest. All the homes were built at or near Energy Star energy efficiency standards. Monitoring included the use temperature sensors, current transducers, measuring airflow, and a condensate tipping gauge. The trials ran from the cooling season of 2006 to mid-2007.

Table 48 provides a more detailed description of the test site homes and heat pumps.

Table 48: Test Site Summary

Site	Heated sq.ft.	Flrs	House UA, Btu/ hr-°F	Whole House U_o[2],Btu/ Hr-°F-Ft^2	USDOE Zone[5]/ HDD_{65}	Heat Pump Size (Tons), Type[3]	Refrig	Duct Location Supply/ Return
Bend[1]	2750 [2]	2	Not	Calc'd	IV/7040	4, M	R-410a	Crawl/ attic
Boise, ID	2550 [2]	2	396	0.064	IV/5727	3, M	R-410a	Crawl/ interior
Ashton, ID	1960 [1]	1	235	0.053	V/8611	4, M	R-410a	All interior
Moses Lake, WA	1568 [1]	1	228	0.042	IV/5836	2.5, S	R-22	All interior
Deer Island, OR	1837 [1]	1	365	0.053	VI/4491	3.5, S	R-410a	Crawl/ attic
Shelton, WA	3100 [3]	2	576	0.066	VI/4250	3.5, S	R-410a	Crawl/ interior
Roseburg, OR	1750 [1]	1	402	0.061	VI/4020	3, M	R-410a	Crawl

[1]site withdrawn from study, November, 2006

[2]heat loss rate of home normalized by area of all components; does not include contribution from air leakage

[3]S=single stage compressor; M= multi-stage compressor

[4]heat pump heats 1,960 ft^2 main level; fully finished lower level of same square footage heated by separate electric furnace

[5]ARI Zone corresponds to DOE weather zone (I through VI). HDD_{65} is Heating Degree Days (base 65° F).

Table 49 displays the heating results from this study against manufacturer advertised HSPF. Average COP and Observed HSPF were derived from as-operated energy in each temperature bin (defined temperature ranges). Quasi HSPF was calculated using the same data but with operating hours in each temperature bin weighted according to the US Department of Energy (USDOE) specifications. It is by the USDOE specified weightings that advertised HSPFs are calculated. Therefore, differences between Observed and Quasi HSPF are due to differences in heat pump operation time. The relationship between Quasi and Target HSPF illustrates how closely the units in the trial performed to label spec ratings.

Table 49: Summary of Annual Heating Performance (HSPF)

Site	Overall COP	Observed HSPF	Quasi HSPF	Nominal HSPF*	Target HSPF**	Comments
Bend	1.4	4.8	5.5	9.0	9.0	Dropped out of program after 3 months of monitoring
Boise	2.2	7.4	8.1	8.6	8.6	Excessive defrost energy usage corrected late in monitoring period
Ashton	1.1	3.6	4.9	8.8	7.7	System oversized vs. heating load
Moses Lake	2.7	9.3	6.2	9.1	9.1	Defective TXV on indoor unit replaced soon after initial installation
Deer Is	2.9	10.0	10.1	9.6	10.9	
Shelton	2.4	8.2	6.2	8.9	10.2	
Roseburg	2.4	8.2	5.3	9.05	10.3	Same unit as Bend; much better performance. Very limited heating data given system installed in late March.

*DOE Zone IV HSPF ("label spec")

**Target HSPF is nominal system HSPF with DOE climate zone correction applied as needed.

Far the most part, performance represented as HSPF was fairly disappointing when compared to manufacturer label spec ratings. Although performance expressed as HSPF was disappointed, the study looked at normalized energy consumption in Table 50. The authors argued that even though HSPF was lower than expected, actual energy consumption for heating is "the true bottom line". What they found was that normalized energy consumption was in line with average usage numbers in the region.

Table 50: Measured Heating Energy Usage

Site	Measured Annual Heating Energy (kWh)	Annual Heating EUI* (kWh/ft^2)	Whole House U_o ($Btu/ Hr-°F -ft^2$)	ARI Climate Zone
Bend	N/A	N/A	Not calculated	IV
Boise	6,402	2.8	0.064	IV
Ashton	4,232	2.2	0.053	V
Moses Lake	1,437	0.92	0.042	IV
Deer Is	4,535	2.5	0.053	VI
Shelton	4,086	1.3	0.066	VI
Roseburg	N/A	N/A	0.061	VI

*EUI = (measured annual heating energy/house size)

The authors decided to use ARI EER as a target for performance instead of SEER as it is easier to compare COP and EER scores. Furthermore, SEER is not well suited for the Pacific Northwest due to cooler summer temperatures causing heat pumps to perform mostly in part load. For the most part, cooling performance was reasonably in line with manufacturer data apart from Bend (incomplete data) and Ashton.

Table 51: Summary of Cooling Performance

Site*	Average COP	EER*	ARI EER	Measured Annual Cooling kWh	Cooling Duty Cycle**	Comments
Bend	1.4	4.5	12.3	N/A	17%	Dropped out of program after 3 months of monitoring
Boise	3.4	10.3	11.7	1424	10%	Spends most time in compressor Stage 1
Ashton	2.8	8.3	12.0	871	5%	Almost always in part load operation
Moses Lake	3.4	10.0	12.5	412	6%	
Roseburg	3.5	11	12	521	9%	Same unit as Bend but correctly installed

Deer Island and Shelton sites did not require mechanical cooling during the monitoring period.

*EER taken as average cooling performance (KW/ ton) at 95 ºF.

**Percentage of time mechanical cooling operates (not including any defrost usage in winter).

It is worthwhile to note that there were some issues with the installation of some of the heat pumps. The thermostat at the Ashton site did not support a heat pump and the indoor unit was installed incorrectly while the thermostatic expansion value malfunctioned at Moses Lake. These issues were addressed before monitoring so they did not affect results but they do highlight the need for proper installation and monitoring for irregularities.

Conclusions

Difficulties were experienced during installation, but after the problems were resolved systems performed as expected by authors at most locations. Some sites underperformed but still met expectations in terms on annual kWh usage for heating. Issues from the units ranged from easy to very hard to diagnose. The authors commented that parasitic defrosting activity will require more attention.

ASHP Case #11: Measured Performance of a Low Temperature Air Source Heat Pump (2013)[63]

Study Details	
Purpose	To demonstrate the heating operation of a low temperature heat pump, as built by Hallowell International.
Location	Madison, CT, USA
Model	Acadia 048
Specifications	Central Split System COP: > 2.0 at -10°F Capacity: 48,000 Btu/h Compressor: Multi Stage
Parameters	The heat pump was installed in a house built in 1962 with a heating area of 2,010 ft^2. It was set in a two-zone configuration, with the air handling unit in the attic supplying both the first floor zone and the second floor zone. Heating operation was monitored over two winters, 2009 and 2010.

It is important to note that Hallowell International, the manufacturer of the Acadia 048, has gone out of business. Therefore, this study should be thought of as a review of the dual compressor heat pump technology, rather than a review of just this particular model.

Figure 59 shows the test site, a detached family dwelling in south-central Connecticut. The heat pump replaced an oiled-fired boiler heating system that worked in a two zone configuration. The installed heat pump was setup to deliver heat in a similar two zone (1st floor and 2nd floor), individually temperature controlled fashion. The oiled-fired boiler had been located in the basement while the air handling unit for the heat pump was installed in the attic. Polyurethane spray foam was utilized to insulate the attic and minimize losses from the placement of the air handling unit. Ducts were also insulated in foil-facing fiberglass.

Figure 59: Test Site (Heat Pump is Located at the Back of the House)

Figure 60 illustrates the multi stage performance of the heat pump. Mode 1 uses one cylinder in the primary compressor, Mode 2 makes use of both cylinders, Mode 3 incorporates the use of a booster compressor as well as a heat exchanger, while Mode 4 adds electric resistance heating on top of everything else.

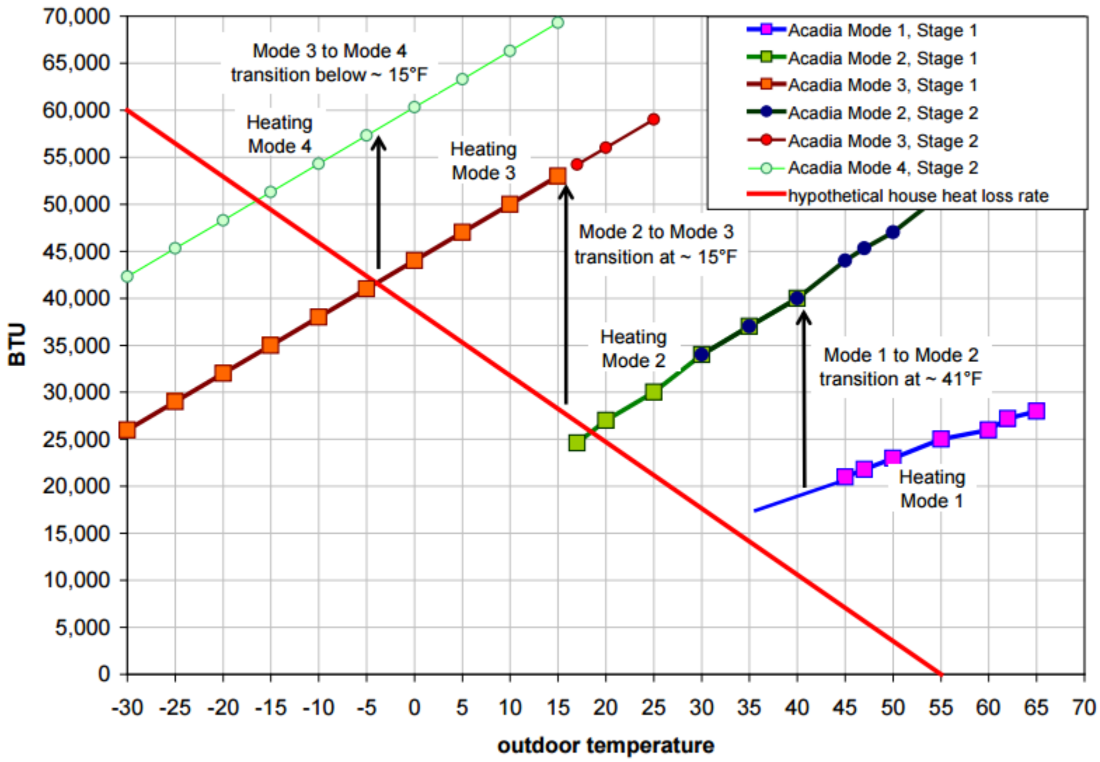


Figure 60: Acadia 048 Mode Transitions Heat Output vs. Outdoor Temperature (Manufacturer Ratings)

Heating performance was measured using outdoor temperature, indoor temperature, supply and retain air temperatures, airflow, power consumption, and system status (defrost, heating). Measurements were taken with a Campbell Scientific CR1000 data recorder every minute.

Using this information the authors calculated seasonal COP (SCOP) using two methods. Using the total heat delivered and total energy consumed they arrived at a SCOP of 3.22 for the first winter and 2.68 for the second winter. Using the ratio of slopes method shown in Figure 61 they reached SCOPs of 2.78 and 2.83 for the respective winters. During the testing period a temperature of -10°F (-23°C) was not reach so the manufacturer's big claim could not be tested. However, at the coldest temperature of 5°F (-15°C), COP did stay above 2.0 at 2.5.

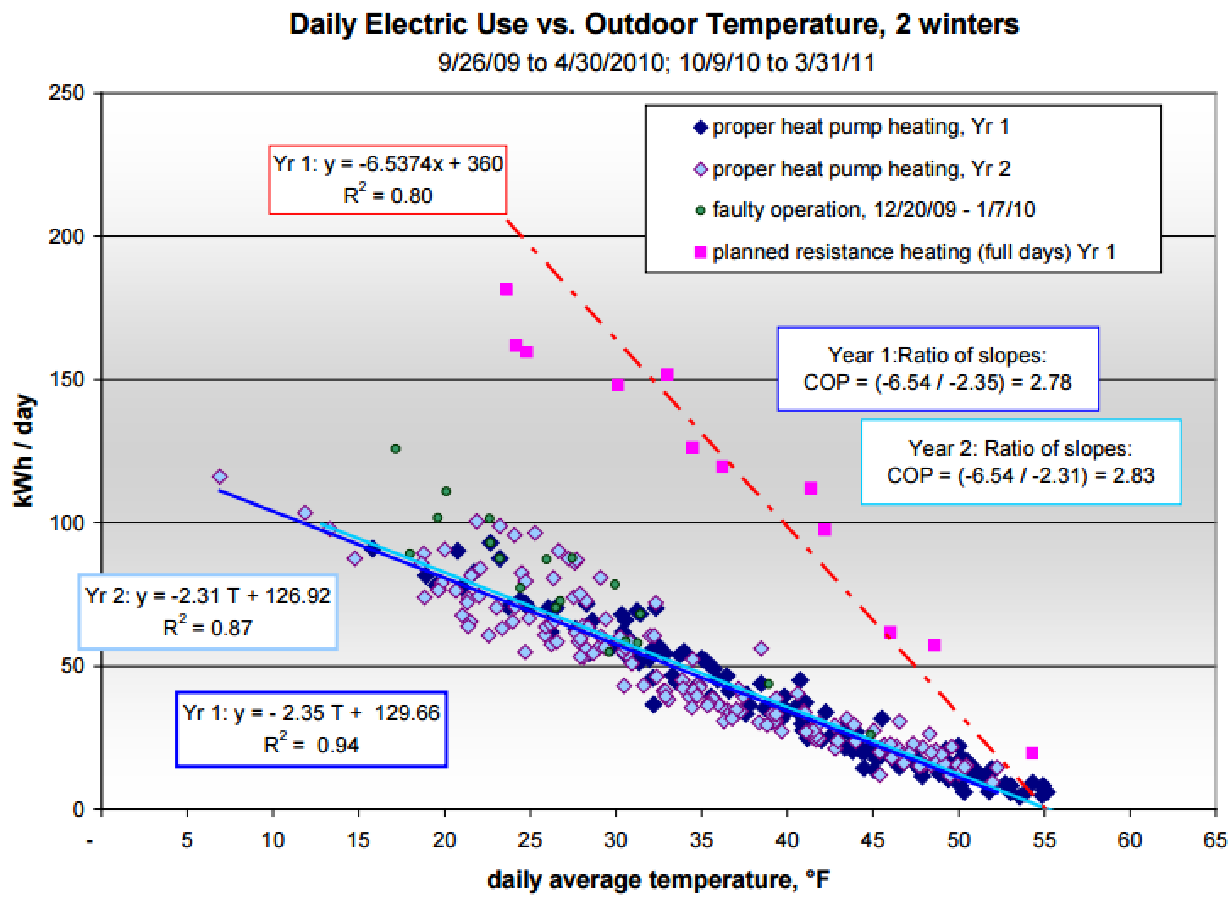


Figure 61: Daily Total Electric Energy Used by Heat Pump Compared to Daily Total Electric Energy Used by Electric Resistance Heater across the Heating Season (Linear Regression)

Johnson also compared these results to laboratory tests performed by ETL Semko following ARI Standard 210/240-2006. In this case field performance correlated well with laboratory results, the exception being when an excessive amount of ice formed on the outdoor heat pump unit as seen in Figure 62. Defrost cycles should be capable of removing all ice, in this case the defrost cycles were apparently not running long enough; meltwater was refreezing on the metal frame (Figure 63).

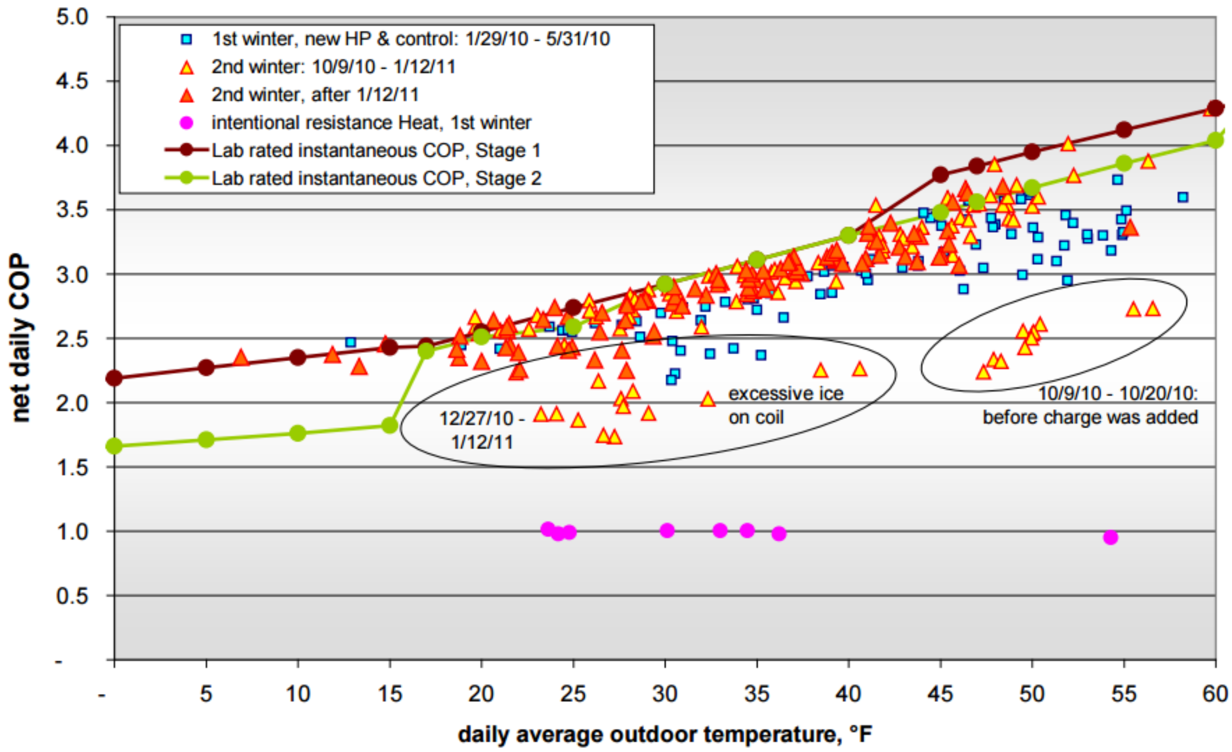


Figure 62: Net Daily COP Measured on Site Compared to Laboratory-Rated Efficiency

Figure 63: Ice Accumulation on Outdoor Coil (Ice was not removed during Defrost Cycles)

Manufacturer performance data was verified in terms of heating output in Figure 64. In Figure 64 green dots represent measurements taken in one minute intervals while the red dots represent the resistance heating that was used during defrost cycles. The majority of data points cluster around rating lines. There are also quite a few that fall well below rated output, this is due to the system needing to warm up at the start of each operating cycle.

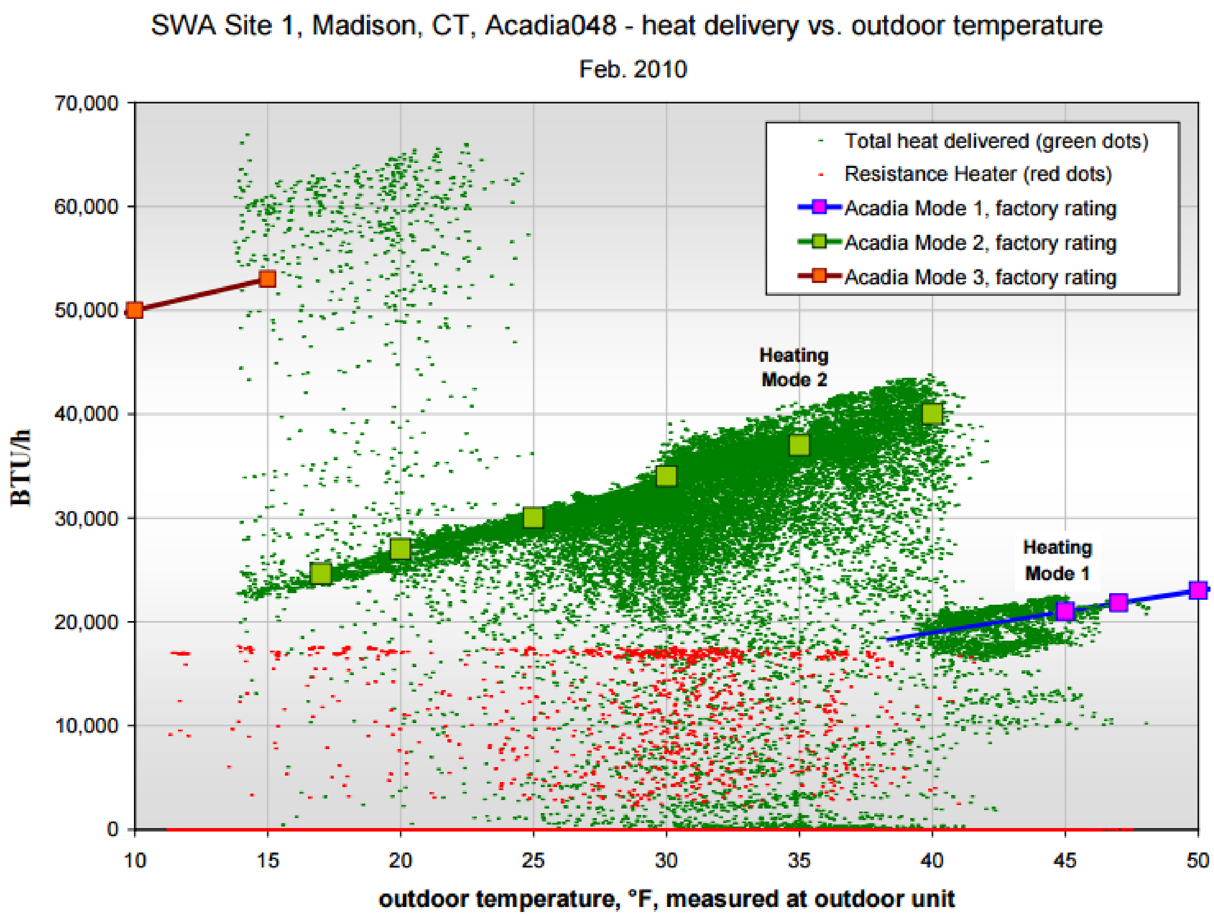


Figure 64: Minute-by-Minute Data for February 2010 showing Btu Output Rate during each Operating Minute

Rated efficiency was verified in the same fashion in Figure 65, with each point representing a COP calculated for each minute data point. Similarly, the majority of data points cluster near the rated efficiency lines. Once again, data points appear significantly below the rated lines due to the system warming up between cycles. The author deduced from the data that it was a “modest amount” showing that the system warmed up relatively quickly. Data points significantly above rated performance were attributed to situations where the compressor has shut off and the air handling unit processes heat that remains in the coil.

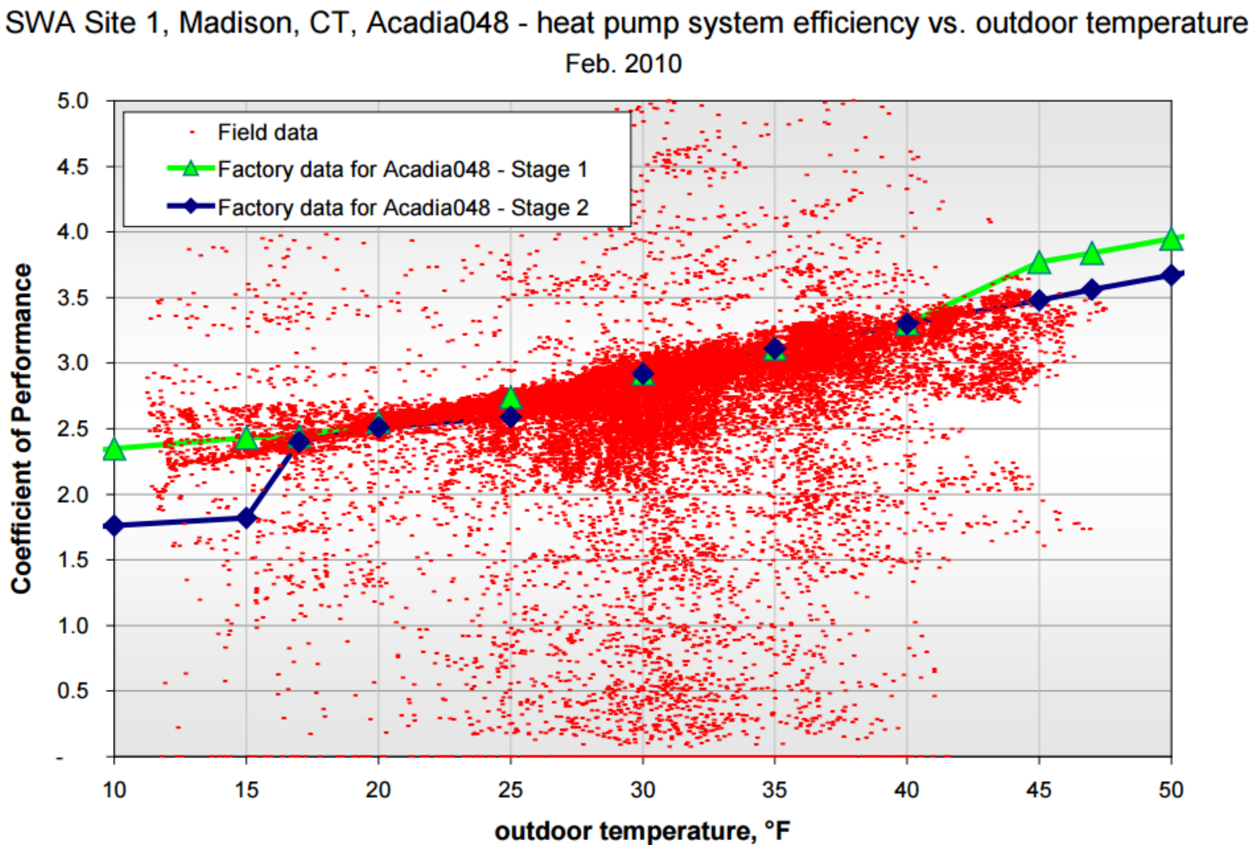


Figure 65: Minute-by-Minute Data for February 2010 showing COP during each Operating Minute

From the study's results, the heating operating costs of the LTHP was compared to that of other heating systems in Table 52. The Acadia 048 was found to have the third lowest operating cost behind a ground source heat pump (GSHP) and a 90% efficient natural gas furnace. The GSHP was assigned an "optimistic" SCOP value of 4.0.

Table 52: Cost of Heating with Various Fuels and Systems

	Fuel Cost[a]	Fuel Cost per Million Btu Delivered	Annual Heating Cost to Deliver 60 Million Btu
Acadia Heat Pump, SCOP = 2.78[b]	$0.1687/kWh	$17.78	$1,067
Central, Ducted Electric Heat, 100% Efficiency	$0.1687/kWh	$49.43	$2,966
Baseboard Electric Heat, No Duct Losses	$0.1687/kWh	$42.01	$2,521
Premium 2-Speed Heat Pump,[c] SCOP = 1.78	$0.1687/kWh	$27.77	$1,666
Natural Gas, 70% AFUE[d]	$1.41/100 ft^3	$19.54	$1,172 + $135 = $1,307
Natural Gas, 90% AFUE[d]	$1.41/100 ft^3	$15.20	$912 + $135 = $1,047
#2 Fuel Oil, 70% AFUE[d]	$2.70/gal	$27.85	$1,671 + $135 = $1,806
GSHP, SCOP = 4.0	$0.1687/kWh	$12.36	$741

[a] Electricity cost = $0.1687/kWh from www.cl-p.com/rates/averagebill.aspx; natural gas cost = $1.41/ccf from Yankee Gas data. Fuel oil cost = $2.70/gal from the Energy Information Administration, past winter average for Connecticut. All fuel costs are as of June 2010.
[b] LTHP operating costs have been adjusted to eliminate the negative impact of operating the heat pump intentionally on strictly electric resistance heat.
[c] The "premium" heat pump was located in central New Hampshire and tested for National Rural Electric Cooperative Association-Cooperative Research Network. See footnote 8, next page.
[d] Estimated AHU fan operating cost of $135 (average of this system, both winters) has been added to the annual operating cost of fossil-fired systems. This system used an electronically commutated fan motor; a constant speed fan could use more energy.

Although performance and energy savings were found to be quite good, reliability quickly became an issue. During the second heating several issues arose. In the owner's own words "There have been issues with a faulty control panel and most recently a loss of heating/cooling capacity due to a refrigerant leak. The only way to actually prove that there were operating issues is through the ongoing efficiency study by CARB. I can only imagine what other people might be experiencing when trying to explain odd system operation to their installer without daily monitoring and data feedback."

The author also noted that a study funded by the Bonneville Power Administration found significantly lower COP values (less than 2.0) in the field. The other study ran into several installation issues such as high external static pressure and a broken outdoor temperature sensor. The effects of these installation issues on performance were unclear.

Conclusions

Field performance for this LTHP agreed with manufacturer data, third party laboratory data, and demonstrated the potential of the technology. However, due to Hallowell going out of business, it will require other large manufacturers to develop the technology. Johnson named Carrier, with their Infinity Series Heat Pump with Greenspeed Intelligence which takes the inverter-driven technology common in mini-splits systems and places it in the more common central split system configuration, as an example.

Appendix B - Ground Source Heat Pump (GSHP) Review

GSHP Case #1: Investigation of a Ground-Source Heat Pump Retrofit to an Electrically Heated Multi-Family Building (2002)[64]

Study Details			
Purpose	To determine potential and economic benefits of retrofitting electrically heated apartment buildings with Ground Source Heat Pumps (GSHP), specifically water-to-water heat pumps. Specifically investigating the feasibility of replacing the existing baseboard heaters with a fan-assisted hydronic baseboard of approximately the same size and shape or alternatively, radiant panels.		
Location	Toronto, ON, Canada		
Model	Carrier 50RWS036[65]	Premier P034W	Trane WXWA026[66]
Specifications	GPM 9.0 *Cooling*: 31,200 Total Capacity 16.2 EER Btuh/W 50°F minimum EST *Heating*: 27,200 Total Capacity 3.3 COP 20°F minimum EST Standard high-efficiency scroll compressor design	Scroll compressor *Specifications were not legible	GPM 7 *Cooling (Load EWT 45°F)*: 16.9 MBH 11.9 EER *Heating (Load EWT 100°F)*: 23.6 MBH 3.2 COP Hermetic compressor C-200 heat exchanger
Parameters	The sample building was a 642 suite, 2 building apartment complex with a water-to-water heat pump installed. The two building complex would require one heat pump per suite and 2494 fan coils in total. The ground heat exchanger consists of 230 vertical bores each 350 ft. long (average bore length of 125 ft. per apartment). The water-to-water heat pumps would require a piping distribution system to be retrofitted to the building from a central mechanical room (could be fitted in common areas such as stairwells and corridor ceiling spaces). Detailed parameters include: Low noise output Achieve the same thermal output with lower water supply temperatures Low space requirements Lower operating costs Enable air-conditioning (may require space dehumidification separately to avoid surface condensation) Low installation/capital cost		

Replacing electric baseboard heating with fan-assisted baseboard designs allows for lower operating temperatures required from efficient heat pump operation. The cost of fan-assisted baseboards needs to be around $300 per four-foot module to be viable. Conclusions from the study recommended that smaller capacity water-to-air heat pumps would be better for this application, being a multi-unit residential building. This study researched multiple water-to-water heat pump models, the majority of which outlined the manufactured rated data with no comparative field performance data. Carrier 50RWS036, Premier P034W, and Trane WXWA026 were the three models that had **both** rated and field data. It should be noted that heating load for the hypothetical building was calculated using the DOE 2.1 energy simulation software therefore the assumptions were made concerning the outdoor temperature reset controls for the heat pumps, heat pump water circulation pumping electricity consumption, main building and GSHP loop pumping electricity consumption and heat pump coefficient of performance.

Cost analysis was based on the same sample 2 building apartment complex which houses a total of 642 suites. Total labour and capital costs total $3,494,399. Annual savings were set at $205,754 with annual maintenance costing $57,831. Cost per suite is $5,443 and the payback period is 23.6 years.

The study references a comparison between electric heating retrofits to natural gas heating as well as the heat pump comparison (Cases were undertaken by the Ontario Ministry of Environment and Energy and Consumers Gas:

Table 53: Comparison between Electric Heating Retrofits to Natural Gas[67]

Case	Building	Retrofit Cost	Annual Savings	Suites	Cost/Suite	Simple Payback
1	11 Storey Apartment	$480,926	$13,964	108	$4,453	34.4
2	14 Storey Apartment	$771,538	$55,654	156	$4,946	13.9
3	6 Storey Apartment	$303,460	$2,158	60	$5,058	140.6
4	11 Storey Apartment	$394,976	$30,427	101	$3,911	13.0
5	6 Storey Apartment	$433,174	$46,397	114	$3,800	9.3

A second cost analysis was done to compare a retrofitted mini-split system which would bring cooling to the suites with the remaining electric baseboards providing heat:

Table 54: Cost Break-Down of the Mini-Split Unit

	Cost ($)
Mini-split unit	892,298
Installation	242,924
Engineering Fee	10,000
Total Cost	1,145,223

In this example, the mini-split system would provide the desired cooling and the existing electric baseboards would provide the required heating.

The retrofit would be a costly alternative. Major parts include: appropriate sized fan coils, water-to-water heat pumps for each suite, in-suite piping, a retrofitted mechanical room, ground source heat exchanger, and distribution piping for the entire building. The ground heat exchanger consists of 230 vertical bores each 350 ft. long (average bore length of 125 ft. per apartment). The study is based on the desired location so it is extremely relevant.

The annual energy savings for the building totaled 2,429,104 kWh (this calculation took into account the annual central pump energy use). The value is taken from the total energy savings 2,614413 kWh minus the annual central pump energy use, 185,309 kWh. To determine a dollar savings amount an electricity charge was taken from an EE4 simulation of a similar building. The charge represents the total building electricity cost including electrical demand divided by the building energy consumption in kWh. Annual savings totaled $205,745.

Table 55: Carrier 50RWS036 (Entering Source Temperature between 30°F to 40°F)

	COP- EST of 20 °F (-6.6 °C)	COP- EST of 30 °F (-1 °C)	COP- EST of 40 °F (4.4 °C)
Rated	5.0	5.22	5.69
Field	--	3.49	4.21

*EST- Entering Source Temperature, **COP-Coefficient of Performance

*** Efficiency data was taken from manufacturer data sheets therefore no field data was available

Efficiency data was taken from manufactured data sheets therefore no field data was available.

Table 56: Premier Series P034W (Entering Source Temperature between 30°F to 40°F)

	COP- EST of 30 °F (-1°C)	COP- EST of 40 °F (4.4°C)
Rated	4.4	5.1
Field	2.9	3.3

*EST- Entering Source Temperature, **COP-Coefficient of Performance

Manufactured COP was taken at 5.0 GPM, 1.6 PSI, Entering Load Temperature (ELT) of 100°F, Load Flow of Gallons Per Minute (LGPM) of 5.0.

Field data was noticeably lower than manufactured rated data.

Table 57: Trane WXWA026 (Entering Source Temperature between 25°F to 45°F)

	COP- EST of 25 °F (-3.8°C)	COP- EST of 45 °F (7.2 °C)
Rated	2.76	3.52
Field	2.14	2.75

*EST- Entering Source Temperature, **COP-Coefficient of Performance

Load is 4.0 GPM, PSI is 1.66, Entering Load Temperature of 100°F.

GSHP Case #2: Monitoring Data for Residential GSHPS - Energy Design Update (2008)[68]

Study Details	
Purpose	To challenge the scarcity of good monitoring data found in residential ground-source heat pumps. Rob Aldrich of Steven Winter Associates provided data for the Connecticut house.
Location	Connecticut, USA
Model	Water Furnace Envision Geothermal/Water Source Indoor Split (Model 038)
Specifications[69]	*Full Capacity Modulation:* 9 gpm flow rate 1200 cfm *Cooling:* 34,300 capacity Btu/h 20.4 EER Btu/h *Heating:* 33,100 capacity Btu/h 4.5 COP
Parameters	Building Type: Residential (1 House) Closed loop, horizontal (2,700 ft of PEX tubing buried 6 ft. below grade in 2 trenches). Testing for field data abided by AHRI/ASHRAE/ISO 13256-1.

Table 58: COP for WaterFurnace Envision GSHP (Model ND038)

	COP- EWT of 50 °F (10°C)
Rated	5.0[70]
Field	3.5

It should be noted that there were large standby loads of the heat-pump system, when operating at full capacity, COP 3.9 and 4.1, standby loads totalling 45 watts results in lower overall COP. Data was taken at full capacity modulation.

Study #2 Details	
Purpose	To challenge the scarcity of good monitoring data found in residential ground-source heat pumps. Andy Shapiro of Energy Balance provided data for three Vermont houses.
Location	Vermont, USA
Model	Open-loop water-to-water GSHP (1 Econar, 2 WaterFurnace)
Specifications	Not specified but rated COPs included in study.
Parameters	Building Type: Residential (3 Houses) Connected to standing column wells; heat distributed through in-floor hydronic radiant tubing. Homes ranged in size from 1,800 to 2,800 square feet.

Table 59: COP for WaterFurnace and Econar Models

	COP- EST- N/A	COP- EST- N/A
Rated	WaterFurnace- 4.1	Econar- 3.7
Field	2.75	2.75

*N/A= sufficient data was not included in the study

The Entering Source Temperature is unkown for this study as well as the exact models used for Econar and WaterFurnace. Homes ranged from 1,800 to 2,800 sq ft. All three homes were tight and well insulated with designed heating loads between 25,000 to 28,000 BTU/h. Installation cost ranged between $18,000 to $30,000 per house, not including well drilling. Average COP over 3 winter months was 2.75.

This case has some specific issues: Econar specifications claimed that the heat-pump unit has a maximum output rating of 130°F, but the unit installed “barely makes 118°F or 119°F”. The authors found that the lack of maturity in the GSHP industry and unfamiliarity with the heat pump complexities leave much room for error. GSHP also increase utility peak loads during cold weather. Builders should as a general rule de-rate a GSHP’s COP by 26%-30% to obtain proper heating-season COPs.

GSHP Case #3: U.S. Department of Energy- Residential Ground Source Heat Pumps with Integrated Domestic Hot Water Generation: Performance Results from Long-Term Monitoring (2012)[71]

Study Details	
Purpose	Document installed operational space conditioning efficiencies of the houses' Ground Source Heat Pump system.
Location	Pine Mountain, GA, USA
Model	Not Specified
Specifications	ETL Listed Mark, Energy Star
Parameters	Building Type: Residential (2 Houses) 2 test homes- 2,024 ft^2, 1-story; 2,946 ft^2, 2-story. 2% leakage, R-30 Roof, R-22 walls

Table 60: Seasonal Average COP for both Homes

	House 1 COP	House 2 COP
Winter Early 2010 (Heating)	4.86	2.65
Summer 2010 (Cooling)	5.24	4.26
Winter 2010 to 2011 (Heating)	3.44	2.36

Field Seasonal average COP

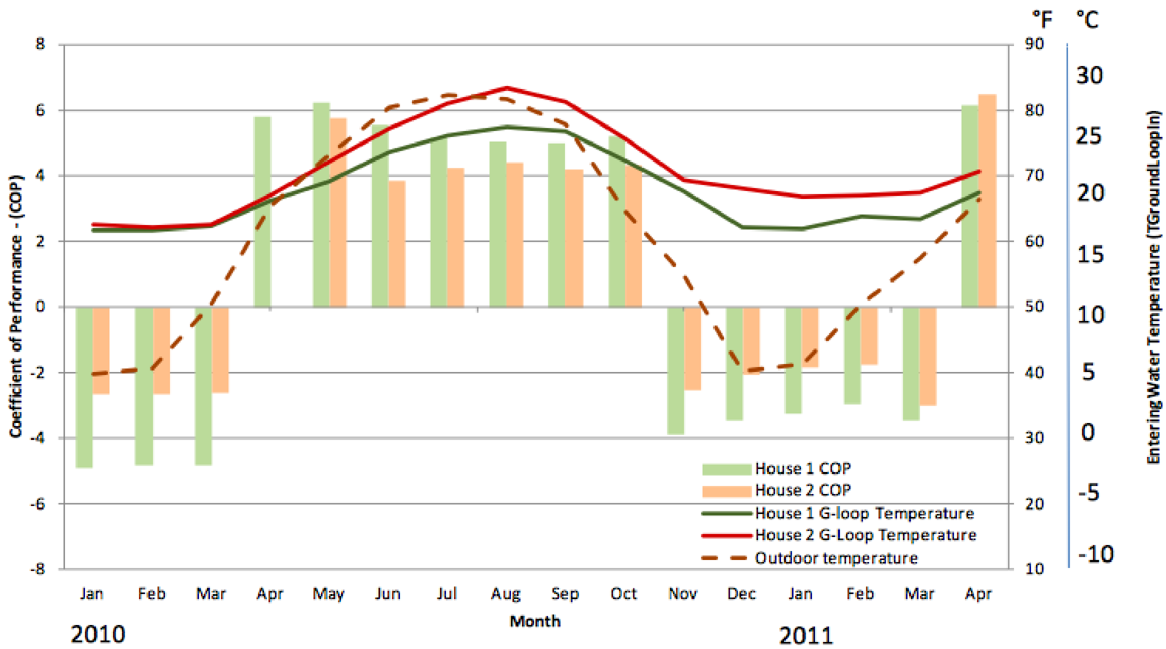
The study team calculated COP values every 10 seconds and average the data on a minute and hourly basis. Based on hourly data, monthly average COPs were created, weighted by runtime in each mode.

Table 61: Equipment Rated COPs at Given EWTs

House 1: EWT 60°F-70°F	Rated	4.86-6.25
	Field	2.4-5.3
House 2: EWT 60°F-70°F	Rated	4.85-6.15
	Field	1.8-3.8

The heating COP for House 1 for the winter of early 2010 was 4% to 22% lower than the manufacturer's range of 5.05 to 6.25 for the winter EWT (Figure 38). The 2010-2011 winter season observed a COP of 3.44 which was substantially worse but comparable to the rated performance of a high-efficiency (90+% annual fuel utlization efficiency) furnace due to the differences in source energy.

The heating COP for House 2 was 2.65 in early 2010 and declined during the 2010-2011 winter, averaging 2.36 for the season which was approximately 50% lower than manufacturer's listed COP for the winter EWT.



EWT and monthly average COP for both houses; heating COPs are shown as negative values, and cooling COPs are shown as positive values. (Data for House 2 in April 2010 are unavailable because a data logger malfunctioned.)

Figure 66: Entering Water Temperature and Monthly Averages for Both Houses

Cost analysis was unavailable for this study. These findings are somewhat relevant to the GTA with respect to summer months reaching above 25°C however the winter months between December to February reach only as low as 5°C which is a much milder winter season. The study provided both manufactured rated data and field data for three of the GSHP models. The specific GSHP models used in the study were not identified.

This study was based on new homes therefore retrofit costs and timelines were non-applicable for the study. Both houses use dual-capacity GSHP with House 1 having a 9.1 kW output capacity and House 2 having a 13.4 kW output capacity. The ground heat exchanger consists of a closed loop in two (House 1) or three (House 2) vertical bores, each 180 ft. deep using two 1-in.-diameter polyethylene pipes with a U-bend at the bottom end of each bore hole circulating at 15% methanol and 85% water mixture. Upgrades were made to comply with the 2008 Building America benchmark definition of 50% energy savings.

GSHP Case #4: US Department of Energy- An In-Depth Look at Ground Source Heat Pumps and Other Electric Loads in Two GreenMax Homes (2012)[72]

Study Details		
Purpose	The intent was to obtain valuable information for consumers and builders about strategies to provide near-zero electrical homes.Research intended to answer the following question, among others: What is the installed system efficiency of these GSHPs? How do they differ from units' rated efficiencies?	
Location	Black River Falls, Stoughton, WI, USA	
Models	WaterFurnace Synergy 3-D SDV038	WaterFurnace Envision NDV038
Specifications[73,70]	3-ton dual speed heat pump 23.7 EER 4.5 COP Copeland Scroll UltraTech compressors R-410A refrigerant *Full Capacity Modulation:* 9 gpm flow rate 1200 cfm *Cooling (*EWT 59°F)*:* 37,100 capacity Btu/h 19.6 EER Btu/h *Heating (*EWT 50°F)*:* 31,100 capacity Btu/h 4.6 COP	3-ton dual-speed heat pump 30 EER 5 COP R-410A scroll or scroll compressors R-410A refrigerant *High Speed ECM (EWT 30*°F)*:* 9 gpm flow rate 1250 cfm *Cooling (*EAT 80/67°F)*:* 40.5 total cooling capacity MBtu/h 27.8 EER *Heating (*EAT 70°F)*:* 27.2 total heating capacity MBtu/h 3.88 COP
Parameters	Building Type: Residential (2 Houses) Both systems used horizontal closed, pressurized ground loops in two trenches at depths of 8 ft.	

It should be noted that in the manufacturer rated data for the WaterFurnace Envision NDV038 3-ton dual-speed heat pump, at entering water temperatures of 20°F to 30°F, both heating and cooling was not recommended.

Table 62: WaterFurnace Envision System Operation Limitations

Operating Limits	Cooling		Heating	
	(°F)	(°C)	(°F)	(°C)
Air Limits				
Min. Ambient Air	45	7.2	45	7.2
Rated Ambient Air	80	26.7	70	21.1
Max. Ambient Air	100	37.8	85	29.4
Min. Entering Air	50	10.0	40	4.4
Rated Entering Air db/wb	80.6/66.2	27/19	68	20.0
Max. Entering Air db/wb	110/83	43/28.3	80	26.7
Water Limits				
Min. Entering Water	30	-1.1	20	-6.7
Normal Entering Water	50-110	10-43.3	30-70	-1.1
Max. Entering Water	120	48.9	90	32.2

Minimum/maximum limits are only for start-up conditions, and are meant for bringing the space up to occupancy temperature. Units are not designed to operate at the minimum/maximum conditions on a regular basis.

Table 63: Specifications for Black River Falls & Stoughton Homes

Specifications	Black River Falls	Stoughton
Heating System	WaterFurnace Synergy 3-D SDV038 water-to-air ground source heat pump (18.5 EER/4.0 COP)	WaterFurnace Envision NDV038 water-to-air ground source heat pump (20.1 EER/4.2 COP)
Cooling System	WaterFurnace Synergy 3-D SDV038 ground source heat pump	WaterFurnace Envision NDV038 ground source heat pump
System Parameters	N/A	Two 110-ft trenches at a depth of 8 ft, sperated by 15 ft.
Floor Area	2,352 ft^2	4,638 ft^2

Both test homes are located in the International Energy Conservation Code Cold Climate Zone 6A. The home in Black River Falls, Wisconsin was monitored between June 2009 and June 2011 and the Stoughton, Wisconsin home was monitored between May 2010 and June 2011.

Table 64: Rated Efficiencies of GSHP Models

GSHP	Model Number	House	Low Stage		High Stage	
			EER	COP	EER	COP
WaterFurnace Synergy 3-D heat pump	SDV038	Black River Falls	23.7	4.5	18.5	4.0
WaterFurnace Envision 3-ton dual speed	NDV038	Stoughton	30.0	5.1	20.1	4.2

Ratings performed at a EWT of 77°F in cooling mode and 32°F in heating mode.

These findings are relevant to the GTA with respect to summer months reaching above 25°C however the winter months, December to February, have a seasonal low of 5°C which is a much milder winter season than the GTA.

The study discusses the discrepancy between manufacturer rated efficiencies and field of “literature” efficiencies and how “installed efficiencies are always below the rated efficiencies”. According to the ASHRAE/ISO 13256-1 standards, the “effective power input” used in the calculation of COP/EER should include the compressor, the water pump, the air handler fan, and all associated controls. However the fan power used in the calculation of a unit’s COP/EER does not include flow resistance from ducts, or resistance of the ground loop. These design details are unknown to the manufacturer therefore the current rating method allows for a fair comparison of equipment.

Table 65: Measured Efficiencies of GSHPs

	Black River Falls		Stoughton	
	Overall	Steady-State	Overall	Steady-State
Heating COP	2.7	3.1	2.6	2.7
DHW COP	–	1.9	1.4	2.0
Cooling EER	17.5	17.0	15.0	16.7

Results are from both house's entire monitoring period. It accounts for all energy use of GSHP including all standby electricity use. Steady-state is defined as the system being in operation for a full 15 minutes logging interval.

Table 66: Rated Versus Measured System Efficiencies

	ISO/ARI Rated Heat Pump Efficiency (COP/EER)		Measured Steady State Efficiency (COP/EER)		Performance Difference (COP%/EER%)	
	Low Stage	High Stage	Low Stage	High Stage	Low Stage	High Stage
Black River Falls	4.5/23.7	4.0/18.5	3.1/18.1	3.1/15.9	31%/23%	23%/14%
Stoughton	5.1/30.0	4.2/20.1	2.7/16.7	2.7/–	47%/44%	36%/na

Resistance was not taken into account when calculating the system COP therefore the measured monthly COP is lower than the manufacturer rated data. Based on the discrepancy, the GSHP are not significantly higher than alternative space conditioning methods, including the inverter driven compressor air-source heat pumps available in the market.

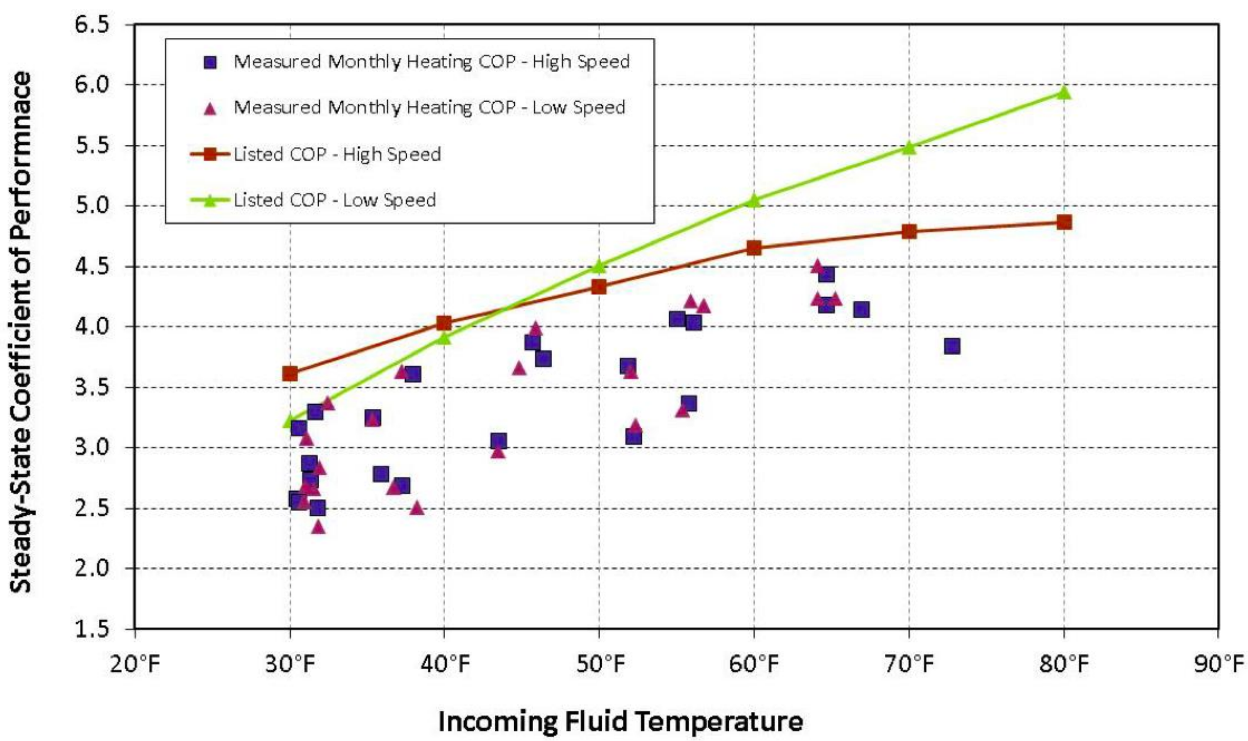


Figure 67: Measured vs. Literature COP of Black River Falls GSHP for Space Heating

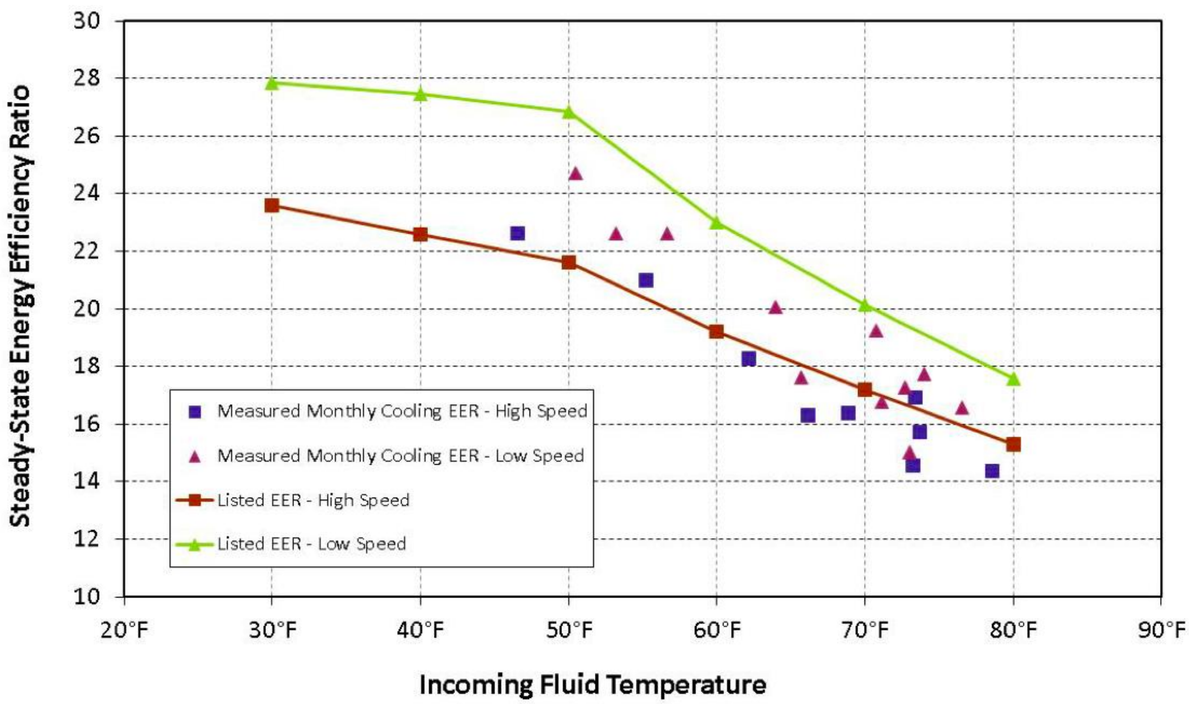


Figure 68: Measured vs. Literature EER of Black River Falls GSHP for Space Cooling

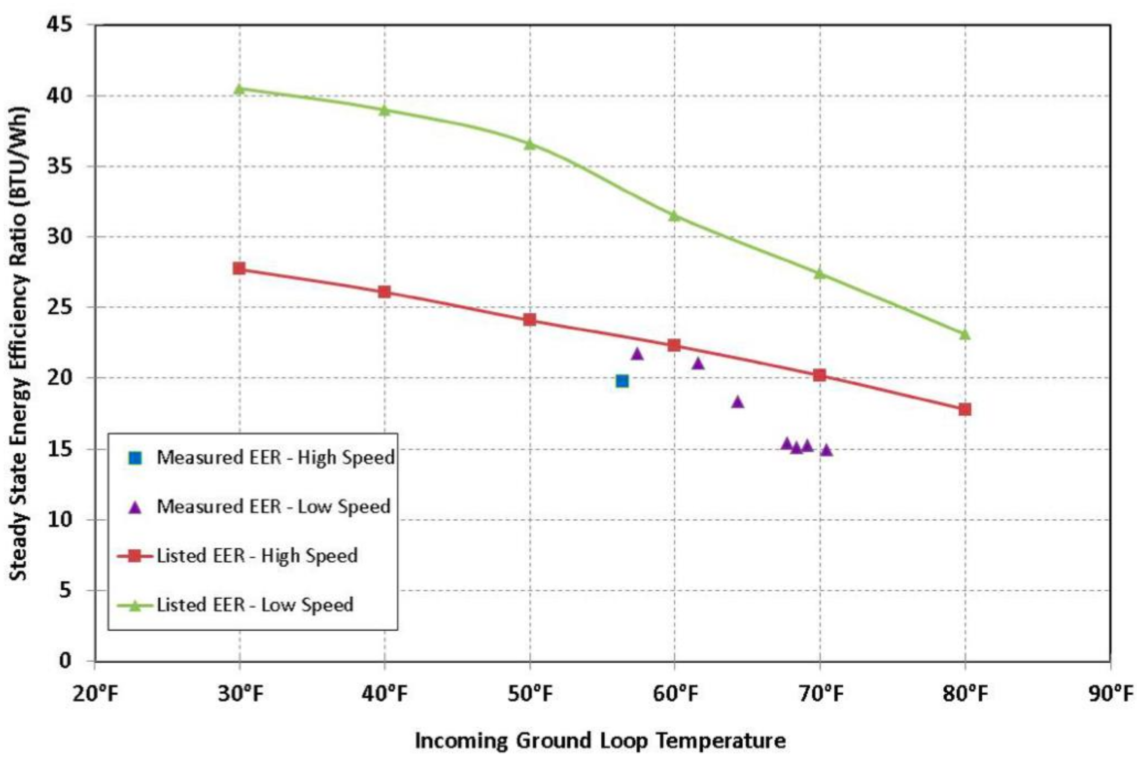


Figure 69: Measured vs. Literature EER of Stoughton GSHP for Space Cooling

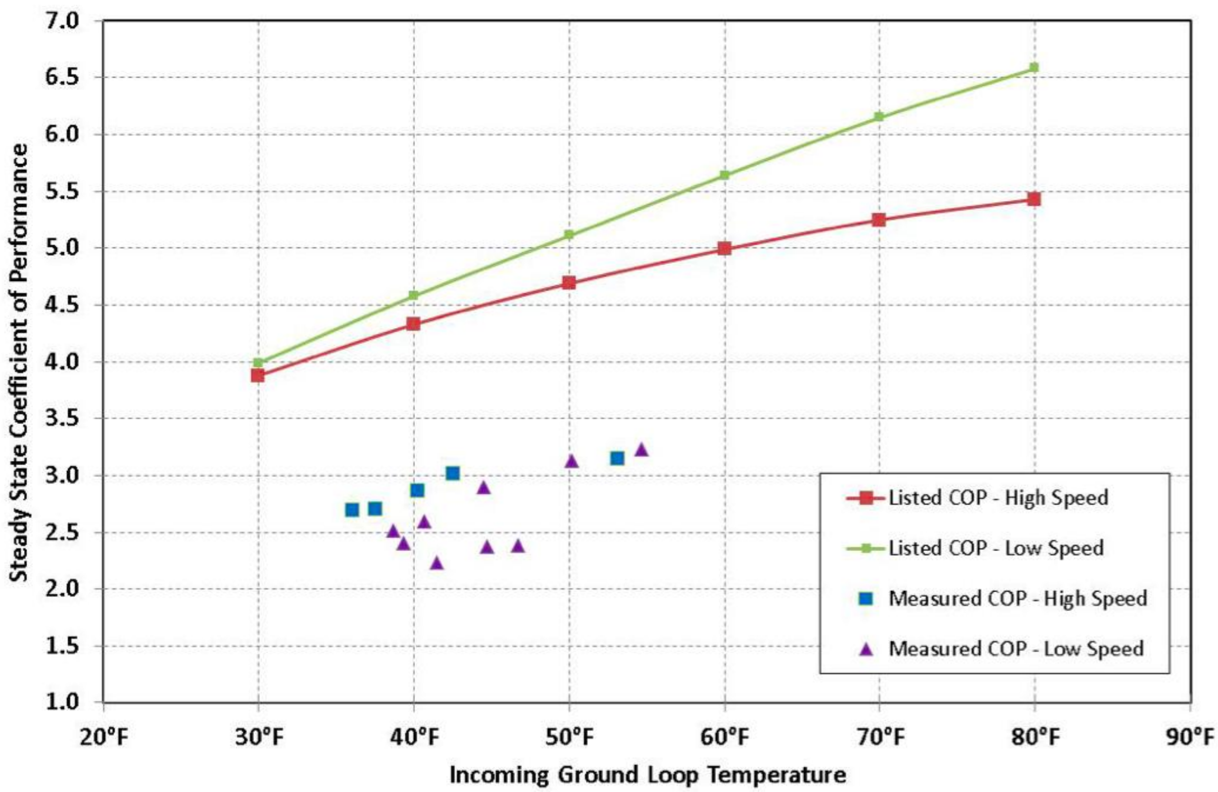


Figure 70: Measured vs. Literature COP of Stoughton GSHP for Space Heating

Environol 1000 solution (21.4% Ethanol) was used as the pump solution for these models. Due to the detail in this study, multiple energy saving mechanisms were used; domestic hot water desuperheaters, photovoltaic systems, efficient lighting fixtures and appliances, therefore the environmental performance specifically for the ground source heat pump systems were not identified. This study was based on new homes therefore retrofit costs and timelines were non-applicable for the study.

GSHP Case #5: Performance Assessment of Urban Geoexchange Projects in the Greater Toronto Area: Peel House A (2015)[74]

Study Details	
Purpose	Retrofit a multi-resident home with a primary heating and cooling Geoexchange system
Building Type	Residential (1 residential group home)
Location	Peel, Ontario, Canada
Model	SCW-048-1B Earthlinked compressor unit with 4 Tons nominal heating capacity
Specifications	50 MBtu/hr rated heating capacity 28.6 Btu/hr per ft^2heating capacity 48 MBtu/hr rated cooling capacity 27.4 Btu/hr per ft^2cooling capacity 3.5 rated COP 15.0 rated EER Commissioned 2009
Parameters	Residential group home was 1750 $ft^{2.}$ Ground-loop with direct exchange with 4 vertical boreholes extending 100 ft deep. The heating and cooling is accomplished via forced-air hydronic coils housed in a pair of air handlers (1 which is multi-zoned). The monitoring period was February 2013-January 2014

Table 67: Total Seasonal Heating and Cooling COPs

	COP
Rated	3.5
Field Data - Heating	2.8±0.5
Field Data - Cooling	3.2±0.6

*10.9±2 EER

The COP was adjusted to exlude the distribution of the circulator pump power. The initial months of the cooling season, with a low load and cool ground temperatures, the COPs are high. As the ground warms and the load increases, the COP decreases. The operational ground temperatures for this unit are not known. The average cycle time for both heating and cooling is outlined in the study.

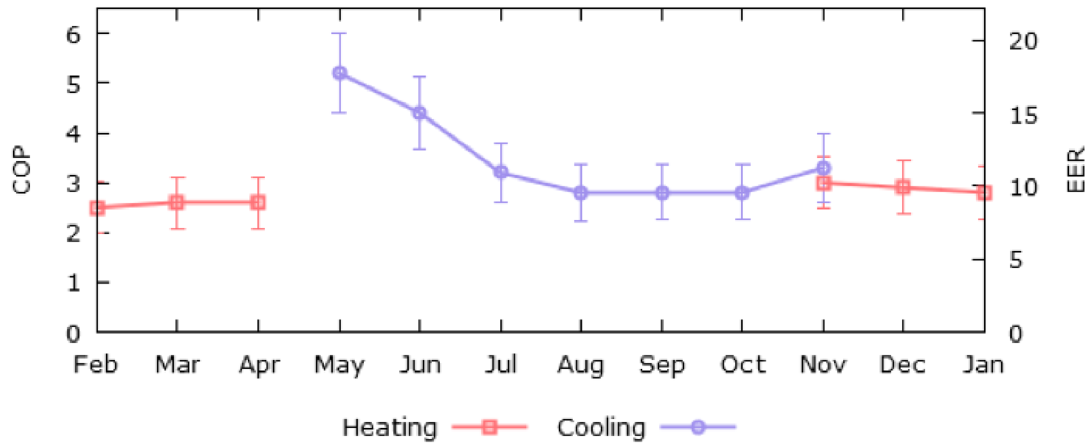


Figure 71: Monthly Cooling Load COP

The cooling mode COP has a notable decline as the cooling season progresses due to increases in load and local ground temperatures. The heating and cooling cycle times are 10 min and 20 min respectively.

Conclusions

- Cycling time guidelines should be established and integrated into system commissioning procedures (settings of balance of system components have a large impact on the system perforamcne and are easily overlooked)
- Matched-pair temperature sensors should always be used in geoexchange monitoring systems to reduce uncertainty in determining the difference between entering and leaving temperatures
- Instrumentation should be installed on both the building and the ground loop side of the heat pump
- Ground loop modeling is recommended to determine if imbalance is prohibitively large
- The relative merits and costs of implementing time-of-use control should be examined further for potential application in future sites

The cost and construction details of the retrofit were not included in the study. This geoexchange system was sized correctly at 28.6 Btu/hr heating capacity per $ft^2$of building. The total annual heating and cooling loads are 13.1 kWh/$ft^2$and 9.1 kWh/ft^2. The GHG savings were calculated to be 990 kg eCO2per rated heating ton. This information may be useful for benchmarking exercises. As seen in Chart X, the COP for this system is very low—likely because the average instantaneous capacity is also low. This installation has no ground loop instrument so a major determinant of performance is now known. The low performance may be related to the short cycle times, which are some of the shortest seen in this study. However, the low cycle time does not appear to be due to system oversizing as the system PTIU appears to be in an acceptable range for approximate design heating and cooling days. The low cycling time could be related to the aquastat settings that determine at which temperature the heat pump turns on and off.   There are large decreases in system COP/EER as the heating or cooling season progresses. For example, the June EER is 60% greater than the August COP. This is also likely related to the seasonal changes in ground loop temperature in the vicinity of the borehole.

Table 68: GHG Reduction Analysis for Peel House A

Heating Scenario	Efficiency	Heat Delivered [MWh]	Electricity Consumed [MWh]	Eq. CO_2 Emissions from Electricity [103 kg eCO_2]	Natural Gas Used [m^3]	Eq. CO_2 Emissions Natural Gas [103 kg eCO_2]	GHG Emission Reduction Achieved by Using Heat Pump [103 kg eCO_2]	Equivalent number of cars off the road [cars/year]
Heat Pump	2.8	23.0	8.2	0.9	0	0	N/A	N/A
Natural Gas Heating	0.75	23.0	0.0	0.0	2960	5.6	4.7	1.4
Natural Gas Heating	0.84	23.0	0.0	0.0	2643	5.0	4.1	1.2
Natural Gas Heating	0.95	23.0	0.0	0.0	2337	4.4	3.5	1.0
Electric Resistance	1	23.0	23.0	2.5	0	0.0	1.6	0.5

Table 69: Peel House A Geoexchange Performance Metrics

System Sizing	
PTIU – design heating day	0.70
Maximum PTIU – heating month	0.55
PTIU – design cooling day	0.90
Maximum PTIU – cooling month	0.57
Total annual heat delivered [kWh per ft^2]	13.1
Total annual heat removed [kWh per ft^2]	9.1
Maximum average monthly heating mode cycle time [min]	11
Maximum average monthly cooling mode cycle time [min]	20
System Efficiency	
Annual heating mode COP	2.8
Annual cooling mode EER	10.9
Ground Loop Sizing	
Lowest heating mode EST [^oC]	N/A
Highest cooling mode EST [^oC]	N/A
Imbalance [kWh per ft borehole length]	+15
System Electrical Energy Consumption	
Total annual heating [kWh per ft^2]	4.8
Total annual cooling [kWh per ft^2]	2.9
Total annual [kWh per ft^2]	7.7
Emissions Savings	
Annual GHG savings [kg eCO_2 per rated heating ton]	990

GSHP Case #6: Performance Assessment of Urban Geoexchange Projects in the Greater Toronto Area: Peel House B (2015)[74]

Study Details	
Purpose	Retrofit a multi-resident home with a primary heating and cooling Geoexchange system
Building Type	Residential (1 residential group home)
Location	Peel, Ontario, Canada
Model	SCW-048-1B Earthlinked compressor unit with 4 Tons nominal heating capacity
Specifications	50 MBtu/hr rated heating capacity 9.3 Btu/hr per ft^{2}heating capacity 48 MBtu/hr rated cooling capacity 9.0 Btu/hr per ft^{2}cooling capacity 3.5 rated COP 15.0 rated EER Commissioned 2009
Parameters	Residential group home was 5,360 ft^2. Ground-loop with direct exchange with vertical loop, 4 vertical boreholes extending 100 ft deep. The heating and cooling is accomplished via forced-air hydronic coils housed in **5** air handlers in mechanical closets throughout the building, creating a multi-zone system. Distribution was done through a multi-zone air handler with hydronic forced-air heating and cooling from buffer tank. The cooling mode buffer tank setpoint is between 6 and 80C. The heating mode buffer tank setpoint is 400C.The monitoring period was January 2013-December 2013

Table 70: Total Seasonal Heating and Cooling COPs

	COP
Rated	3.5
Field - Heating	3.5±0.8
Field - Cooling	3.8±0.6

*13.0±2 EER

In the initial months of the cooling season, with low load and cool ground temperatures, the monthly COP reaches above 4.4, however, as the ground warms and the load increases, the monthly COP decreases notably down to as low as 3.2.

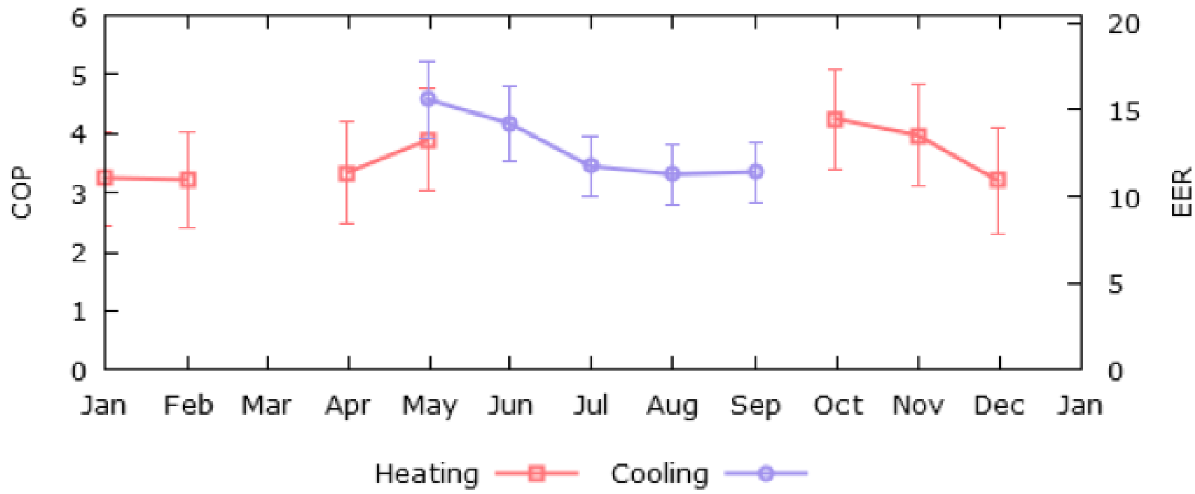


Figure 72: Monthly COP and EER Performance

The seasonal heating mode COP is 3.5 and the seasonal cooling mode EER is 12.6 (cooling mode COP of 3.8).

Conclusions

- Matched-pair sensors should always be used in geoexchange system performance analysis to limit the uncertainty of the results
- Acceptable ranges of system balancing (i.e. kWh/ft) were developed to aid in the analysis of geoexchange systems
- The system installed in Peel House 2 performed notably better than Peel House 1, the obvious difference being the shorter length of cycle times
    - The average cycle time for both heating and cooling are outlined in the study
- The system was sized appropriately, heat pump sizing and load information was presented and normalized to building square footage

Inclusion of the Entering Source Temperature would have been helpful in comparing this model and system to others. The cost and construction details of retrofit were not included in the study. Heating and cooling mode cycle times are 25 min and 45 min respectively during peak heating and cooling months. The heating and cooling loads of the building are comparable: total heating and cooling loads for the year were 24,000±6000 and 21,000±3000 kWh respectively. The total heat delivered to and removed from the ground were 26,000±3000 and 17,000±6000 kWh respectively. With the missing data from March the total heat removed from the ground would approximately total 19,000 kWh. The system was sized appropriately for the loads operated near its rated efficiency values.

The system was sized appropriately for the loads and operated near its rated efficiency values. The cooling capacity of the unit is lower than rated values but this did not affect EER notably, because it also operated with a lower power draw in cooling mode. The reason for the low cooling capacity is not clear.

Table 71: Peel House A Geoexchange Performance Metrics

System Sizing	
PTIU – design heating day	0.82
Maximum PTIU – heating month	0.68
PTIU – design cooling day	0.88
Maximum PTIU – cooling month	0.68
Total annual heat delivered [kWh per ft^2]	4.6
Total annual heat removed [kWh per ft^2]	4.0
Maximum average monthly heating mode cycle time [min]	27
Maximum average monthly cooling mode cycle time [min]	41
System Efficiency	
Annual Heating mode COP	3.5
Annual Cooling mode EER	13.0
Ground Loop Sizing	
Lowest heating mode EST [^{o}C]	N/A
Highest cooling mode EST [^{o}C]	N/A
Imbalance [kWh per ft borehole length]	+12.5
System Electrical Energy Consumption	
Total annual heating [kWh per ft^2]	1.3
Total annual cooling [kWh per ft^2]	1.1
Total annual [kWh per ft^2]	2.4
Emissions Savings	
Annual GHG savings [kg eCO_2 per rated heating ton]	1100

Table 72: GHG Reduction Analysis for Peel House B

Heating Scenario	Efficiency	Heat Delivered [MWh]	Electricity Consumed [MWh]	Eq. CO2 Emissions from Electricity [103 kg eq. CO2]	Natural Gas Used [m3]	Eq. CO2 Emissions Natural Gas [103 kg eq. CO2]	GHG Emission Reduction Achieved by Using Heat Pump [103 kg eq. CO2]	Equivalent number of cars off the road [cars/year]
Heat Pump	3.5	24.0	6.9	0.8	0	0	N-A	N-A
Natural Gas Heating	0.75	24.0	0.0	0.0	3088	5.8	5.1	1.5
Natural Gas Heating	0.84	24.0	0.0	0.0	2758	5.2	4.5	1.3
Natural Gas Heating	0.95	24.0	0.0	0.0	2438	4.6	3.9	1.1
Electric Resistance	1	24.0	24.0	2.6	0	0.0	1.9	0.6

The Entering Source Temperature is unavailable which limits the ability to fully compare the results to other results.

GSHP Case #7: Performance Assessment of Urban Geoexchange Projects in the Greater Toronto Area: TRCA Restoration Services Building (2015)[74]

Study Details	
Purpose	Toronto and Region Conservation Authority (TRCA) centre acts as a showcase for sustainable building design
Building Type	Commercial (office building)
Location	Toronto, Ontario, Canada
Model	WaterFurnace EW060 water-to-water heat pump
Specifications	3 heat pumps 60.7 MBtu/hr heating capacity per heat pump 15.2 Btu/hr per ft^2 heating capacity 61.1 MBtu/hr cooling capacity per heat pump 15.3 Btu/hr per ft2 cooling capacity 3.0 COP 13.5 EER Commissioned 2007
Parameters	The estimated size of the building is 12,000 ft^2. The ground loop is comprised of three horizontal slinky-style ground loops (loop length is undetermined), a style of loop that Is cheaper than vertical to implement and requires less space than conventional horizontal loops. The system is power by three Waterfurnace EW060 ground source heat pumps operating in parallel. The heat pump charges a buffer tank which is used for radiant in-floor heating and forced- air cooling. The distribution is always on, having constant flow. Supplemental cooling achieved using in-floor loops. The monitoring period was February 2013 to July 2014.

Table 73: WaterFurnace EW060 Water-to-Water Heat Pump Performance Data

	COP
Rated	3
Field	3.5

Annual Cooling mode EER 14.1

Lowest heating mode EST was 1°C, highest cooling mode EST was 20°C

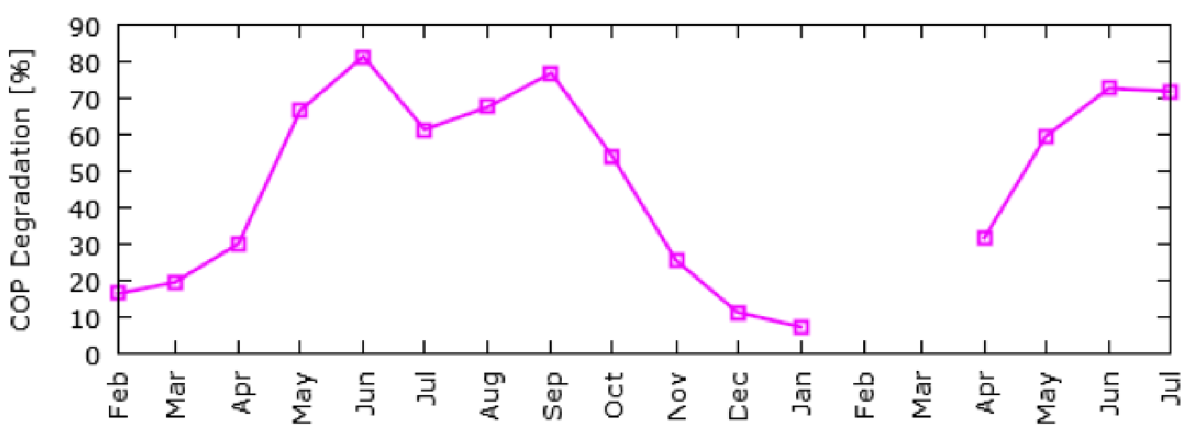
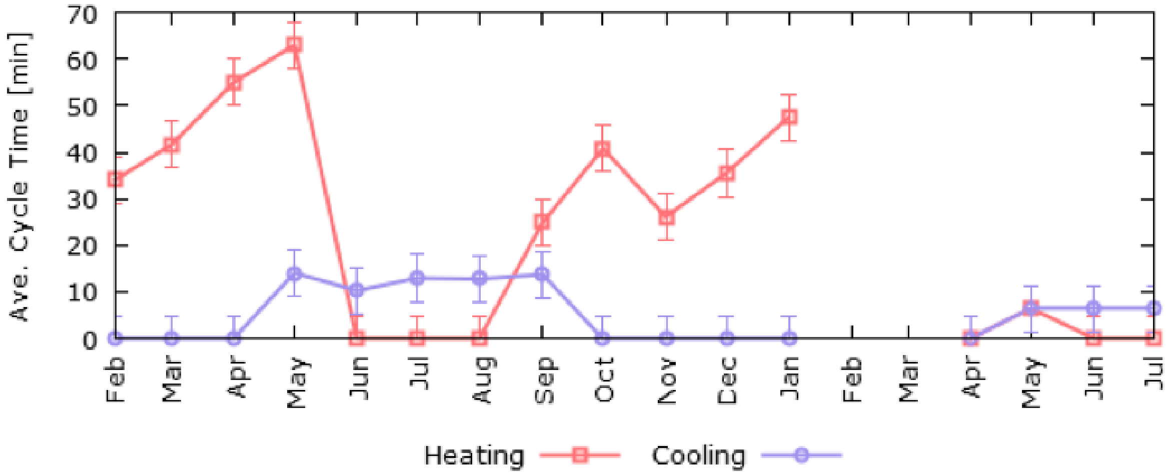


Figure 73: COP Degradation (Due to Constant Flow Operation of Circulator Pumps)



Heating mode cycle: 30-60 minutes
Cooling mode cycle: 10 minutes

Figure 74: Average Monthly Heating and Cooling Cycles

Conclusions

- The heat pump us appropriately sized for the heating load on a heating sample day of Jan 23rd, 2013, the heat pump was on 88% of the time suggesting the heat pump is sized well however a sample cooling day of July 17th, 2013 had the heat pump on for 36% of the time suggesting it is more than needed for the cooling load of the building
- Installation of the units should have interlocked circulator pumps to the heat pump itself to avoid operation and energy consumption of the circulatory pumps when the heat pumps are off (creates an extra load and doesn't benefit the system)
    - Approximately $500 in operating costs could be attributed to the circulator pumps
    - Operating the circulator pumps in constant flow decreased the COP by as much as 80% (10 to 20% in heating months)
- Constant flow operation severely limits the performance
    - It is necessary to have an experienced technician or electrician interlock circulator pumps to the heat pump according to the guidelines in the installation manual
    - Constant flow operation of the circular pumps decrease the monthly COP by as much as 80% and increased annual operating costs by 50%

The cost and construction details of the build were not included in the study. In general, the heat pump appears to be sized appropriately for the loads and if the constant flow operation of the circulators is ignored, the heat pump appears to be operating near manufacturer ratings.

Table 74: Restoration Services Building Geoexchange Performance Metrics

System Sizing	
PTIU – design heating day	88
Maximum PTIU – heating month	68
PTIU – design cooling day	36
Maximum PTIU – cooling month	16
Total annual heat delivered [kWh per ft^2]	N/A
Total annual heat removed [kWh per ft^2]	N/A
Maximum average monthly heating mode cycle time [min]	55
Maximum average monthly cooling mode cycle time [min]	14
System Efficiency	
Annual Heating mode COP[1]	3.5
Annual Cooling mode EER[2]	14.1
Ground Loop Sizing	
Lowest heating mode EST [^oC]	1
Highest cooling mode EST [^oC]	20
Imbalance kWh per ft borehole length	N/A
System Electrical Energy Consumption	
Total annual heating kWh per ft^2 [3]	2.8
Total annual cooling kWh per ft^2 [3]	0.3
Total annual kWh per ft^2 [3]	3.1
Emissions Savings	
Annual GHG savings [kg eCO_2 per rated heating ton]	N/A

[1]Not an annual value

[2]Chosen from the monthly of July because it is likely to be near the total seasonal average EER

[3]This does not include the constant flow operation of the circulator pumps and assumes all heat pumps are delivering/removing the same amount of heat at the same efficiency

Examination of the viability of time-of-use geoexchange system control could have a positive impact on energy consumption; approximately 20% of the electricity fuel cost could have been saved if the mid and on-peak loads were shifted to an off-peak time-of-use bracket.

GSHP Case #8: Performance Assessment of Urban Geoexchange Projects in the Greater Toronto Area: Earth Rangers Centre (2015)[74]

Study Details	
Purpose	Retrofit installed at the Earth Rangers Centre in 2010 when the parking lot was expanded.
Building Type	Commercial (office building)
Location	Vaughan, Ontario, Canada
Model	Carrier 30HXC 086
Specifications	83 tons (996 MBtu/hr) nominal capacity 16.2 Btu/hr per ft^2 heating capacity Variable Capacity Commissioned 2004
Parameters	The estimated size of the LEED-Platinum building is 60,000 ft^2. The ground loop below the parking lot consists of 44 vertical boreholes reaching a depth of 120 m, 17.7 ft borehole per MBtu/hr nominal capacity. The building uses radiant in-floor/slab distribution for heating and cooling. To avoid radiant slab cooling causing condensation, the building automation system regulates flow through the slabs to control the cooling slab temperature to above the dew point. High thermal mass reduces peak heating and cooling demand. The distribution system can be directly interfaced with ground loop via a heat exchanger, bypassing the heat pump, referred to as "free-exchange" which allows for highly efficient cooling mode operation. The monitoring period was January 2013 to November 2013.

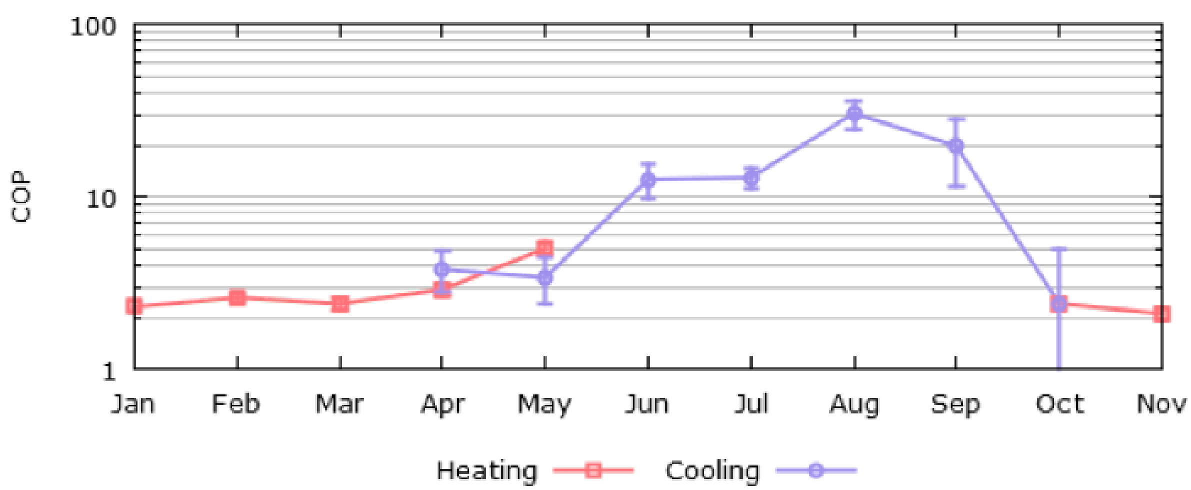


Figure 75: Log Scale of Monthly COP

Monthly COPs shown on log scale due to wide range of COPs observed. The free-exchange operation is the cause of the high cooling mode COPs. It is unclear why there are low heating mode COPs.

Table 75: Performance Metrics for Carrier 30HXC 086

	COP
Rated	N/A
Field Data - Heating	2.4±0.2
Field Data - Cooling	8.2±2

*13.0±2 EER

Conclusions

- The seasonal cooling mode COP resulting from free-exchange operation is 8.2
- The reason for the remarkably high cooling COPs are: radiant slab distribution, a very large thermal mass, and very low entering source temperatures (free-exchange may not be available on all geoexchange models due to the specific building requirements)
  - Free-exchange is not possible with air-source heat pump technology
- the was slightly imbalanced with approximately 25% more heat being removed from the ground than rejected
- 25% of the electricity fuel cost could be saved by shifting the entire load to off-peak
- the heat COP is low and the reason is unclear

The small temperature variation in EST would likely mean that the ground loop was oversized to some degree if this were a typical installation. However, in this case, to make use of free-exchange operation the ground loop likely needs to be oversized so as to maintain fluid temperatures that are cool enough to cool the building directly. The heating COP is low and it isn't clear why that ought to be the case. The cooling COP is very impressive due to the free-exchange mode of operation.

Free exchange operation can increase monthly cooling mode COPs by between 2 to 3 times compared to conventional heat pump operation. Free exchange involves using the ground loop to directly cool a building without the use of a heat pump. This is especially relevant as air-source heat pumps gain in popularity because air-source heat pumps are not able to operate in free-exchange mode and therefore they are not capable of these exceptionally high cooling COPs. Free-exchange worked well in this application because the ground loop temperatures were exceptionally cool and the radiant-slab distribution system had a very large heat exchange surface area, allowing warmer fluid temperatures to be used for cooling.

GSHP Case #9: Heating and Cooling Performance Analysis of a Ground Source Heat Pump System in Southern Germany[75]

Study Details	
Purpose	The GSHP was installed in an office building that was built in 2008
Location	Nuremberg, Germany
Model	Uponor GmbH SWP 75 I
Specifications	Electric input: 8.7 kW (one compressor), 16.9 kW (two compressor) 3.9 COP 8.0 EER SEER increased from 6.1 to 8.2 with annual increase rate of 8.7% over a 4-year operation (length of study) Seasonal COP decreased from 4.1 to 3.4 with an annual decreasing rate of 4.0% during 4-year operation
Parameters	The heat pump was installed in an office building. The building has 3 floors and a basement totaling 1530m^2. The system is comprised of 18 boreholes of diameters ranging from 121 mm to 180 mm that are 80 m in length. Monitoring period was from March 2009 to October 2012.

Table 76: Performance Metrics for Uponor GmbH SWP 75 I

	COP
Rated	3.9
Field Data - Heating	3.4*
Field Data – Cooling (EER)	8.0

*Estimated with energy loss considered for typical winter day

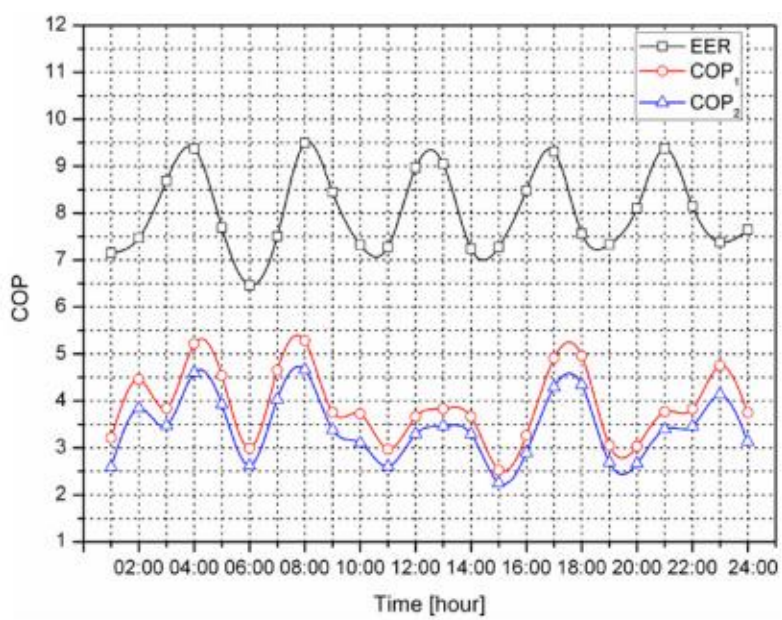


Figure 76: Daily Performance of GSHP for Typical Summer and Winter Day

The heating period in Nuremberg, Germany lasts from November to March with the daily mean temperature in January varies from -9°C to 1°C. The mean daily temperature during the cooling period, from June to August, can reach 28°C. The maximum heating load of the building was estimated to be 50 kW and 80 kW for the cooling load. During the cooling period, the weather is usually hot and the mean daily temperature can reach up to 28 ◦C. The main cooling period ranges from June to August with mean yearly cooling time of 850 h.

The performance of the GSHP systems may be overestimated if energy loss during the system operation is neglected. With the energy loss considered, the estimated COP for a typical winter day was 3.4; this indicates the performance of a system can be substantially influenced by the energy loss in the horizontal connecting pipes. Without considering the energy loss in horizontal connecting pipes the estimated COP for heating the building in a typical winter day is 3.9 (75% of the maximum value). The EER is 8.0 for cooling the building in a typical summer day. The GSHP system operated intermittently in winter and continuously in summer. Findings suggest that GSHP systems have an increasing trend in heating performance but a decreasing trend in cooling performance. This is caused by the unevenly distributed heating and cooling load of the building (which deserves further research). Thermal imbalance needs to be seriously considered in design and implement future GSHP systems in order to avoid reducing in efficiency of GSHP systems over long-term operation.

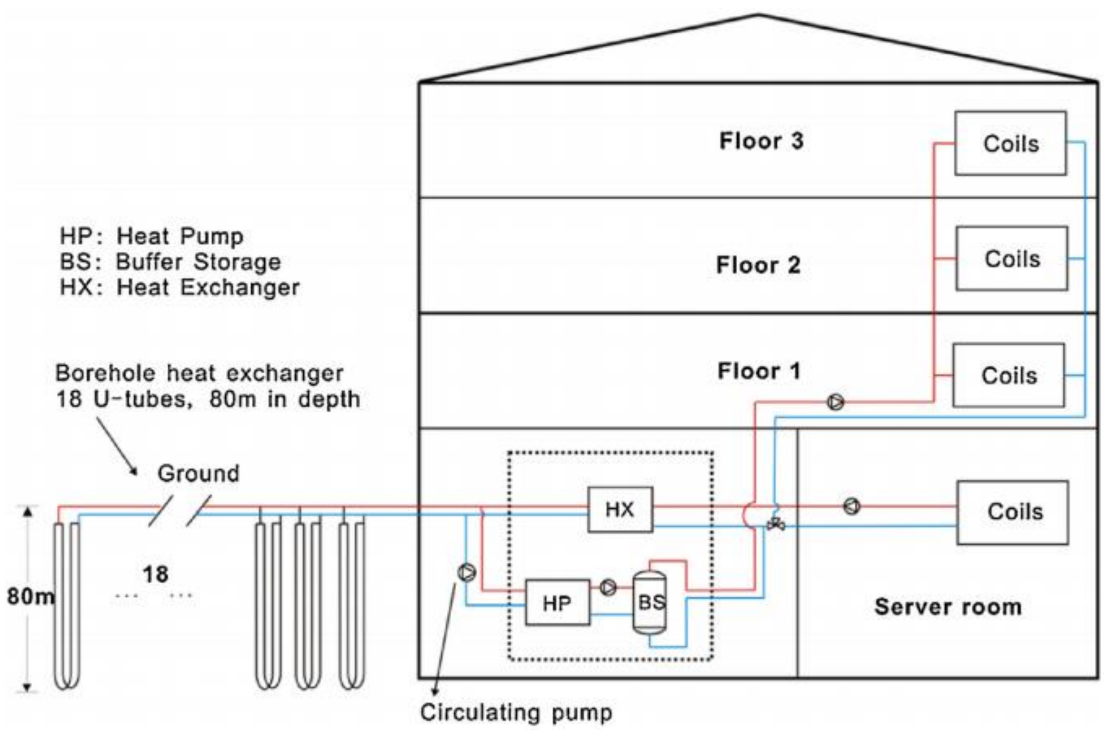
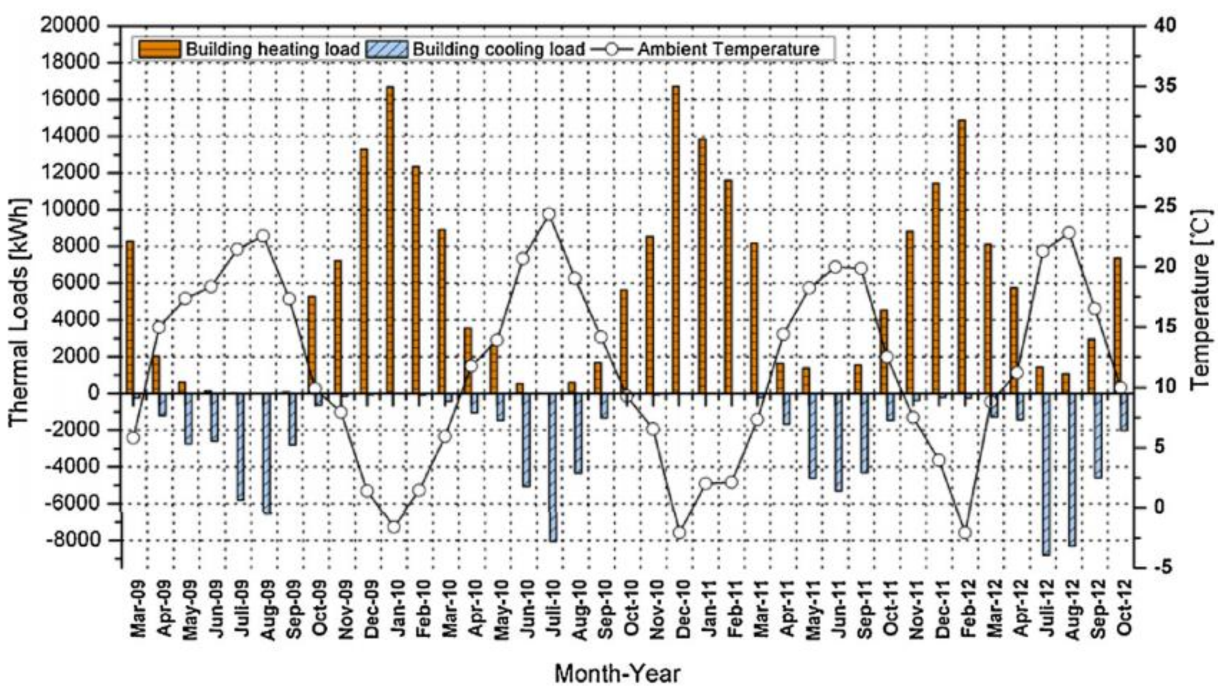


Figure 77: Schematic Diagram of GSHP System - Nuremburg, Germany

Table 77: Specification of the Heat Pump and Water Circulating Pumps

Components	Specification
Heat pump	Manufacture: Uponor GmbH, Hassfurt, Germany Model: SWP 75 I Electric input: 8.7 kW (one compressor), 16.9 kW (two compressor)
Water circulating pump (To borehole heat exchanger)	Manufacture: WILO AG, Dortmund, Germany Model: TOP-S65/13 Power: 960 W
Water circulating pump (To server room)	Manufacture: WILO AG, Dortmund, Germany Model: Stratos ECO 25/1-5 Power: 5.8–59 W
Water circulating pump (To floors)	Manufacture: WILO AG, Dortmund, Germany Model: Stratos ECO 40/1-8 Power: 25–590 W
Water circulating pump (To roof)	Manufacture: WILO AG, Dortmund, Germany Model: Stratos ECO 40/1-8 Power: 18–310 W
Water circulating pump (To heat radiators)	Manufacture: WILO AG, Dortmund, Germany Model: Stratos ECO 40/1-8 Power: 18–310 W



Positive values indicate energy for heating, negative ones for cooling.

Figure 78: Monthly thermal demand of the building between March '09 & October '12

Table 78: Amount of Thermal Exchange of the Borehole Heat Exchangers in Subsurface

Operational mode	Diameter (mm)	Thermal load (MWh)				Diameter (mm)	Total (MWh)	Difference (%)
		2009	2010	2011	2012			
Heating	121	9.06	19.42	15.52	9.75	121	83.27	0.00
	165	9.20	19.28	15.40	10.13			
	180	9.50	19.69	16.36	11.31	165	84.64	1.64
Cooling	121	−7.23	−7.14	−5.99	−9.16			
	165	−7.69	−7.46	−6.25	−9.25	180	86.15	3.45
	180	−7.75	−7.41	−5.94	−8.18			

Amount of thermal exchange of the Borehole Heat Exchangers (BHEs) in subsurface. The amount of thermal exchange is estimated separately for the heating mode and cooling mode. Positive values indicate the energy for heating of the building and negative ones for cooling. The total amount of energy of the BHEs is calculated using the absolute values, containing both heating and cooling load.

Table 79: Energy Distribution of the GSHP System between March '09 & October '12

Time (Year)	BHE Load		Operation Time		Power Input	
	Heating (MWh)	Cooling (MWh)	Heating (h)	Cooling (h)	Heating (MWh)	Cooling (MWh)
2009	27.76	22.66	1373.67	2845.00	8.84	3.70
2010	58.38	22.02	2735.67	2213.50	17.59	2.88
2011	47.27	18.17	2753.50	2741.17	17.71	3.56
2012	31.19	26.59	1944.00	2480.50	12.50	3.22

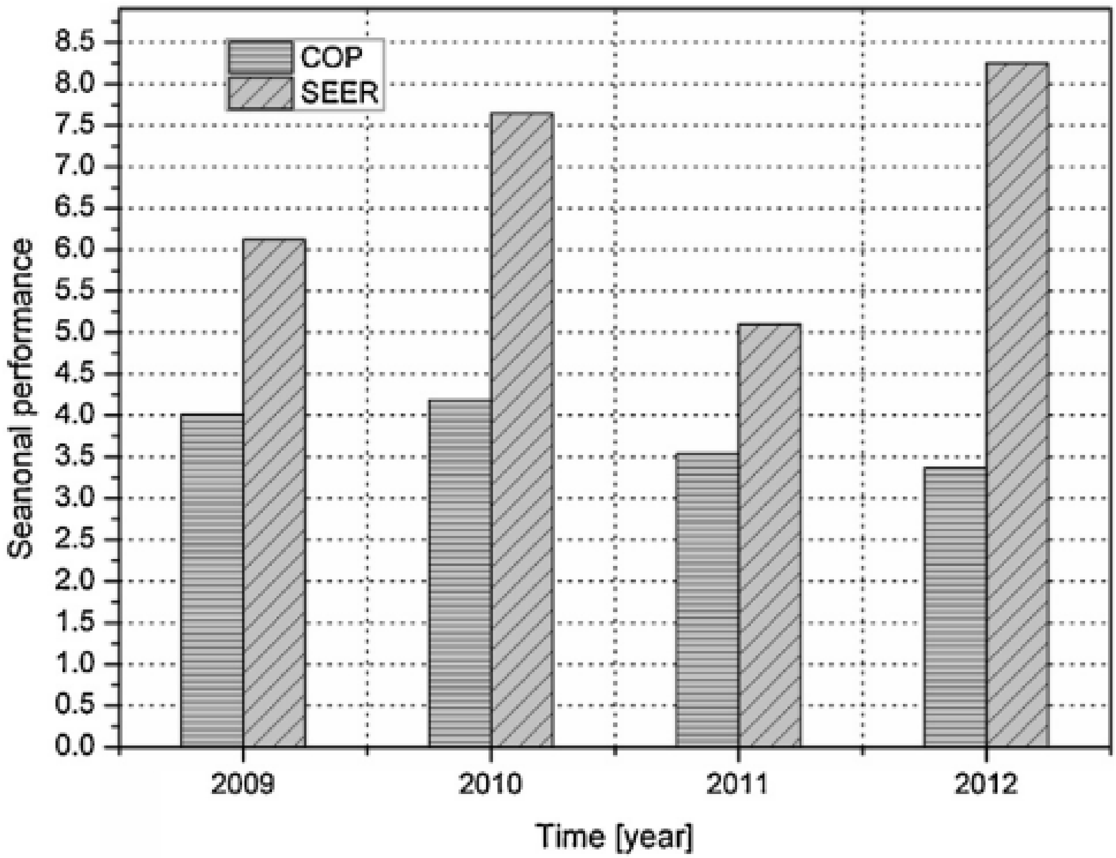


Figure 79: Seasonal COP of the GSHP System (March '09-October '12)

SEER values drop due to TRT measurements in the borehole filed the GSHP system was shut down between July and August 2011, resulting in sharp decline.

According to the monitoring data the GSHP system operates intermittently in winter and continuously in summer. The estimated heating load of the building is around 2.0 times larger than the cooling load. The results further indicate that thermal load of the building was strongly affected by the outdoor ambient temperature. It is also found that there has minor difference of the thermal load of the BHEs with three different drilling diameters. The daily COP is found to be 3.9 for heating the building in a typical winter day and the EER is 8.0 for cooling the building in a typical summer day. With taken into account the energy loss in the horizontal pipe the daily COP drops to 3.4. This fact indicates that the performance of GSHP system can be substantially influenced by the energy loss in the horizontal connecting pipes. For seasonal cooling performance, the SEER values are found to increase from 6.1 to 8.2 with an annual increasing rate of 8.7% over a 4-year operation of the GSHP system. On the other hand, the seasonal COP is observed to decrease from 4.1 to 3.4 with an annual decreasing rate of 4.0% during the same period.

GSHP Case #10: Performance and Control of Domestic Ground-Source Heat Pumps in Retrofit Installations (2011)[76]

Study Details	
Purpose	Study the performance of vertical GSHP in the coldest city in Turkey.
Location	Erzurum, Turkey
Model	See Table 80
Specifications	See Table 80 *Heating (average)*: Heat pump COP minimum 2.65 Heat pump COP maximum 3.0 System COP minimum 2.12 System COP maximum 3.0
Parameters	See Table 80. Conducted in the Energy Laboratory of Ataruk University. Measurements were taken between January and May of 2007.

Table 80: Technical Features of the Experimental Set-Up

Cycle	Equipment	Technical Specifications
Ground heat exchanger cycle (water-antifreeze solution)	Ground heat exchanger	Vertical double U-tube; inside diameter and material of tube: 32 mm, polyethylene; borehole depth: 53 m; bore diameter: 105/8"; backfill material: virgin soil
	Water-antifreeze circulation pump	Manufacturer: Wilo, type: TOP-S25/7, 3-stage variable speed, power supply: 220-240 V/1-50 Hz
Heat pump cycle	Refrigerant	R134a
	Compressor	Manufacturer: Copeland; hermetic scroll type: ZR40k3-TFD-522; power supply: 380-420 V/3-50 Hz; displacement: 9.4 m^3h^{-1}, compressor power input (kW): 2.57 (3.5 HP)
	Condenser	Plate HE; water mass flow rate in condenser (l/h): 1200, capacity (kW): 8, fouling factor (m^2KW^{-1}): $86x10^{-6}$; heat transfer surface area (m^2): 0.92
	Expansion valve	Manufacturer: danfoss; type: TN 2 (R-134a); PS=34bar; range of evaporation temperature: -40/+10°C
	Evaporator	Plate HE; water mass flow rate in condenser (l/h): 1080; capacity (kW): 5.7, fouling factor (m^2KW^{-1}): $86x10^{-6}$; heat transfer surface area (m^2): 0.92
Unit of heating cycle	Water circulation pump	Manufacturer: Wilo; type: TOP-S30/10, 3-stage variable speed, power supply: 220-240 V/1-50 Hz
	Expansion tank(s)	Manufacturer: Baymak; type: TM 7.5; volume: $0.0075m^3$, pre-charging pressure: 100 kPa; maximum pressure: 600 kPa

Table 81: Experimental Measurements in Average and Calculated Results (10/min mass flow rate)

Measured and calculated parameters	January	February	March	April	May
Evaporation pressure (bar)	2.1	2.1	2.2	2.1	2
Condensation pressure (bar)	14.15	14	14	14.6	14
Temp. of R134a at compressor inlet (°C)	21.9	21	27.1	21.1	21
Temp. of R134a at compressor outlet (°C)	89	84	90.2	88.7	84.3
Temp. of R134a at condenser inlet (°C)	86	82.5	89.1	83.4	80.1
Temp. of R134a at condenser outlet (°C)	43.5	44.3	45.2	44.5	44.3
Temp. of R134a at evaporator inlet (°C)	-9.4	-8.8	-8.1	-8.3	-8.8
Temp. of R134a at evaporator outlet (°C)	-9	-7.3	-6.9	-6.8	-7.1
Temp. of water/antifreeze solution at GHE outlet (°C)	4.13	3	2.4	2.1	3
Temp. of water/antifreeze solution at GHE inlet (°C)	-3.5	-3	-1.6	-1.7	-2.4
Supply water temp. of heating unit from condenser (°C)	47.5	46.6	52.4	47.8	46.6
Return water temp. of heating unit to condenser (°C)	41.3	39.9	44.8	39.8	39.6
Soil temp. in depth of 53 m (°C)	5.82	5.94	7.11	7.79	8.46
Total power input to the circulating pump at heating unit and brine circulation pump (kW)	0.62	0.68	0.68	0.57	0.55
Power input to the compressor (kW)	3.63	3.51	3.93	3.43	3.32
Heat rate of the condenser (kW)	9	9.3	10.6	9.6	9.3
Heat extraction rate per meter of bore depth (kW/m)	0.083	0.089	0.103	0.095	0.092
COP	2.48	2.65	2.7	2.8	2.8
COPs	2.12	2.22	2.3	2.4	2.4

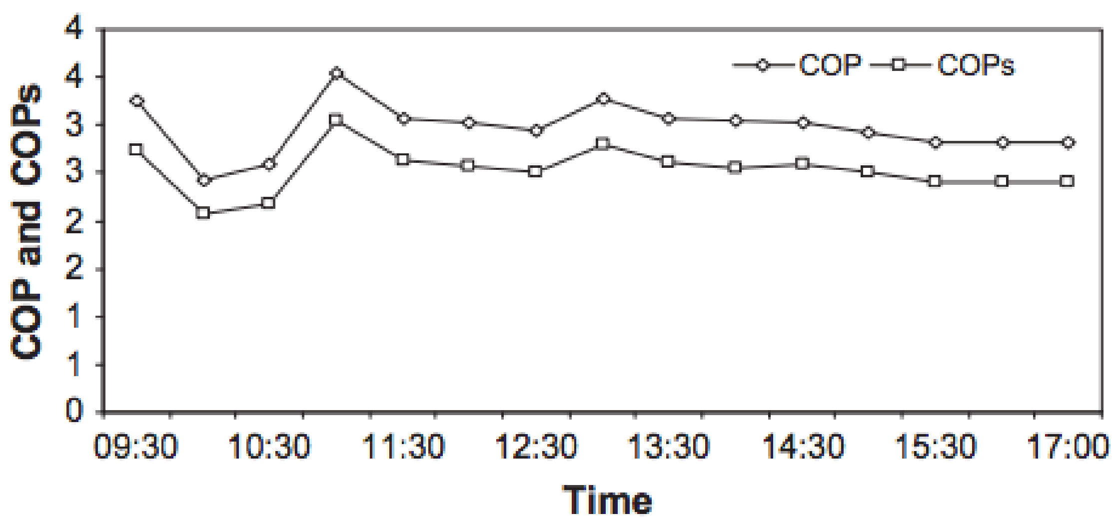


Figure 80: Daily Variation of Heat Pump COP and Overall System COPs

Table 82: Monthly Averages of Soil Temperatures at Several Depths

Month	5 cm (°C)	10 cm (°C)	20 cm (°C)	50 cm (°C)	100 cm (°C)
January	−5.65	−5.29	−4.39	−0.74	3.29
February	−4.98	−4.56	−4.56	−2.03	1.66
March	0.03	0.04	−0.39	−0.43	1.54
April	7.32	7.00	6.11	4.45	3.88
May	13.65	13.18	12.30	10.52	8.49
June	19.84	19.13	18.00	15.71	12.81
July	24.15	23.36	22.19	19.75	16.49
August	24.01	23.45	22.67	21.03	18.51
September	18.08	17.91	17.95	18.20	17.69
October	10.12	10.33	11.03	12.86	14.48
November	1.98	2.43	3.40	6.61	10.04
December	−2.86	−2.53	−1.42	2.08	5.99

The study was conducted in Erzurum, one of the coldest climate regions of Turkey. The overall COP for the system was extremely low when compared to other heat pumps operating under conditions at or near the design values of this study. Important future design properties needed to improve performance include improved pumping performance, good physical properties of virgin ground and backfill material (i.e. thermal conductivity), minimized miscellaneous pressure losses, (i.e. pipe friction, head loss through heat pumps, flow setter or balancing valve losses, etc.) and efficient pump motors should be taken into account. The output water temperature of the condenser remained at the desired level throughout the day (about 42–48°C). The proposed system is more convenient to floor heating than radiator for supply temperatures of 40–45°C. Also during heating process, the temperature of water and antifreeze mixture in the output of the evaporator is constantly reduced. A comprehensive economic analysis should be performed as well as an energy analysis.

GSHP Case #11: Performance and Control of Domestic Ground-Source Heat Pumps in Retrofit Installations (2011)[77]

Study Details	
Purpose	Study focuses on the performance of a group of ground source heat pumps.
Location	Harrogate Borough Council in North Yorkshire, United Kingdom.
Model	IVT Greenline HT Plus C6
Specifications	Scroll type compressor Operating temperatures : -5°C to 20°C
Parameters	The heat pump was installed in a residential (social housing) setting. The buildings monitored are rural retrofitted one or two bedroom bungalows built between 1967 and 1980. The ground source heat pumps were installed in 2007/08 and the monitoring began nearly 2 years after. The system had borehole collectors, connected to a conventional wet central heating system with radiators oversized by 30% by comparison with conventional UK practice for gas fired boiler installations. Space heating and domestic hot water are both supplied by the heat pump with the assistance of a 3 or 6 kW inbuilt electric resistance heater, which is brought incrementally online only as a supplement where necessary, typically during the weekly hot water pasteurization cycle. GSHPs operated in the continuous mode (as recommended by manufacturers and installers). The average floor area of the retrofit was 60-80m^2.

During the winter period of the heating season the heat pumps were able to maintain constant indoor temperatures with little or no use of the additional electric cassette, even in very cold weather. The heat pumps currently available in the UK are designed for larger homes; the minimum capacity offered is 5 kW, which is much more necessary to meet the winter load of a small well insulated home needing 100 W/°C. Consequently heat pumps in the UK are operating more lightly loaded-- if other parameters are normalized then mechanical losses will be proportionately higher, as will parasitic electrical loads such as circulation pumps, resulting in a lower average COP.

Table 83: Performance Metrics for IVT Greenline HT Plus C6

	COP
Rated	4.2[78]
Field Data - Heating	2.4
Field Data – Cooling (EER)	N/A

The data from January 2010 are particularly significant since this was an exceptionally cold winter for the UK but the average consumption of 900 kWh and COP of 2.4 imply a continuous heat output of 2.9 kW which is only 58% of the heat pump capacity of 5 kW.

Authors found that for improving control, there must be a more accurate setting of the radiator circulation temperature control. Monitored homes showed that the temperatures set by installers tends to be too high (erring on the side of keeping occupants warm), resulting in higher radiator temperatures and lower COPs. For new builds architects should be calculating the radiator heat transfer coefficient and heat loss rate and apply a correction for appliance and metabolic heat inputs to arrive at a good estimate of the radiator circulation temperature control constant. In the case of a retrofit project this is unlikely to be practical unless a total refurbishment of the building is being performed. Preferably the heat pump control system should calculate the radiator heat transfer coefficient and heat loss rate of the building in operation using its own sensor measurements and set the radiator circulation temperature control automatically.

Room temperature should ideally be stabilized and varied using conventional closed-loop control which incorporates the first order building model as an exponential lag in the transfer function. This would be beneficial in ensuring that the output from the heat pump is correctly modulated in response to variations in casual heat sources. However the difficulty for the occupants is that the perceptible responsiveness of their heating will always be constrained by so any attempt to achieve a rapid rise in temperature in a high-home will be penalized with a poor COP, while a rapid fall in temperature can only be achieved by opening windows to effectively reduce by increasing heat loss. Possibly the best approach for a control system is that it should combine the provision of clear information that accustoms users to this slow response time with the application of controlled setbacks of varying duration to shape the daily temperature profile and maximum temperature in accordance with their inputs. Development of a control system with these properties is the subject of further work under the present system.

Households with variable occupancy, a lower thermal time constant in the building combined with good radiators has the potential to make a real difference to their energy consumption. Where a high thermal time constant in the building in unavoidable, perhaps as a consequence of exceptionally good insulation, high performance radiators become even more important to maintain controllability.

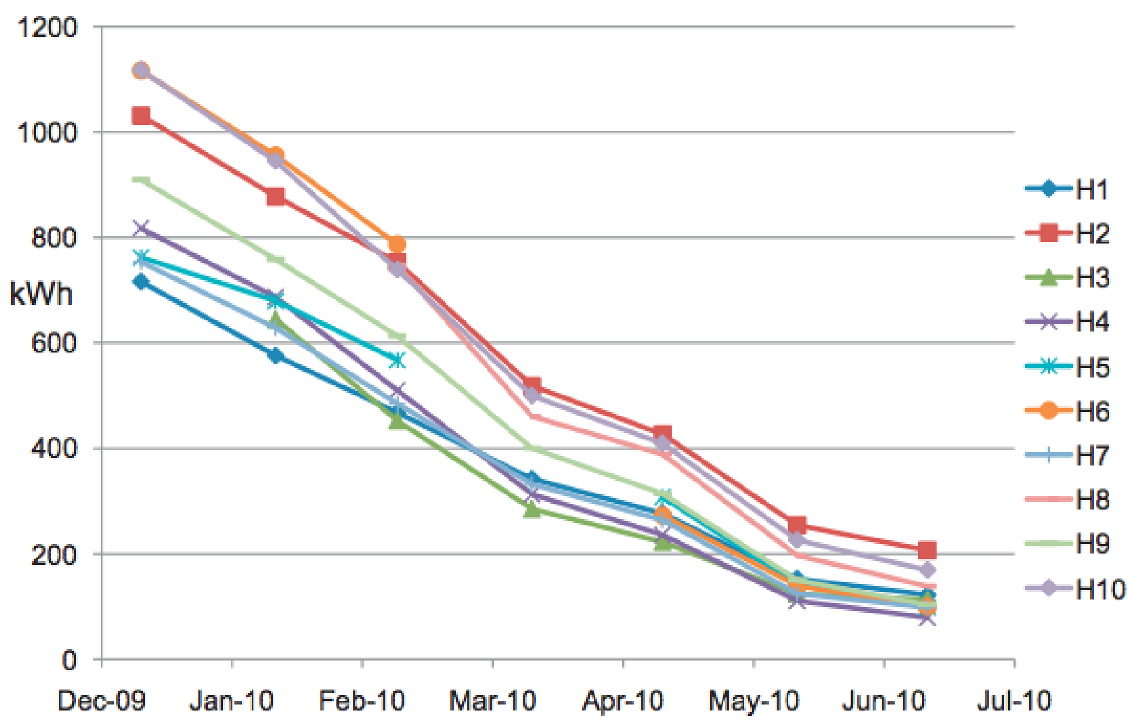


Figure 81: Monthly Electricity Use by Heat Pumps (January to July 2010)

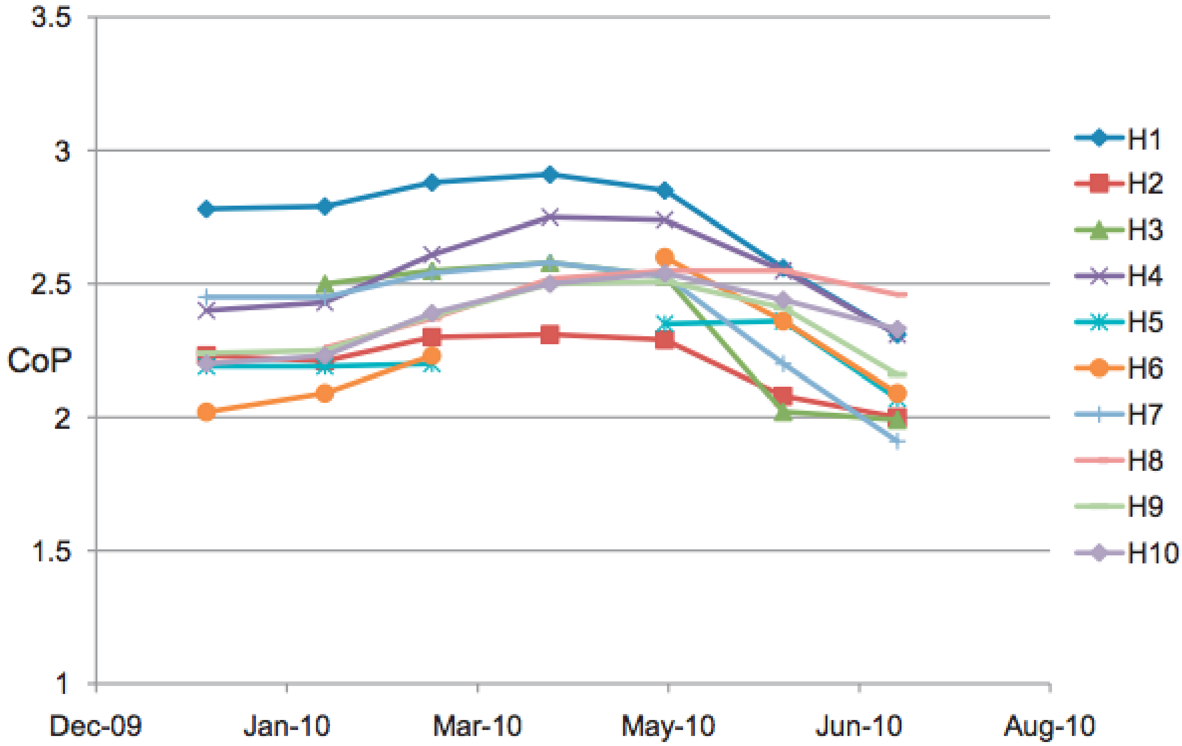


Figure 82: Monthly System COP Values (January to July 2010)

GSHP Case #12: Performance and Economic Feasibility of Ground Source Heat Pumps in Cold Climate (1997)[79]

Study Details	
Purpose	The effect of these parameters on the performance and energy efficiency of GSHPs is studied in this paper based on sensitivity studies conducted using a computer model and climatic and soil data from Nova Scotia, Canada.
Location	Halifax, Nova Scotia
Model	Ground Heat Exchanger Analysis, Design and Simulation (G-HEADS), computer modeling system
Parameters	The test house was a commonly encountered three-bedroom, two-storey detached house with a partially-below-ground basement. The floor area of each floor is 71 m^2, giving a total area of 213 m^2. The house was extensively monitored for a whole year, and heating and cooling energy consumptions for the house were determined for each hour of the year. Horizontal pipe spacing of ground heat exchanger were used for the study.

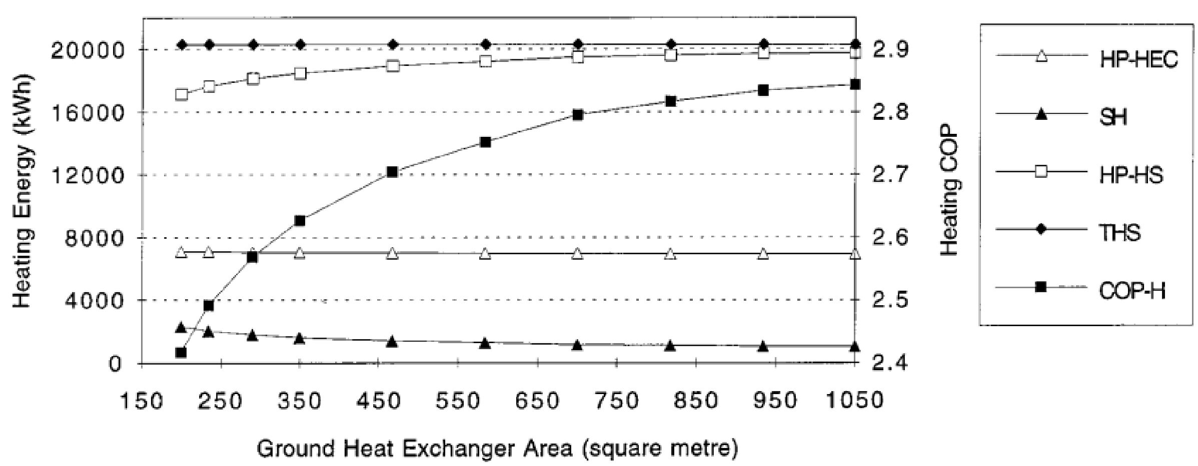


Figure 83: Effect of Ground Heat Exchanger Area on Heating Performance

It can be seen that as the GHE area is reduced, heating COP and heat supplied by the heat pump decrease while supplemental heating energy consumption increases to provide the total heating supplied to the house. It can be concluded from this analysis that determination of an optimum GHE area is important from an energy efficiency perspective. Using a GHE area smaller or larger than an optimum value should be avoided since a larger area does not improve energy efficiency, whereas a smaller area results in a penalty. The optimum GHE area for a typical low energy house in Nova Scotia is approximately 350 m^2, which would require a field of 18.7m by 18.7 m. This size field would fit into most backyards of typical building lots.

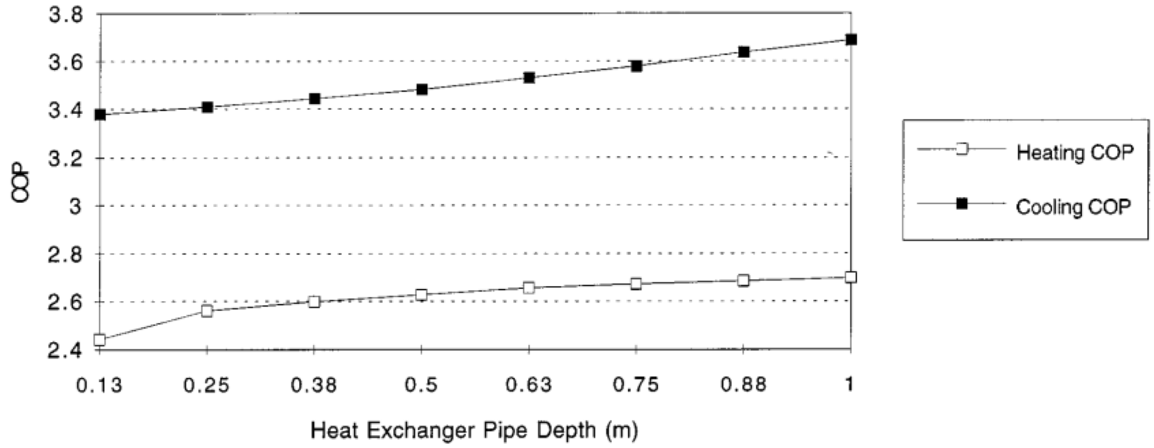


Figure 84: Effect of Ground Heat Exchanger Pipe Depth on COP

The depth of the GHE dictates the amount of excavation necessary for installation, and this has a large influence on the cost of the system not only due to the volume of soil to be removed and replaced, but also due to the fact that the deeper the excavation, the more chance of encountering rock. It is therefore important to determine how close to the surface the GHE can be located without suffering large increases in energy consumption. As the GHE depth is reduced, the available thermal reservoir becomes smaller, resulting in higher energy consumption.

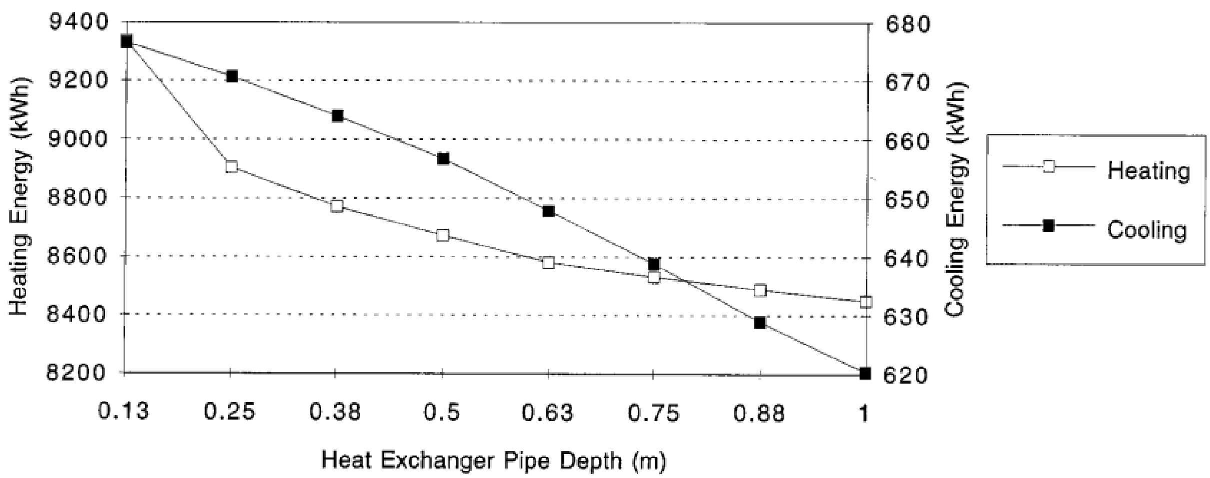


Figure 85: Effect of Ground Heat Exchanger Pipe Depth on Energy Consumption

It can thus be concluded that energy consumption decreases as GHE depth below grade increases. The optimum depth below grade is about 0.4 m, considering the possibility of damage to the GHE piping from regular backyard activities (digging, gardening, possibility of interference with shrub and plant roots, etc.), a depth of 0.5 m would be more practical.

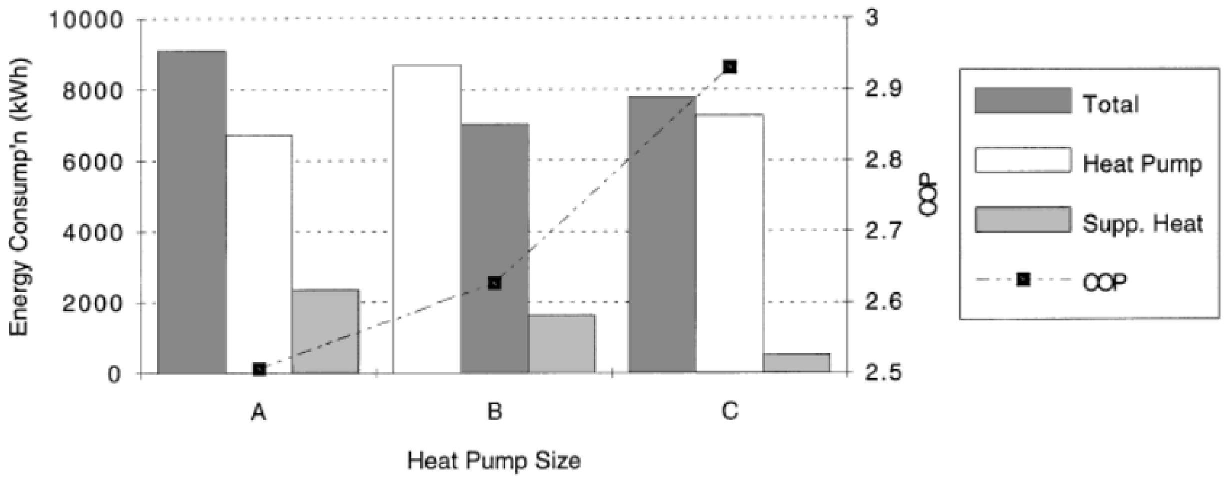


Figure 86: Effect of Heat Pump Size on Performance

Table 84: Nominal Capacities of Various Heat Pump Sizes Included in Study

	Size A	Size B	Size C
Nominal cooling capacity (kW)	9.1	10.5	12.0
Nominal heating capacity (kW)	6.8	7.9	9.7

It can thus be concluded that annual energy consumption will decrease as heat pump capacity increases. Therefore, GSHPs should be sized as large as possible without compromising installation costs or cooling comfort.

The authors concluded that as horizontal pipe spacing of the GHE decreases, heating and cooling energy consumptions also decrease. This is due to the fact that heat transfer surface area increases as pipe spacing decreases. Smaller pipe spacing means more pipe per square meter of yard area. Thus, pipe spacing should be chosen close to 0.5 m taking into consideration the cost of pipe and installation, and its impact on economics.

To determine whether GSHPs would produce any economic benefits for home owners, an economic analysis was carried out to compare GSHPs with the conventional methods of space heating and cooling used in Nova Scotia. The energy requirements of the test house for space heating and cooling are 22,800 kWh and 2,300 kWh, respectively, for the year that simulations were conducted.

Table 85: Comparison of Energy Performance of Energy Performance and Costs for Different Systems

	GSHP	Electric resistance heat and A/C	Oil fired furnace and A/C
Heating fuel	Electricity	Electricity	Oil
Heating value	1 kWh/kWh	1 kWh/kWh	10·84 kWh/L
COP	3·1	1	0·7
Unit cost	\$0·08/kWh	\$0·08/kWh	\$0·36/L
Actual cost (\$/kWh)	0·026	0·08	0·047
Fuel consumption	7370 kWh	22 790 kWh	3000 L
Heating cost (\$)	590	1820	1070
Cooling fuel	Electricity	Electricity	Electricity
COP	3·36	2	2
Unit cost (\$/kWh)	0·08	0·08	0·08
Actual cost (\$/kWh)	0·024	0·04	0·04
Fuel consumption (kWh)	680	1140	1141
Cooling cost (\$)	55	90	90
Total cost	645	1910	1160

Table 86: Comparison of Capital Costs of Various Systems

GSHP system	Increased electrical service	\$500
	Ground source heat pump unit	\$3500
	Ductwork	\$2500
	GHE piping (700 m × \$1·48/m)	\$1040
	Excavation for GHE (excavator 8 hr × \$120/hr)	\$960
	GHE piping installation	\$600
	Total GSHP cost	\$9100
Electric resistance heat and A/C	Increased electrical service	\$500
	Electric baseboard heating system	\$1500
	Ductwork	\$2500
	Split system A/C	\$2500
	Total electric resistance heat and A/C cost	\$7000
Oil fired furnace and A/C	Oil fired furnace	\$2000
	Chimney	\$700
	Ductwork	\$2500
	Oil tank and piping	\$400
	Split system A/C	\$2500
	Total oil fired furnace and A/C cost	\$8100

The capital costs, including material, labour, and taxes, for the four systems were estimated using data from local contractors, equipment suppliers, construction estimating software, and the actual construction costs of the test house.

Table 87: Comparison of Present Worth of Different Heating and Cooling Systems

	Present worth ($)
GSHP	18 775
Electric resistance heat and A/C	35 650
Oil fired furnace and A/C	25 500

Table 88: Comparison of Energy and Capital Costs and Present Worth of Heating Only Systems

	Capital cost ($)	Annual heating energy cost ($)	Present worth ($)
GSHP	9 100	590	17 950
Electric resistance heat	3 000	1 820	30 300
Oil fired furnace	5 600	1 070	21 650

The results clearly indicate that the GSHP is the least expensive to own and operate for heating and cooling of residences.

It would be necessary to conduct a pre-design analysis to determine optimal system parameters that would ensure minimum energy consumption and favourable economics. With the help of computerized building energy simulation models and GSHP simulation models such as that used here, such analysis can be conducted with ease. This study also clearly shows that GSHPs are economically preferable to the conventional space heating and heating/cooling systems used in houses in Nova Scotia. The same conclusion would be applicable to locations with environmental conditions similar to those of Nova Scotia.

GSHP Case #13: Performance Assessment of a Horizontal Loop Coupled Ground Source Heat Pump System[32]

Study Details	
Purpose	This study evaluates the performance of a ground source heat pump (GSHP) system individually and as part of a heating and cooling distribution systems in a semi-attached houses.
Location	Toronto (Vaughan), ON, Canada
Model	WaterFurnaceEW 042 R12SSA
Specifications	13.3 kW high efficiency GSHPconnected to two 152.3 m (500 ft) horizontal loops in the yard, a desuperheater and buffer tank. A propylene glycol mixture was used as the heat transfer fluid.
Parameters	The semi-detached test house, referred to as House B, is a 3-storey south facing Archetype Sustainable House that has been awarded LEED™ Platinum, EnergyStarand GreenHouse certifications. The design heating loads of House B are 7.91 kW and 7.94 kW when outdoor and indoor temperatures are -22°C and 22°C, respectively. Net floor area: 350m^{2}Internal volume: 1036 m^{3}Volumetric flow rate: 665 cubic feet per minute.

For the purpose of the study an Archetype Sustainable House located in Vaughan, Ontario was used. The house was designed and constructed as a laboratory for green building technology testing. For experimentation purposes over 300 calibrated sensors were included in the housing design to monitor the performance of the electrical and mechanical systems as well as energy fluxes into and out of the house. In regard to testing, the cooling period extended from August 23 through to September 15th, 2010 and the heating test season from December 24, 2010 to January 12, 2011.

The performance table below summarizes actual performance data collected during the heating and cooling seasons and compares it to the corresponding EnerGuide and equipment manufacturer ratings. Coefficients of performance for the ground source system exceeded 3 during the heating season with seasonal energy efficiency ratios exceeding 19 during the cooling season. This indicated that the systems provided over 3 kWh of output heat and 5 kWh of output cooling for each kWh of energy consumed. It was found that the GSHP performed particularly well during the cooling season as performance well exceeded both the manufacturer and EnerGuide ratings for the system. During the heating season, the COP for the GSHP was only slightly higher than the manufacturer and EnerGuide ratings.

Table 89: Comparing COP values for the Manufactured, EnerGuide and Field Performance Data

	Manufacturer	EnerGuide	Actual Test	Test Dates	Season
Seasonal Energy Efficiency Ratio (SEER)	12.9	>=14.1	19.7	August 23-Sept 15th	Cooling
Coefficient of Performance (COP)	3.0	>=3.3	3.44	Dec 24th-Jan 12th	Heating

In the investigation, modelled optimization scenarios showed that significant energy savings can be achieved by configuring the systems to operate more efficiently. For the GSHP to the buffer tank and from the buffer tank to the AHU (air handling unit) an optimized setting was found by running the pumps only when the compressor was on. This resulted in a 28% reduction in electricity use as well as an increase in the as-installed COP from 2.64 to 3.68. Furthermore, the GSHP system maintained a more constant COP of about 3.0 regardless of outside temperature conditions.

The annual cost of GSHP energy was found to be $725 with initial equipment costs averaging $34,500. With a simple payback calculation, 23.3 years was found to be the payback period. If life cycle costs and benefits were considered, this price gap would narrow because the ground loop is a one-time cost and the GSHP compressor is subject to fewer mechanical and thermal stresses with a longer expected service life of 20 to 25 years. Table 90 below summarizes the data provided in the study.

Table 90: Comparing Cost Data for the Installed GSHP

	Annual cost of GSHP energy	Annual cost of conventional energy	Initial equipment cost	Simple payback
GSHP	$725	$2,205	$34,500	23.3

The simulations were based on historical weather and ground temperature data from the selected cities including Toronto. Figure 87 shows temperatures, degree days and coefficients of performance for each of the cities during the heating and cooling seasons. During the cooling season, the GSHP system COPs ranged from 5.8 to 6.1. Model simulations for five major Canadian cities showed that GSHP technologies can perform well in the Canadian climate, and that residential GSHP systems are better suited to climates where winter temperatures fall below minus 24°C.

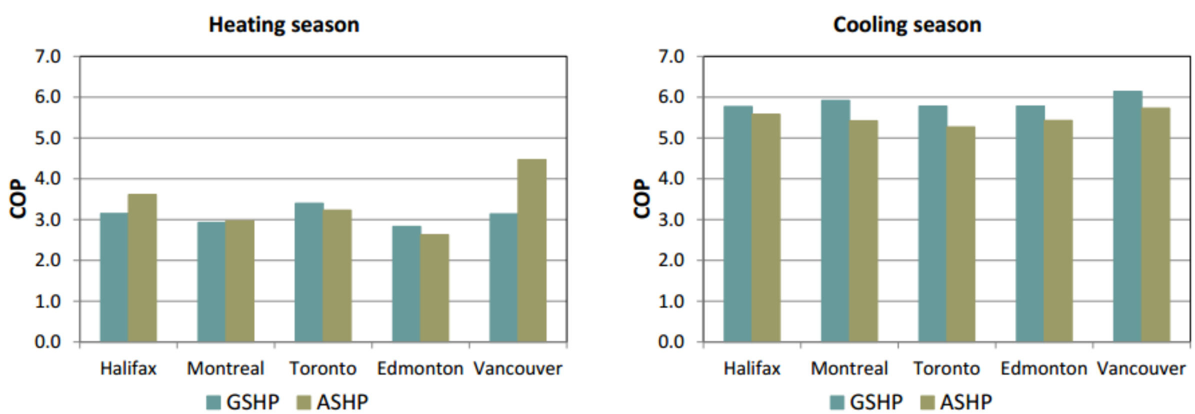


Figure 87: Heating and Cooling Degree Days, Temperatures and Modeled COP for ASHP and GSHP Systems in Selected Canadian Cities

This study evaluates the performance of a ground source heat pump (GSHP) system as part of a heating and cooling distribution systems in a semi-attached house located in Vaughan, Ontario. In relation to applying this GSHP to an urban environment like Toronto, geological and thermodynamic investigations would need to occur onsite of the proposed location, taking into account rock properties, groundwater saturation, temperature profiles, soil stability and thermal diffusivity before a vertical or horizontal ground loop could be installed. Only through onsite testing with would the choice be made as to whether or not this deign would be suited toward a new build or semi-attached home rather than a multi-unit residential retrofit.

Energy savings from the use of these more efficient heat pump systems translated into significant reductions in greenhouse gas emissions relative to conventional alternatives. Annual electricity savings relative to a conventional electric furnace and air conditioner were converted to the equivalent carbon dioxide based on electricity generation sources in Ontario to arrive at emission reductions of 2,449 kg $eCO_2$for GSHP. If instead, the heat pump displaced natural gas during the heating season, the annual emissions reductions would rise to 3549 kg eCO_2. By comparison, average per capita emissions from private vehicles in Canada was 2149 kg eCO_2 in 2007[80]. Thus, the emissions savings from heat pumps are greater than the savings achieved by a family that chooses to replace all annual car travel with zero emission alternatives such as walking or biking.

GSHP Case #14: Evaluation of a Vertical Geoexchange System[81]

Study Details	
Purpose	This study evaluated the performance of a vertical geoexchange system used to heat and cool a semi-detached LEED Platinum house located at the Toronto and Region Conservations' Living City Campus.
Location	Toronto, (Vaughan), ON, Canada
Model	Waterfurnace EW042
Specifications	Ground Source Water-to-Water Heat Pump The system was uniquely equipped with both a vertical and horizontal ground loop with capability to operate with both loops in parallel or a given loop individually. This review will investigate the results of the vertical system alone. The loop parameters are outlined below.
Parameters	A semi-attached house, referred to as House B, is a 3-storey south facing Archetype Sustainable House that has been awarded LEED™ Platinum, EnergyStar and GreenHouse certifications. The home is three stories, with a floor area of 232 m^2 Seasonal Heating load: 18764 kWh Seasonal Cooling load: 2459 kWh

Researchers with the Sustainable Technologies Evaluation Program compared both the heating and cooling performance of a vertical geoexchange system in a semi-detached LEED platinum home. The system was uniquely equipped with both a vertical and horizontal group loop to compare seasonal changes, coefficients of performance and costs associated with each of the designs. The system also had the ability to run the loops simultaneously, allowing for direct comparisons. However, this review will focus on the vertical loop system results. Detailed specifications for the loop are provided in Table 91. A schematic of the loop configuration and the GSHP is provided below.

Table 91: Loop Specifications for Vertical Geoexchange System

Loop Specifications	
Parameter	Vertical Loop
Number of Loops	2
Depth	76.2 m
Length	152 m
Nominal Diameter	1"
Material	HDPE 4710
Volume of both Loops	192/51 L/US gal
Shape	U-loop
Fluid	20% Propylene Glycol 80% water with freezing point of -8°C

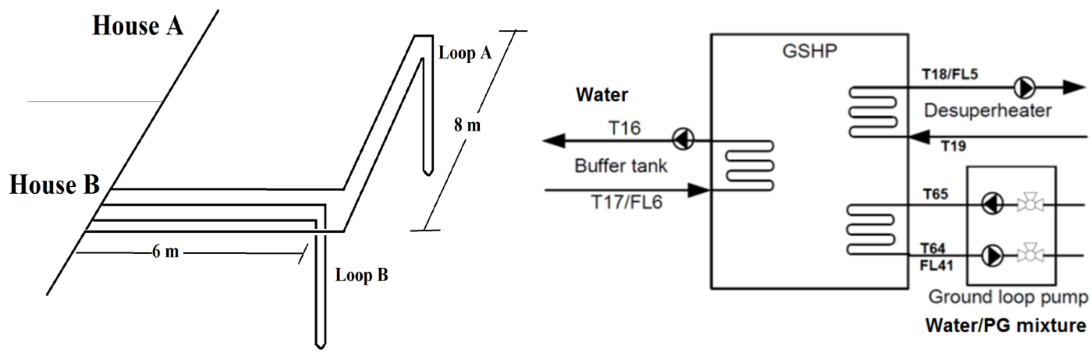


Figure 88: Vertical Loop Configuration (Left) and Schematic of the GSHP (Right)

Research presented in this study investigated the performance of the system when coupled to the vertical loop. In this configuration, the heating and cooling mode COPs were 3.0 and 4.5 respectively. These performance measurements were collected during a two-three week period at the end of the heating season (May 14th and June 4th, 2013) and the beginning of the cooling season (June 21st and July 8th, 2013). They were found to be in reasonable agreement with the manufacturer specifications for the heat pump model as is seen in Table 92 below.

Table 92: Comparing COPs (Coefficient of Performance) for both Vertical and Ground Loop Systems

	Season	Testing Period	Vertical Loop (Field)	Vertical Loop (Manufactured)[82]	Vertical Loop (Energuide)
COP (Coefficient of Performance)	Cooling	June 21st and July 8th, 2013	4.5*	3.6-3.8**	4.1
	Heating	May 14th and June 4th, 2013	3.0***	2.9-3.0****	3.3

*The experimental EST was 16 – 21 ^{o}C, the ELT was 3 – 11 ^{o}C, the source flow rate was 12.7 GPM and the load flow rate was 13.3 GPM.

**The manufacturer specification is determined for an EST of 25 ^{o}C, ELT of 12 ^{o}C, a source flow rate of 11 - 16.5 GPM and a load flow rate of 11 – 16.5 GPM (Water Furnace Manual).

***The experimental parameters were close to, or within the manufacturer-specified ranges, as EST was 1 – 4 ^{o}C, the ELT was 40 – 45 ^{o}C, the source flow rate was 12.7 GPM and the load flow rate of 13.3 GPM

****For the manufacturers' specifications of COP is determined for an EST of 0 ^{o}C, an ELT of 40 ^{o}C, a source flow rate of 11 - 16.5 GPM and a load flow rate of 7 – 16.5 GPM

In regards to entering load temperatures (ELT) and entering source temperatures (EST), the COP of the vertical loop system during heating and cooling modes was shown to be dependent on these values. The effects of the entering load and source temperatures on the vertical geoexchange system COP is presented below in Figure 89.

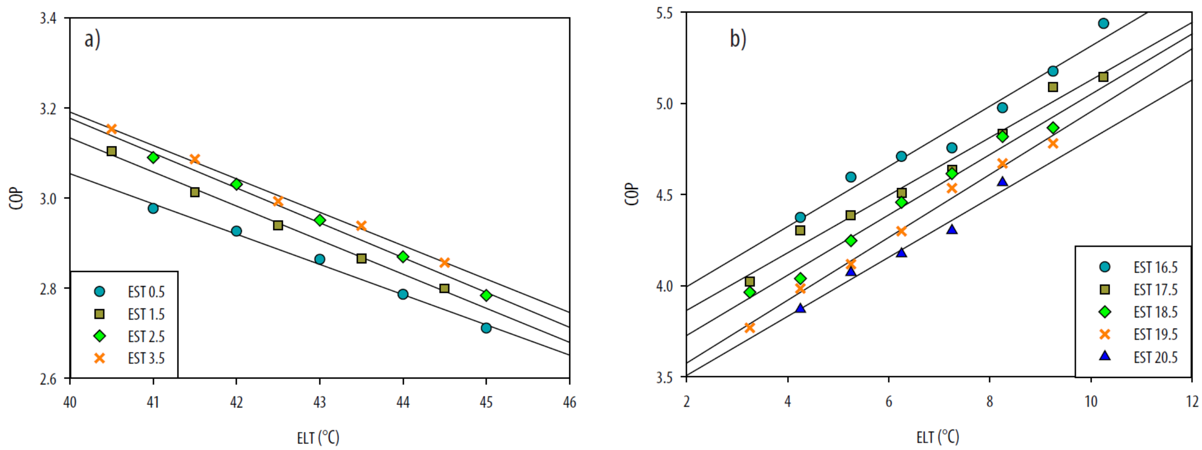


Figure 89: Heating Mode COP increase as ELT decreases (a) and Cooling Mode COP increases as ELT increases and EST decreases (b)

Heating season COPs increased as ELTs decreased and ESTs increased. The reverse occurred during the cooling season. During both seasons, the lower the difference between source and load temperatures, the higher the COP. For the cooling season, it was found that the vertical loop was not able to reject heat back to the ground at a fast enough rate. This resulted in a net heat gain that forced the EST to rise and COP to fall over time.

Figure 90 below shows, as daily averages, the percentage of time that the unit was operational (Part Load Percentage), the average cycle time as well as the heat removed/delivered and electrical power consumption during both the heating and cooling mode testing periods. The cycle time is defined as the quantity of time elapsed between when the unit turns on to begin providing heating or cooling and then subsequently turns off. On any given day there may be many on/off cycles. The relationships generally meet expectations of how the system should perform. During the cooling season, ambient air temperatures were correlated with power consumption, heat/cooling output and heat pump operation time, while it was inversely correlated in the heating season. In cooling mode, it appeared that larger daily average cooling loads, and longer cycle times, were associated with lower COPs. This is likely due to a net heat gain in the ground loop fluid that had a larger effect on longer cycle times.

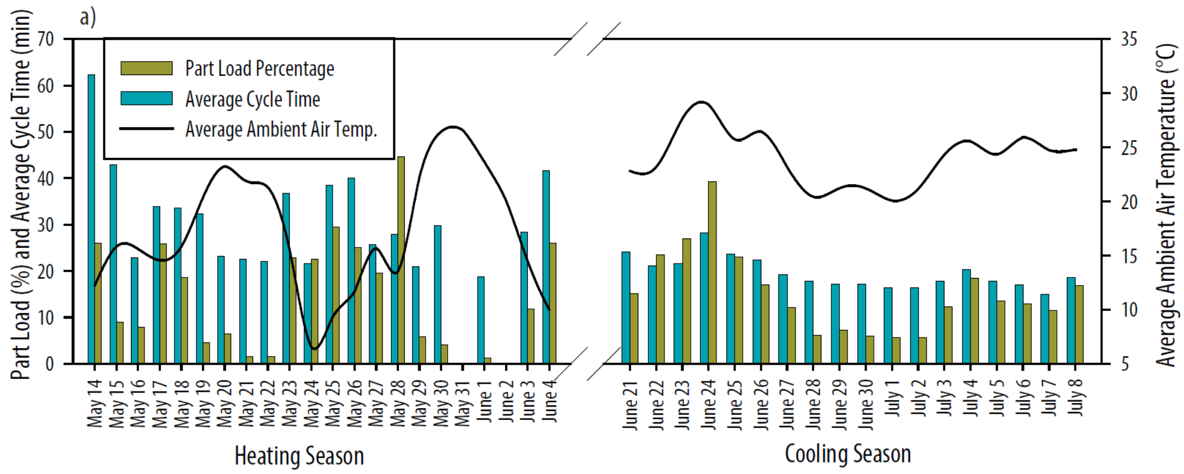


Figure 90: Daily Percentage of Cycled Time and Average Cycle Time for both Heating and Cooling Monitoring Periods

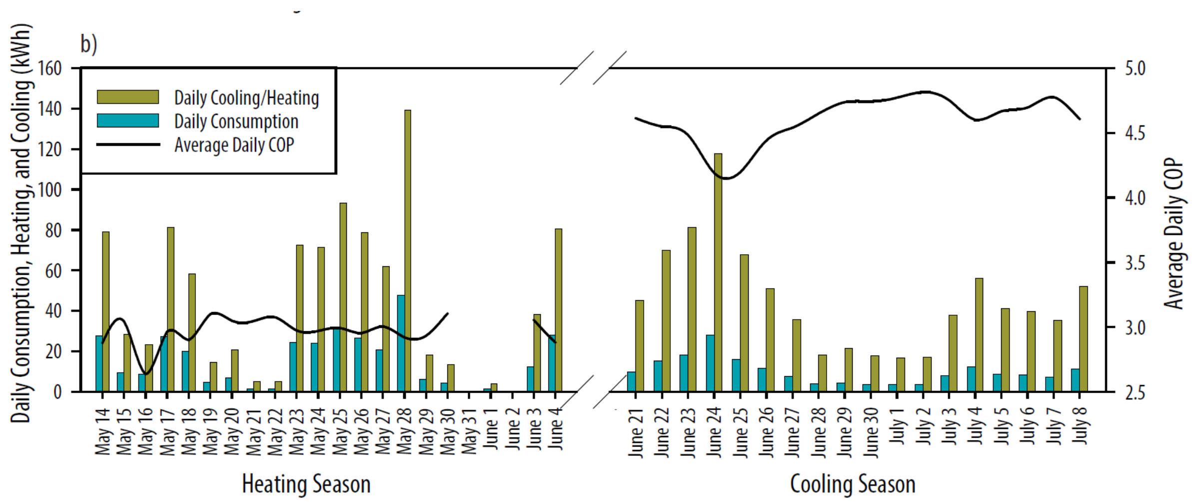


Figure 6. a) Daily percentage of cycled time and average cycle time for both heating and cooling monitoring periods. b)Daily total heat removed or delivered, total electricity consumed and COP for both heating and cooling monitoring periods.

Figure 91: Daily Total Heat Removed or Delivered, Total Electricity Consumed and COP for both Heating and Cooling Monitoring Periods

In Ontario, the average cost of a geoexchange system with a closed vertical ground loop was found to be $8,132 per ton. That means that a 3.5 ton system may cost up to $28,462 with use of a vertical loop. The study also found although single-lot geoexchange systems have relatively high implementation costs, the cost of vertical could be substantially reduced if several adjacent systems are constructed at the same time. This is often the case for new subdivisions designed to condition homes by geoexchange. Furthermore, based on current electricity generation sources in Ontario, the study found that a similar sized geoexchange system would reduce annual greenhouse gas emissions by 3549 kg eCO_2. This equates to 15.3 kg eCO_2/m^2 in the home.

This study evaluates the performance of a ground source heat pump (GSHP) system as part of a heating and cooling distribution systems in a semi-attached house located in Vaughn, Ontario. In relation to applying this GSHP to an urban environment like Toronto, geological and thermodynamic investigations would need to occur onsite of the proposed location, taking into account rock properties, groundwater saturation, temperature profiles, soil stability and thermal diffusivity before a vertical or horizontal ground loop could be installed.

GSHP Case #15: Performance analysis of ground water-source heat pump system with improved control strategies for building retrofit[83]

Study Details	
Purpose	This paper presented a case study and performance analysis of ground water-source heat pump system (GWHP) for a hotel building retrofit.
Location	Wuhan, Hubei, China
Model	MWH-020 McQuay Ground Water Source Heat Pump
Specifications	This system consisted of the GWHP system, an indoor air-conditioner system and a data acquisition system. The GWHP system included two MWH-020 type GWHP units and two circulating pumps. The underground water source for this air-conditioner system came from three pumping wells around the building, 23.6 m depth and 450 mm diameter.
Parameters	The total building area is 2200 m^2 and total air-conditioning area is 1862 m^2. There are eight floors in this hotel building. The cooling and heating load of this hotel are 208 kW and 170 kW, respectively.

In this study, a GWHP system for cooling/heating purpose and sustaining hot water supply was designed for a hotel located in Wuhan, China (Figure 92). An energy analysis was performed in order to evaluate the efficiency of the GWHP system in a commercial sized building. Energy analysis was performed by tests with the cooling period for the hotel designated from June to September and the heating period from November to February. The performance of this GWHP system was tested from June 1st to August 31st in 2012 (summer test) and from December 20th to February 18th in 2013 (winter test).

The unit COP was defined by power consumption of heat pump unit, which includes the compressor and fans for the heat exchangers. The system COP is defined by the power consumption of the system, which includes power consumption for a heat pump and pumping power. The COP of the units and system varied from 2.17 to 9.45 and 1.38-5.52 respectively during the cooling season. The COP of the units and system varied from 2.24 to 7.66 and 1.33-5.69 respectively during the heating season. Since the COP of the units varied widely, the system required significant re-configuring to control the temperature of the water flowing through heat pump.

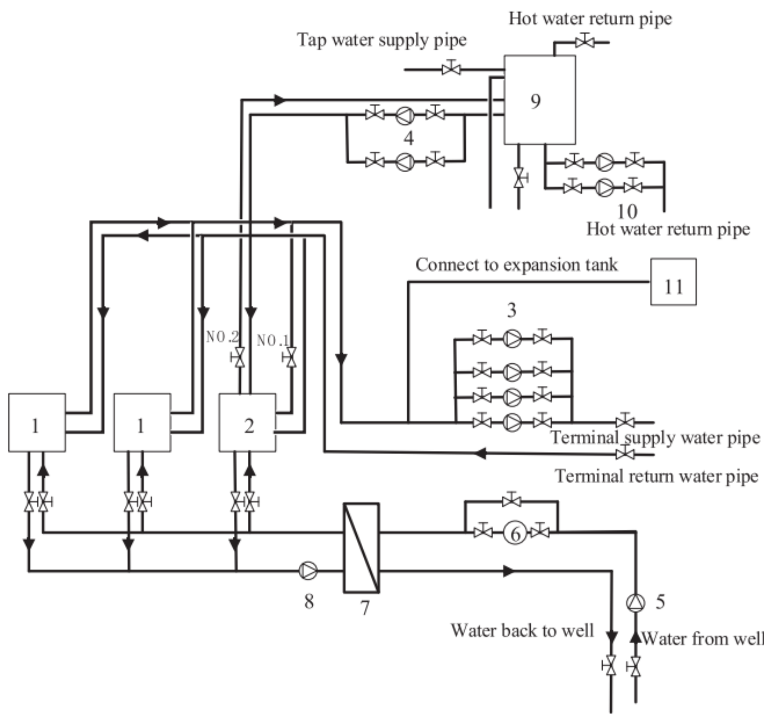


Figure 92: Schematic of the GWHP system used in the study, 1 GWHP Unit, 2 Hot water GWHP unit, 3 Terminal Circulating Pump, 4 Hot Water Circulating Pump, 5 Submerged Pump, 6 Desander, 7 Plate Heat Exchanger, 8 Circling Pump, 9 Hot Water Tank and 10 Hot Water Supply Pump

Table 93: Comparing the Performance Data during the Heating and Cooling Season

	Cooling Season	Heating Season
Testing Dates	June 1st to August 31st, 2012	December 20th to February 18th, 2013
Testing Outdoor Temperature Ranges (°C)	21-35 °C	-1 – 10 °C
System Coefficient of Performance	1.38-5.52	1.33-5.69
Unit COP	2.17 to 9.45	2.24 to 7.66
Manufactured COP	3.7*	4.0**

*Cooling Ambient temp. : 27°C DB / 19°C WB Water In: 30°C Water Out: 35°C

**Heating: Ambient temp. 20°C Water In: 20°C

The temperature and relative humidity profiles for each of the cooling and heating seasons are provided below. During the heating season, testing temperatures reached below zero, with the COPs on these days reaching the lowest values compared to any other day during the testing season. The COP values are illustrated in Figure 95 and 96. This is to be expected due to the extra work involved to absorb the same amount of heat from a cooler heat source.

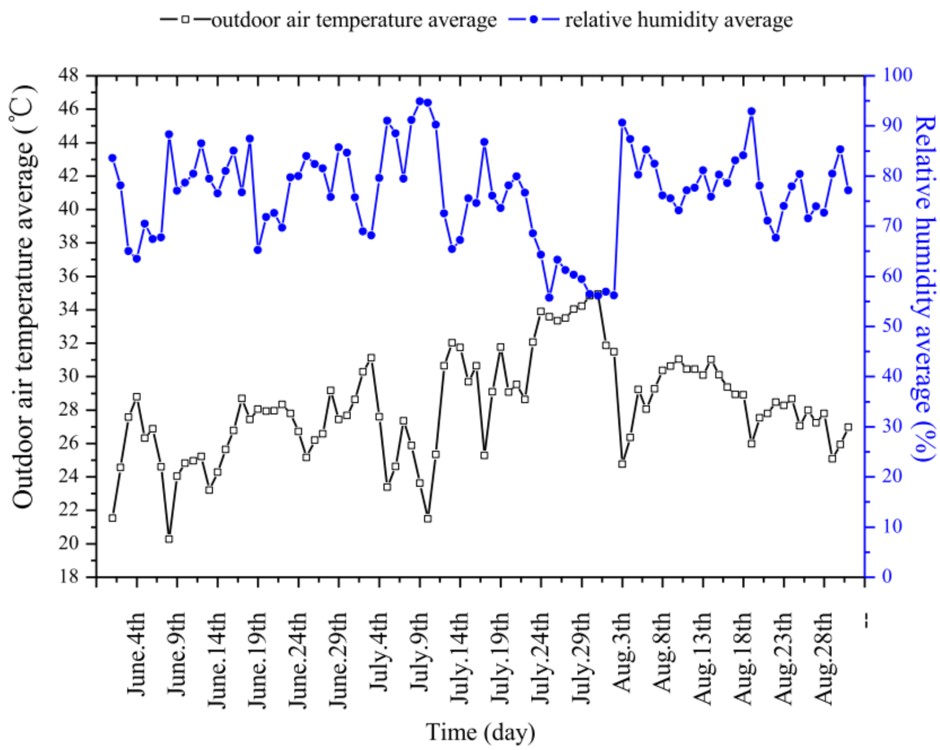


Figure 93: Weather Profile for Testing during the Cooling Season

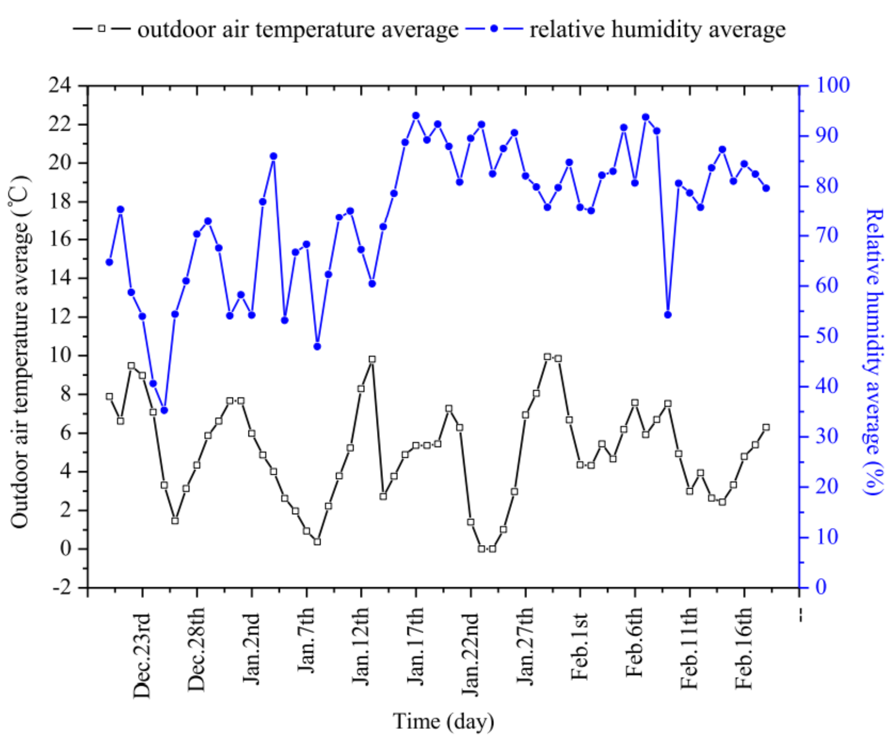


Figure 94: Weather Profile for Testing during the Heating Season

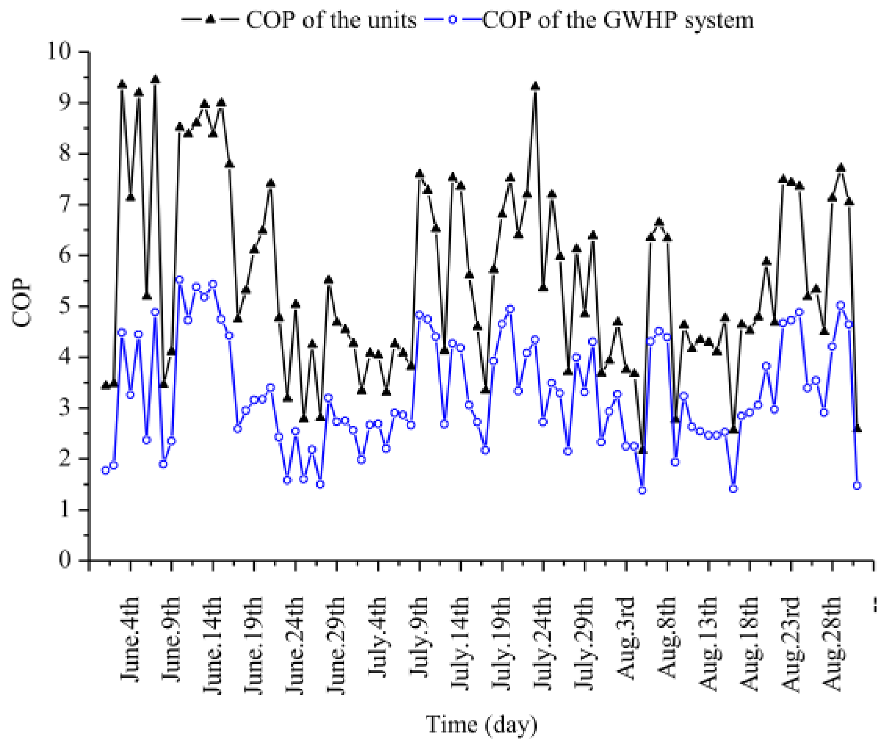


Figure 95: COP of Units and System during the Cooling Season

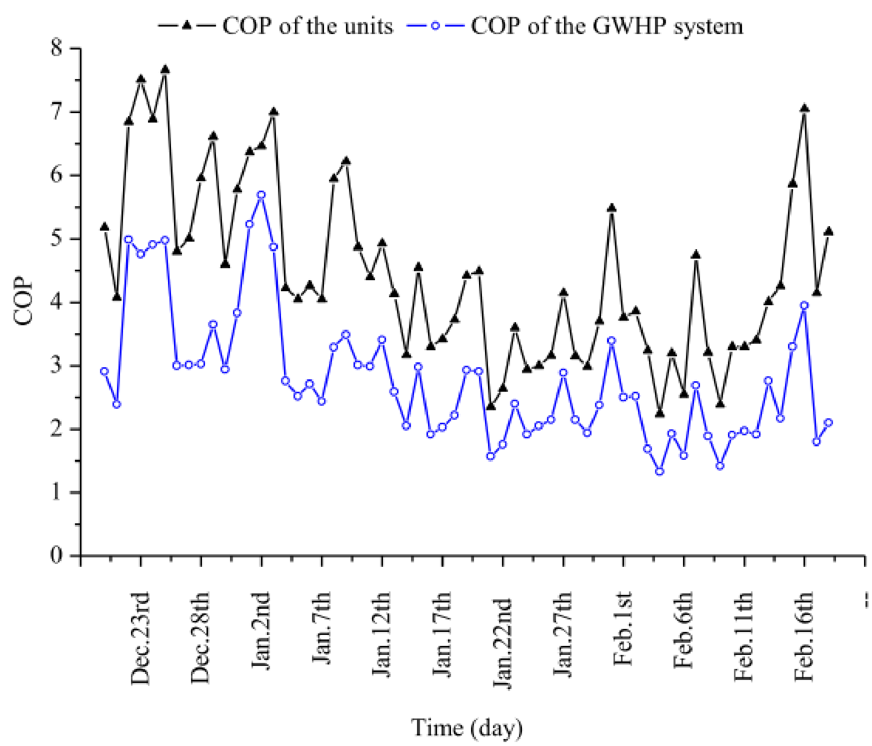


Figure 96: COP of Units and System during the Heating Season

The saving energy percentage of the GWHP system compared with original cooling/heating system was calculated using the following equation:

SEP = (CEo – CEg) / CEo

Where SEP is saving energy percentage (%), CEo is primary energy consumption of original cooling/heating system, CEg is primary energy consumption of GWHP system. The total saving energy percentage of GWHP system was found to be 42.9% compared with original cooling/heating system. Table 94 below outlines the parameters used for the saving energy percentage. The table below outlines the energy consumption and calculated savings from installing the GSHP for the hotel retrofit.

Table 94: Comparing the Cost Savings from the Original Heating/Cooling System to the Installed GSHP

Technology	Cooling Season Energy Consumption	Heating Season Energy Consumption	Total Primary Energy Consumption	Saving Energy Percentage (%)
Original heating/cooling system*	118,800 kWh (electricity)	170.3 t (coal)	48.12 tce	--
GWHP system	47,850 kWh (electricity)	20,152 kWh (electricity)	27.47 tce	42.9%

*Original heating/cooling system consisted of a splitting air-conditioner for cooling and coal fired boiler for heating

Wuhan, China is located in a cooling-dominant area with hot summers and cold winters. Monthly average temperatures range from 3.7°C in January to 28.7°C in July. However, the region has experienced extreme temperatures ranging from -18.1°C to 42°C. Thus, the temperature ranges are applicable to the Toronto climate. The study also investigated the applicability of retrofit GSHPs in an 8 floor multi-unit building, thus the research found is most definitely applicable to urban environments like Toronto, particularly with MURBs. In relation to applying this GSHP to an urban environment like Toronto, the researchers recommended this study for designers applying GWHP technology to building retrofits. As has been stated with many of the ground sourced heat pump designs, geological and thermodynamic investigations would need to occur onsite of the proposed location, taking into account rock properties, groundwater saturation, temperature profiles, soil stability and thermal diffusivity before any vertical or horizontal water sourced loops could be installed in addition to several subsurface groundwater usage permits. Although not directly discussed in the study, the replacement of the coal based boiler to heat the hotel will most definitely will reduce emissions in the coming years.

GSHP Case #16: Feasibility of combined solar thermal and ground source heat pump systems in cold climate, Canada[84]

Study Details	
Purpose	This study examined the viability of hybrid ground source heat pump (GSHP) systems that use solar thermal collectors as the supplemental component in heating dominated buildings. TRNSYS, a system simulation software tool, was used to model yearly performance of a conventional GSHP system as well as a proposed hybrid GSHP system.
Location	Milton, ON, Canada
Model	Atlas AT060
Specifications	An 18 kW (5 tonnes) water-to-air ground source heat pump with desuperheater. Three flat-plate solar thermal panels (Enerworks) connected in series with the total area of 6.81 m^2 (73 ft^2), installed at 45◦ angle. A 0.22 m^3 (60 US gal) hot water tank, Rheem 620 T, with 2×4.5 kW electric heaters. Power-pipe grey water heat recovery model R3-60. It consists of copper tubes wrapped around copper drain pipe. Venmar Vane 1.3HE heat recovery ventilator (HRV). An air to-air HRV with 62 L/s (130 cfm) capacity. The ground heat exchanger (GHX) system consists of four vertical closed loop circuits, joined in parallel. Each borehole has 0.25 m (10 in.) diameter and 55 m (180 ft.) length. They are located in the backyard in 3.6 m (12 ft.) apart from each other and merge at 1.8 m (6 ft.) below grade area.
Parameters	The house was one of the two energy efficient demonstration houses built by a local builder in 2005. The house is a detached 498 m^2 (5360 ft^2) two-storey building.

The purpose of this study is to evaluate the performance and viability of hybrid geothermal heat pump systems with solar thermal collectors. The main objective of this work was to perform system simulation approach to assess the feasibility of this kind of hybrid systems in heating dominated buildings comparing the new system to only a ground source heat pump. An actual residential building was modelled with the results compared to the actual data that were collected by monitoring the related operation of equipment through specific testing phases.

The study found that hybrid ground source heat pump system with solar thermal collectors could be a feasible choice for space conditioning of heating-dominated houses. For the house in this study, the seasonal solar thermal energy storage in the ground of the hybrid system was sufficient to offset large amount of ground loop heat exchanger length that would have been required in conventional ground source heat pump systems. The economic benefits of such system depend on climate, borehole drilling cost, as well as interest rate. Schematics of the solar assisted ground source heat pump (SAGSHP) design and the ground loop layout are provided below (Figure 97 and 98).

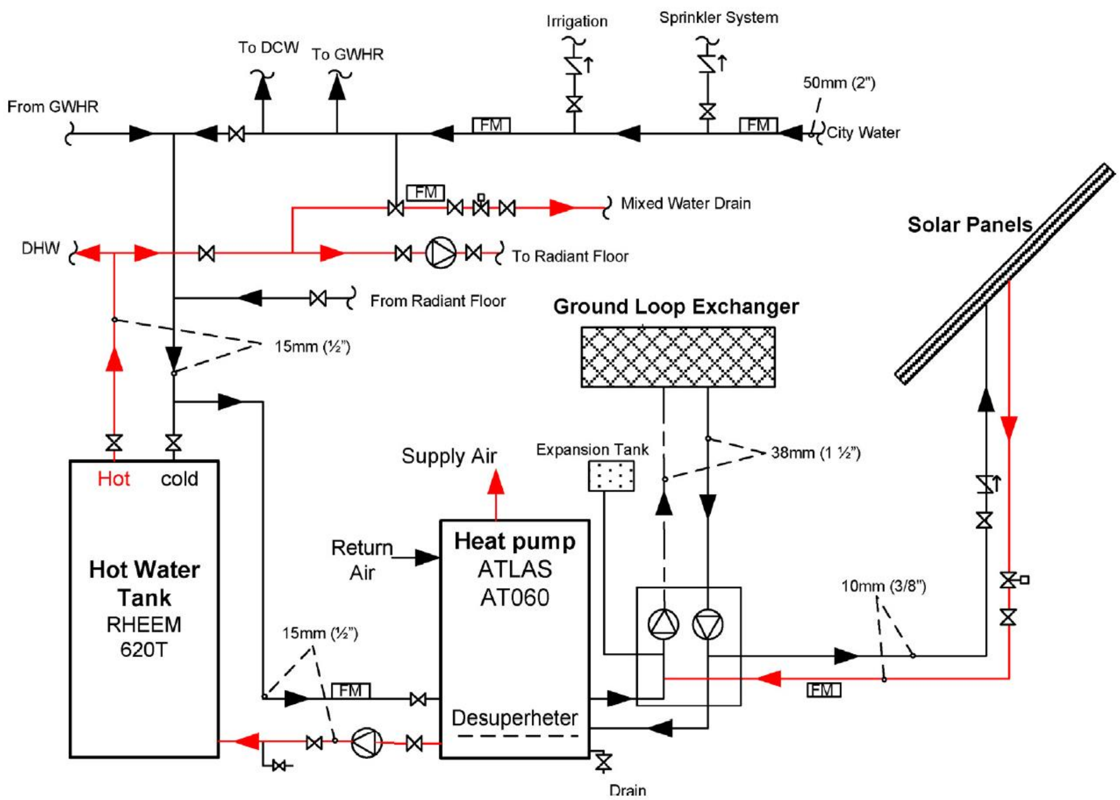


Figure 97: Schematic of the Solar Assisted Ground Source Heat Pump

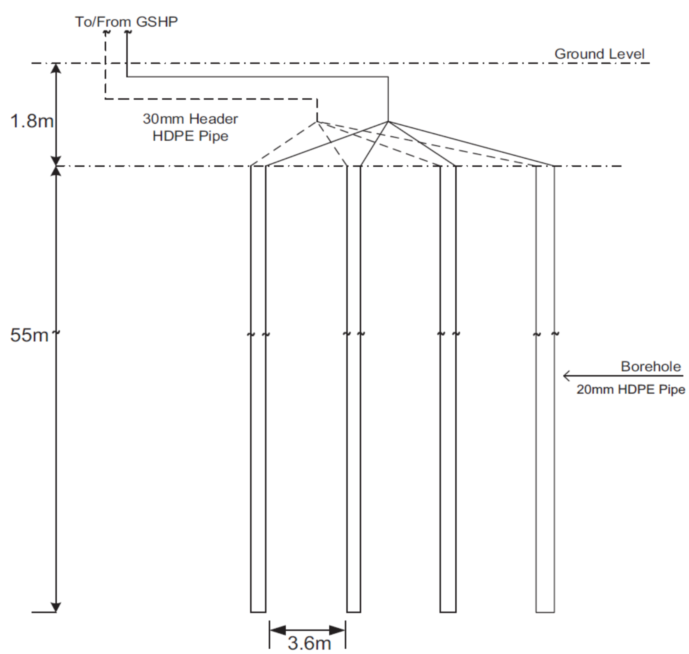


Figure 98: Schematic of the Ground Loop Layout

The ground heat exchanger (GHX) system consisted of four vertical closed loop circuits, joined in parallel. Each borehole had 0.25 m (10 in.) diameter and 55 m (180 ft.) length. They are located in the backyard in 3.6 m (12 ft.) apart from each other and merge at 1.8 m (6 ft.) below grade area shown above. The ground heat exchanger loop is connected in parallel to the solar thermal collectors. Solar collectors are connected in series. The solar collectors receive a percentage of the total flow from the ground loop exchanger. There are two circulation pumps that are part of the heat pump system and they are located at upstream and down-stream of ground heat exchanger.

In terms of annual heat pump performance, Table 95 outlines the field measurements collected for both the SAGSHP and GSHP in addition to the manufactured data reported.

Table 95: Performance Data Obtained for the Standard GSHP System and Solar Assisted Hybrid Design

				COP			Entering Fluid Temperature (°C)		
Season	Testing Dates	Temp. Modes Set	Input Water Temp.	GSHP No Solar Collector	SAGSHP Solar Assisted	SAGSHP Manufact-urer Unit (Atlas AT060)	GSHP No solar collector	SAGSHP Solar Assisted	SAGSHP Manufact-urer Unit (Atlas AT060)
Heating	Oct-April	19 °C	12 °C	2.7	2.78	3.9	8.49°C	10.04°C	0°C
Cooling	May-Sept	21 °C	2.5 °C	7.59	7.54	--	41.37°C	42.12°C	--
Cooling EER		--	--	--	--	15.6	--	--	25°C

In relation to the cost, the study conducted a life-cycle cost analysis taking into account the ground loop heat exchanger installation, the solar collector costs, electricity rates in Toronto as well as current interests compounded annually over a 20 year period. A summary of the costs used can be found in the table below.

Table 96: Data Values Used for Cost Calculations

	Ground loop heat exchanger installation	Solar Collector	Electricity Rate for Toronto	Interest Rate
Cost	$29.00/m	125/m^2	$0.10 per kWh	6%

Table 97: Net Present Value of Hybrid Solar-Ground Source Heat Pump System

Solar Collector		GLHE	Cost Analysis				
			Initial Cost		Operation Cost		
No. of Panels	Area (m^2)	Total Length (m)	Solar Cost	GLHE and HP Cost	Annual Cost	Present Value	Net Present Value
0	0	380	$0	$19040	$2050	$23514	$42,554*
0	0	220	$0	$13760	$2330	$26721	$40,481
3	6.81	188	$851	$12704	$2330	$26723	$40,278**
6	13.62	172.8	$1703	$12202	$2334	$26776	$40,681
9	20.43	150	$2554	$11450	$2337	$26804	$40,807
12	27.24	135	$3405	$10955	$2335	$26786	$41,146

*Standard GSHP
**Identified in study as the optimum balance between the GLHE size and solar collector size

A 20-year life-cycle analysis of the system (Table 97) showed only small economic benefit for the hybrid system compared to the system with only a GSHP. This was due to the low borehole drilling cost of $33/m. At the time of study the borehole drilling costs were estimated to be in the range of $29/m to $39/m for different ground conditions. However, for the case of higher drilling costs the economic benefits would be considerable, because of the 15% reduction of GLHE length due to the three solar collectors.

Table 98: Comparing System Performance for Toronto Climate

	Solar Collector		Ground Loop Heat Exchanger			Annual System Energy	
	# of Panel	Area (m^2)	Length (m)	4 Boreholes/length (m)	Min. EFT (°C)	Heating (MJ)	Cooling (MJ)
GSHP	0	0	220	55	1	44,793	6434
SAGSHP	3	6.81	180	45	0	44,749	6631

Conclusions

In relation to the viability of the system, the result of this study have shown that the hybrid ground source heat pump system combined with solar thermal collectors is a feasible choice for space conditioning for heating-dominated houses and is possible in the Toronto region. For the house in this study, the seasonal solar thermal energy storage in the ground in the hybrid system was sufficient to offset large amount of ground loop heat exchanger length that would have been required in conventional GSHP systems. However, the overall economic benefit of such system depends on climate, as well as current borehole drilling cost associated with many ground source heat pump installations.

GSHP Case #17: Performance of Ground Source Heat Pumps in Manitoba[85]

Study Details	
Purpose	This study monitored ten homes over an extended period during all heating, cooling and shoulder months to determine the average Seasonal Coefficient of Performance (SCOP) and Seasonal Energy Efficiency Ratio (SEER) of typical heat pump systems operating in an "as-installed" environment.
Location	Various locations in Manitoba: one test site in northern Manitoba, one test site in central Manitoba, eight test sites in southern Manitoba (mix of urban and rural). See map below.
Model	Six different heat pump brands were monitored; manufacturers and model numbers were not disclosed. Heat Pump Types: Five single stage units Five dual stage units Nine water to air units One water to air and water (combination) unit Six heat pumps were equipped with a brushless permanent magnet DC type fan motor Four heat pumps were equipped with permanent split capacitor fan motors (PSC motors) Loop Types: Three closed horizontal slinky loops One closed horizontal two pipe loops Four closed vertical loops One well to well system (open loop) One lake loop (closed)
Specifications	The ten homes monitored are a biased sample since most of the homes were volunteered for the project by experienced and established heat pump contractors and /or distributors that were contacted and nine of the systems were relatively new (less than three years old). The one older system in the study was the only open loop (well to well system) in the study.
Parameters	The intent of the site selection was to monitor various heat pump makes, models and loop configurations, in different geographic locations within Manitoba. It was also intended to monitor only heat pump systems that were designed and installed by established and experienced contractors. All units were equipped with the desuperheater option

Manufacturers of geothermal heat pumps have traditionally reported coefficients of performance (COP) of 3.1 to 4.0 and energy efficiency ratio (EER) of 14 to 24. These efficiency levels are based on instantaneous tests conducted under controlled conditions and do not consider all of the losses that may occur in an installed system operating in varying conditions.

This study presents the findings Manitoba Hydro has conducted with industry and other partners to determine the actual geothermal system performance over an entire heating and cooling season. Thus the goal of this study was to evaluate and monitor the measured performance values of "as installed" ground sourced working systems. Since Manitoba is a heating dominated climate there are concerns regarding the long term thermal performance of the ground loop. This study measured the annual energy imbalance that is placed on the ground loop due to heating, cooling, and hot water (desuperheater). The annual energy imbalance is calculated by subtracting the quantity of heat rejected to the ground from the quantity of heat removed from the ground loop in a one year period.

The table below outlines the available data on each of the test houses used in the study. In the published study, Appendix A: General House Descriptions was omitted; therefore the only available data on the models used is the type of ground source heat pump installed. Manufactured values (COPs, SEERs) were included in the analysis however; the company and model number was not disclosed. The map (Figure 99) below with corresponding red dots outlines the test sites.

Table 99: Housing Specifications for Each Test Site in Manitoba

Number	Ground Heat Pump Source Installed*
1	Well to Well
2	Lake Loop
3	Horizontal Loop
4	Vertical Loop
5	Horizontal Loop
6	Horizontal Loop
7	Vertical Loop
8	Vertical Loop
9	Horizontal Loop
10	Vertical Loop

*Specific model numbers, manufacturers and design parameters were omitted from the published study

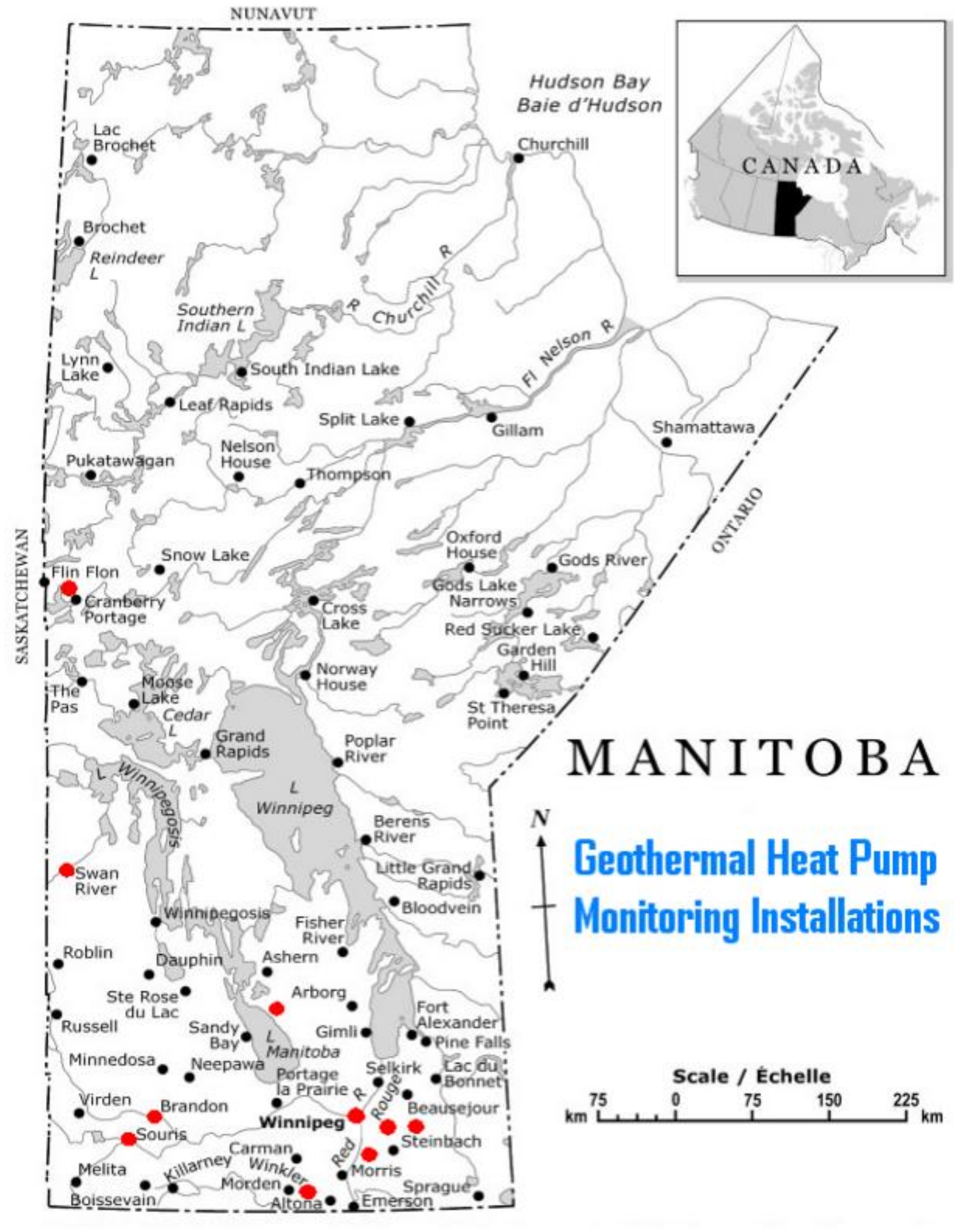
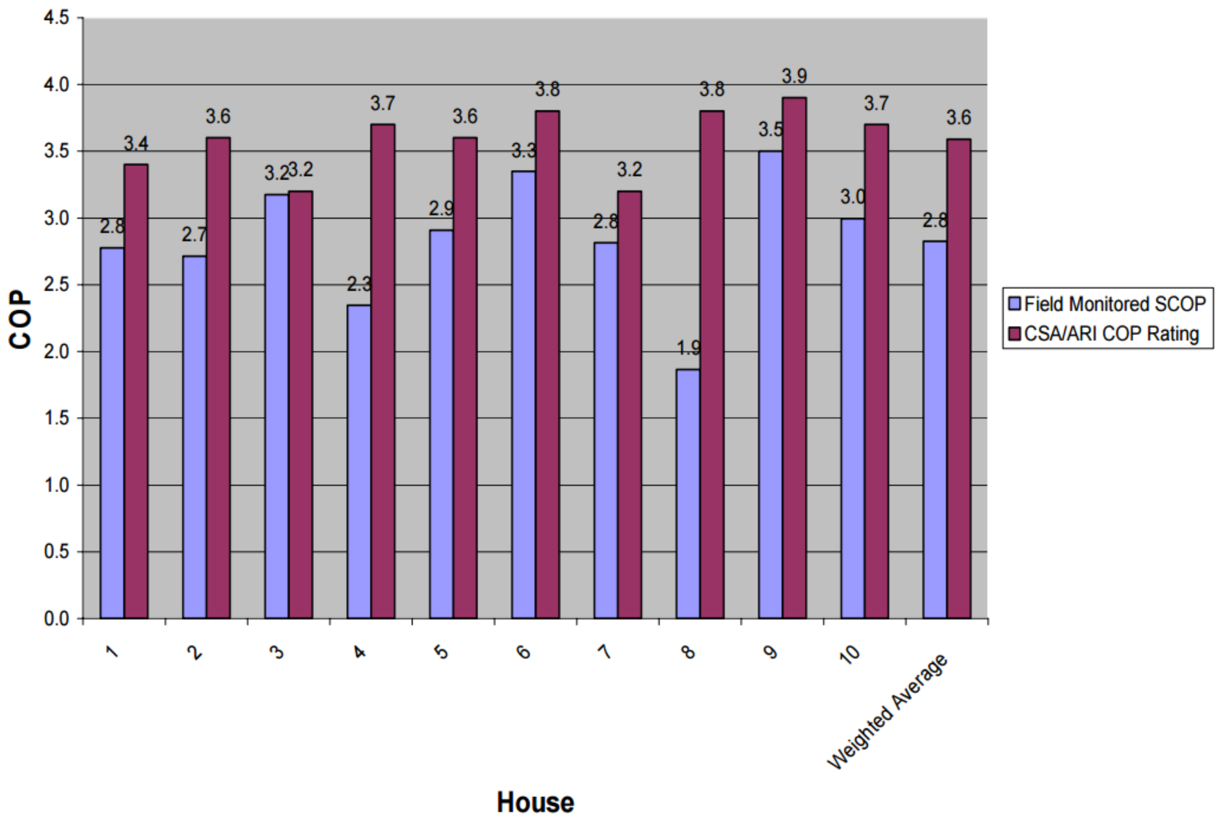


Figure 99: Map of Monitored Sites for Manitoba Hydro Study

Heating Season Performance Review

The manufacturers ARI (Air-Conditioning & Refrigeration Institute) and CSA (Canadian Standards Association) tested COPs ranged from 3.2 to 3.9 with an average COP of 3.6. The field monitored test data showed that the seasonal coefficient of performance (SCOP) during the heating season of the monitored ground source heat pump systems ranged from 1.9 to 3.5 with an average of 2.8 over a one year period (see Figure 57 below). SCOP is defined as the total energy (heat) delivered by the system divided by the total energy input to the system over one heating season.



1	Well to Well
2	Lake Loop
3	Horizontal Loop
4	Vertical Loop
5	Horizontal Loop
6	Horizontal Loop
7	Vertical Loop
8	Vertical Loop
9	Horizontal Loop
10	Vertical Loop

Figure 100: Field Monitored SCOP vs. Manufacturer's CSA/ARI COP

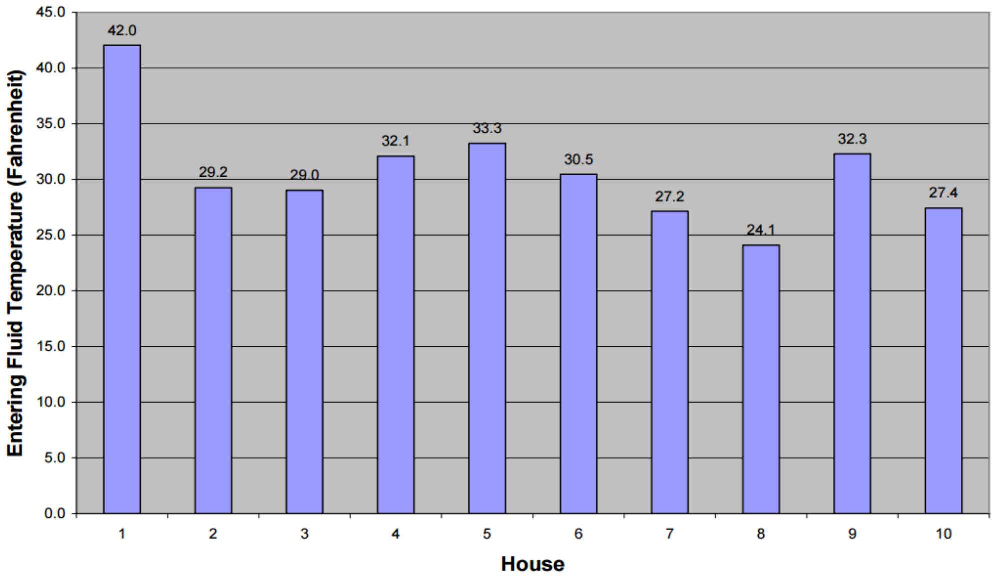
The actual seasonal performance of a ground source heat pump was expected to be lower than the manufacturer stated COP (COP based on CAN/CSA 13256 Test Standard “Water-source heat pumps-Testing and rating for performance”). According to the authors, this is because the test standard does not account for the energy consumed by an auxiliary heater that may be required, shortcomings in the actual system field installation and design, fluid pumping power required to overcome the external resistance of the ground loop heat exchanger piping, the standard includes for only internal resistance of the unit itself, the fan motor power required to overcome the external resistance of the connected ductwork, the standard only includes for the internal resistance of unit itself, any start-up and shut down cycling losses, variations in entering water temperatures, equipment malfunctions, variable homeowner operation and lifestyle, any lack of system maintenance (air filters etc.) and improper system commissioning.

Entering Fluid Temperatures

The closed loop systems operated with average annual entering water temperature of 36.0°F (4.2°C) which is slightly greater than the 32°F (0°C) temperature that is required by the CSA/ARI test. This should have resulted in slightly improved field performance figures for closed loop systems. Conversely the well to well system operated at an average annual entering water temperature of 44.9°F (7.2°C) which is slightly lower than the 50°F (10°C) temperature that is required by the CSA/ARI test. This should have resulted in slightly decreased field performance figures for the well to well system.

The weighted average annual entering fluid temperature for the nine closed loop systems ranged from 32.8 ° F to 39.5°F (0.4° C to 4.2° C) with a weighted average of 36.0° F (4.2°C) see Figure 101 below. This is just slightly greater than the 32°F (0 ° C) temperature that is required by the CSA/ARI test for closed loop heat pumps. The well to well system had a weighted average annual entering water temperature of 44.9°F (7.2°C) which is slightly lower than the 50°F (10°C) entering water temperature which is the test temperature requires by the CSA/ARI test for open loop systems. From information provided by several heat pump designers, most systems in Manitoba are designed with minimum entering water temperatures of 25°F to 30°F. (-4°C to -1°C) The actual minimum entering water temperature ranged from 24.1°F to 33.3°F (-4.4°C to 0.7°C) for the closed loop systems and 44.2°F (6.6°C) for the well to well system. The horizontal loops provided the highest entering water temperatures. All of the vertical loops were drilled in overburden ranging from 50 to 200 ft. deep.

Entering fluid temperature data collected during the study period (Figure 101) were within reasonable design parameters. However, the closed systems being monitored were still relatively new, between one and three years old. This study does not provide enough data to determine the sustainability of long term loop and system performance.



1	Well to Well
2	Lake Loop
3	Horizontal Loop
4	Vertical Loop
5	Horizontal Loop
6	Horizontal Loop
7	Vertical Loop
8	Vertical Loop
9	Horizontal Loop
10	Vertical Loop

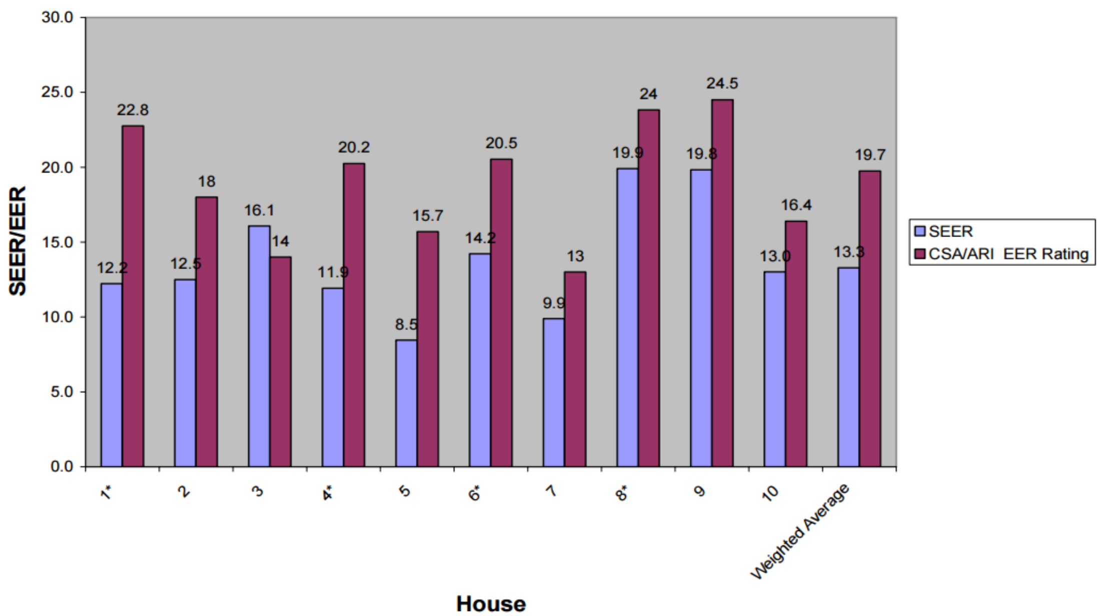
Figure 101: Minimum Entering Fluid Temperature (Heating Season)

Cost Savings for Heating Season

The heat pump systems provided 6,855 to 42,277 kWh of heating energy to the homes. The average quantity of heating energy provided to the 10 homes was 24,523 kWh85. Average annual electricity savings of 15,842 kWh during the heating season equates to $998 (based on April 1, 2009 PUB approved Manitoba Hydro Residential Electricity Rates) when compared to electric resistance heat. This annual savings amount would be reduced to $578 when compared to a high efficiency natural gas furnace (natural gas prices based on May 1, 2009 PUB approved Manitoba Hydro Residential Natural Gas Rates and includes the Basic Monthly Charge of $13/month).

Cooling Season Performance Review

The ground source heat pump CSA 13256 test standard "Water-source heat pumps- Testing and rating for performance" rates cooling efficiency by an Energy Efficiency Ratio. Similar to the COP ratio, the EER is an instantaneous test based on specified conditions. Central split air conditioning systems which are the most common residential cooling systems in Manitoba are rated by SEER (Seasonal Energy Efficiency Ratio). The SEER rating is supposed to provide a customer with a more accurate value to compare operating costs between units over an entire cooling season. The current minimum SEER rating for a central air conditioner is 13. The test data showed that the field monitored Seasonal Energy Efficiency Ratio (SEER) during the cooling season for these ground source heat pump systems ranged from 8.5 to 19.9 with an average of 13.3 over the 2007 cooling season. SEER is defined as the total energy (heat) removed by the heat pump system (Btu's) divided by the total energy input to the system (watt hours) over one cooling season. The weighted average manufacturer rated EER of the ten units included in this study is 19.7 based on the CSA 13256 test standard (see Figure 102 below).



* CSA/ARI EER Ratings for two stage units is a weighted average of the part load and full load ratings based on actual compressor part load and full load run hours (cooling mode).

1	Well to Well
2	Lake Loop
3	Horizontal Loop
4	Vertical Loop
5	Horizontal Loop
6	Horizontal Loop
7	Vertical Loop
8	Vertical Loop
9	Horizontal Loop
10	Vertical Loop

Figure 102: Field Monitored SEER versus ARI/CSA EER Rating

Similar to COP, the SEER of a ground source heat pump will generally be lower than the manufacturer's stated EER (EER based on CAN/CSA 13256 Test Standard "Water-source heat pumps-Testing and rating for performance"). This is due to the fact the test standard is an instantaneous test that does not include cycling losses, may not reflect actual system installation and design, only includes the fluid pumping power required to overcome the resistance of the unit itself (not the bore field piping), only includes the fan power required to overcome the resistance of the unit itself (not the connected ductwork), does not account for variations in entering water temperatures, does not account for variable homeowner operation and does not account for lack of system maintenance.

Cost Savings for the Cooling Season

The average annual electricity consumption for these units during the cooling season was 772 kWh ($49). The estimated average annual cooling savings compared to a central air conditioner with a SEER of 13 is 17 kWh was $1. This may not be fair comparison since the assumed SEER of 13 for central air conditioners is at test conditions and may not reflect the actual field performance of these units. Actual field performance of conventional central air conditioners could also be expected to be lower than laboratory test results which could increase the potential cooling savings.

Table 100: Cost Savings Review for both the Cooling and Heating Season

Cost Savings for Each Season		
Parameter	Heating	Cooling
Average annual electricity consumption	24,523 kWh	772 kWh
Savings	15,842 kWh ($998)	17 kWh ($1)*

*compared to a central air conditioner with a SEER of 13, at test conditions and may not reflect the actual field performance of these units

The results of this study indicate that there are potentially significant energy savings in a Manitoba climate when utilizing a ground source heat pump compared to electric resistance heat. Annual energy savings estimates for a ground source heat pump compared to electric heat should utilize an estimated Seasonal Coefficient of Performance (SCOP) instead of the ARI/CSA certified steady state COP. The estimated SCOP can be calculated by accounting for the additional fan, pump, and auxiliary heater electricity requirements that are not included in the CSA/ARI test standard. The cooling season savings when compared to a new central air conditioner does not appear to be significant. The major benefit for a ground source heat pump compared to a central air conditioner is that the unit itself is indoors and not exposed to the outdoor elements.

Appendix C - Gas Absorption Heat Pump (GAHP) Review

GAHP Case #1: Robur Gas Absorption Heat Pump, Ground Source (2013)[86]

Study Details	
Purpose	To compare the field vs. manufacture lab* heating efficiency of Robur Gas Absorption Heat Pumps (GAHP) , Ground Source
Location	Germany
Model	Robur Ground Source Gas Absorption Heat Pump (GAHP) – Specific Model Not Specified
Specifications[87]	Performance Range: Max: -15°C to 45 °C Up to 40.9% utilization of ground source renewable energy, exceeding peak Efficiencies of 169% (Equivalent to COP 4.23 on energy conversion factor of 2.5.) Suited for: Multi-family homes as well as tertiary and commercial buildings -especially existing buildings, where natural gas is by far the most popular source of energy.
Parameters	Tested at the German Engler-Bunte-Institute (EBI) of the Karlsruhe Institute of Technology (KIT) by the HLK Stuttgart GmbH, IGWP - Initiative Gaswärmepumpe - Gas Heat Pump Initiative* System temperature in study: 45 °C - 55 °C

*Lab data provided by Robur is measured according to The Verlag des VereinsDeutscherIngenieure (VDI) and is the simplified method for the calculation of the annual coefficient of performance (COP) and the annual utilization ratio of sorption heat pumps - gas heat pumps for space heating and domestic hot water.

Compared to a boiler, the GAHP primary energy savings and CO_2 reductions are up to 27%.It also allows for the use of more renewables such as biogas, which can be replaced for natural gas. A condensing gas boiler using 20% biogas is shown to produce 9.88 kg CO_2/a, while a ground source heat pump also using 20% biogas will produce 8.23 kg CO_2/a (Figure 103).The performance data was given in the format of heating efficiency per year. The numeric value for heating efficiencies and COP's are interchangeable, therefore COP's are reported. As shown in the performance table (Table 101) below the manufacture lab data measured according to VDI 4650-2 is 1.47. Field data seemed reasonably in line with manufacturer lab data.

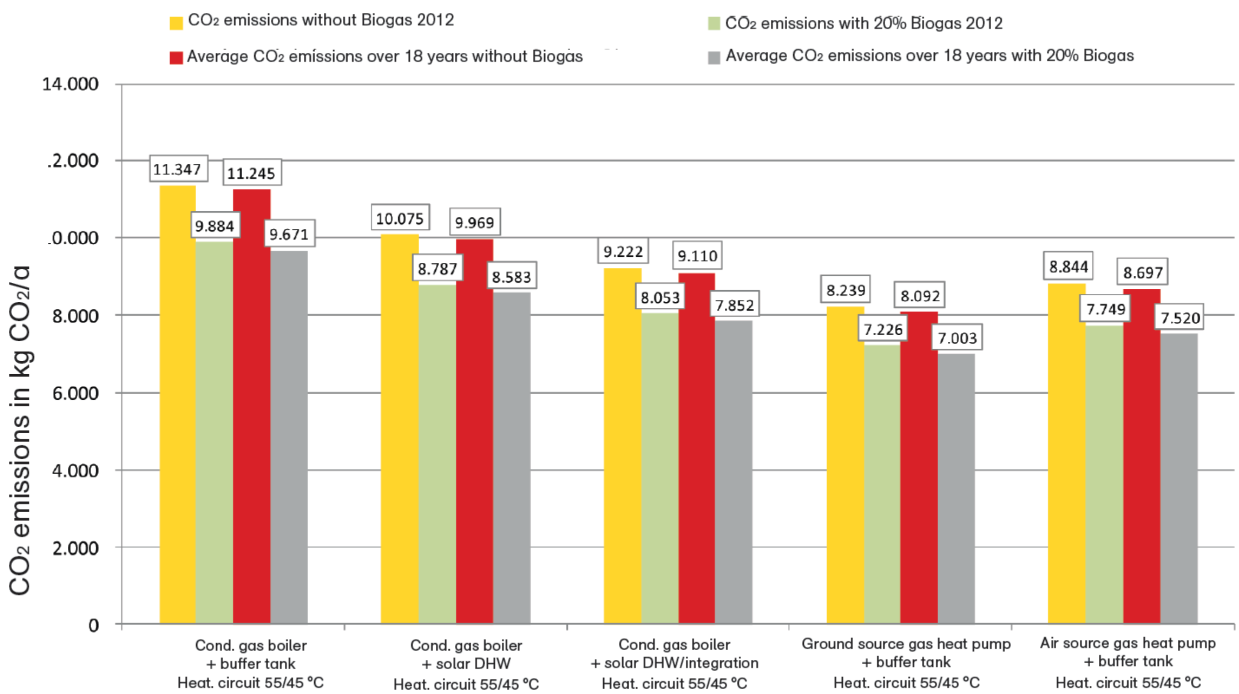


Figure 103: CO_2 Emissions Robur GAHP in Comparison to Condensing Versions with/without Solar Heating (Refurbished 6-FH)

Table 101: Gas Utilization Efficiency (GUE) Data Reported as COP for GAHP – Ground Source

Manufacturer Data	1.47
Field	1.41

The study done by IGWP - Initiative Gaswärmepumpe - Gas Heat Pump Initiative has information on heating efficiency (COP), calculated manufacture data, field data and CO_2 emissions. However, the study only gives heating efficiencies per year and fails to mention COP's at different temperatures. Also, the study does not provide specific information on ease of retrofit with ground source gas absorption heat pumps or any relevant costs. Generally, ground-source heat pumps are expensive to install because boreholes need to be drilled so that the heat exchanger piping can be placed vertically or trenches need to be dug out so that the piping that carries the heat exchange fluid can be placed horizontally. The ground source gas absorption heat pump uses a water-ammonia solution instead of an environmentally harmful refrigerant.

Conclusions

The study by IGWP provided the heating efficiency per year for ground sourced Robur gas absorption heat pumps. Field tests generally confirmed the reliability of Robur GAHPs as well as overall customer satisfaction. The efficiencies measured under practical conditions reveal the potential of this technology as the field data was only slightly off the manufacturer data. Using a natural gas absorption heat pump allows incorporation of renewable sources of energy such as biogas.

GAHP Case #2: Gas and Renewable Energy, Field Test of Robur Gas Heat Pump, Air Source (2013)[88]

Study Details	
Purpose	To compare the field vs. manufacture lab* heating efficiency of Robur Absorption Heat Pumps (GAHP) – air source
Location	Limhamn, Sweden
Model	Robur Air Source gas Absorption Heat Pump (GAHP) – Model: E^3A
Specifications[87]	Electrical power use: 0.90kW
Parameters	Tested by the Danish gas companies' Technical Committee on Gas Utilisation and Installations (FAU GI) and Swedish gas companies through the Swedish Gas Technology Centre (SGC). System temperatures in study: Input source: 2-8°C, Output supply: 44-55°C Manufacturer stated temperature: Max: 40°C Min: -20°C Used in: Multi-family homes as well as existing tertiary and commercial buildings

For the purpose of this study, an old fire station now that is now being used as a day care centre for the disabled elderly in Limhamn, Sweden was examined (Figure 104). It is used during normal working hours on weekdays only. A pre-existing condensing gas boiler installed in 1986 is used for peak demand. The operation and performance were studied in a field test during 2012. The performance table below summarizes actual performance data from January 10, 2012 – February 1, 2013. The coefficient of performance (COP) that resulted from the test study was lower than the manufactured COPs.

Figure 104: Limhamn Old Fire Station now used for Day Care Activities

Table 102: Gas Utilization Efficiency (GUE) Data Reported as COP for GAHP – Air Source

	COP
Manufacture Lab Data	1.65*
Field	1.07

Note: 1.65* is the peak level of performance given by the manufacturer

The main observation is that the heat pump efficiency was not as high as anticipated. This is most likely caused by unsatisfactory integration of the gas heat pump and pre-existing gas boiler in the heating system. The data from the study was based on tests done by Danish Gas Companies' Technical Committee on Gas Utilisation and Installations (FAU GI) and the Swedish Gas Technology Centre (SGC). The study lacked communication on ease of retrofit, as it did not provide any information about retrofitting opportunities or challenges with air source gas absorption heat pumps. Generally, retrofitting air source heat pumps is relatively feasible since it requires only outdoor installation and minimal number of pipes for transporting the heat inside to the house. There is reliable safety with this heat pump because it is installed outdoors and it does not use any environmentally harmful refrigerants. The study does not effectively report environmental performance. It lacks information on energy savings, quantitative data on greenhouse gas emissions relative to conventional alternatives, environmental hazards such as noise and potential of leaks. However, according to another study which reports on Robur Absorption Air Source Heat Pumps, there are numerical values for CO_2 reductions. A condensing gas boiler using 20% biogas emits 9.88kg CO2/a, whereas the Robur air source gas heat pumps emits 7.7488kg CO2/a[86]. The study also fails to provide COP's at different temperatures. The input source considered by the study is that of 2-8°C. This is not ideal for Toronto's climate, as winter weather conditions in Toronto are frequently sub-zero.

As per the manufacturer, the cost per kWh of a Robur Gas Absorption Air Heat Pump is less than the electric heat pump by 0.98 cents per kWh[87]. It is less expensive to install a gas absorption air source heat pump than it is to install a gas absorption ground heat pump. The payback time for a well operating installation with 130% annual efficiency is estimated to be 6 years.

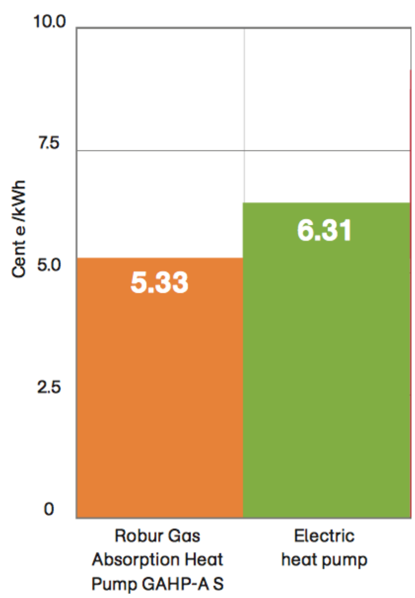


Figure 105: Cost in Cents e/kWh of a Robur Gas Absorption Heat Pump (GAHP-Air Source) and a Conventional Electric Heat Pump

After carrying out the study in an old fire station building, the results of performance efficiency were not as high as expected. Based on other GAHP studies, this study has a considerable variation from the manufacturer data and the field data. The building had an old pre-existing gas boiler, which was kept intact during the study. It is concluded that air sourced gas absorption heat pumps produce less CO_2 emissions than gas boilers. The authors hypothesize that the performance results were low because of unsuccessful integration of the air soured gas heat pump with the gas boiler. The cost of using gas absorption heat pumps will be less than electric heat pumps if the cost of natural gas in the geographical location of study is less than the cost of electricity.

GAHP Case #3: First North American Case Study: Geothermal Gas Fired Absorption Heat Pump (2008)[89]

Study Details	
Purpose	Due to the fact that natural gas absorption heat pumps, were commissioned in March 2007, this study focuses on reviewing the first-year performance of Robur Gas Absorption Geothermal Heat Pumps (GAHP) – water source
Location	Boucherville, Quebec, Canada
Model	Robur water Source gas Absorption Heat Pump (GAHP-W) – Model: Not specified
Specifications	Water source gas absorption heat pumps electrical power use: 0.41kW[2] In study electric use for space heating: 10 GJ (2,800 kWh)
Parameters	Tested by The Natural Gas Technologies Centre of Canada 5, 167-m deep wells were drilled to ensure that most of the energy required for space heating and the production of domestic hot water (160 kW) could be extracted from the ground through the use of three single-capacity (38 kW) absorption heat pumps (GAHP-W from Robur). Space heating system in study: 45°C for the duration of the heating season[90] Manufacturer stated information: Max: 45 °C Min: -15°C[87] Used in: A geothermal system was retrofitted into a 24-unit multi-residential building[90]

The first documented North American geothermal system, functioning with natural gas absorption heat pumps, was commissioned in March 2007. The performance has been provided based on the performance measured at Benny Farm between March 07 and April 08. Benny Farm is a neighborhood in Montreal that has been developed to provide housing for WWII veterans and their families. The system was commissioned in March 2007, but tenants started moving into the building only a year later. As of April 2008, the absorption heat pumps had operated a total of 7,600 hours. To meet the building space heating load during the heating season (October 1 to March 31), only one heat pump was necessary 52% of the time. Similarly, two or three heat pumps were sufficient to meet the demand 47.7% and 0.1% of the time, respectively. Hence, two heat pumps were sufficient to meet most of the space heating requirements during the 2007-2008 winter season (not counting hot water consumption). The space heating energy consumption from April 2007 to March 2008 was 960 GJ, 80% of which came from the burning of natural gas, 19% from the renewable geothermal source, and 1% from electrical power.

Figure 106: The Benny Farm Community and the 3 Installed Gas Absorption Water Source Heat Pumps

Table 103: Gas Utilization Efficiency (GUE) Data Reported as COP for GAHP – Water Source

	COP
Manufacturer Data	1.74
Field Data	1.25*

*125% gas utilization efficiency was the same throughout the heating season despite the ground temperature variation.

The study completed by Natural Gas Technologies Centre Canada is the first Canadian case study analyzing geo-thermal absorption heat pumps. The study includes performance data, but not manufacturer data. Manufacturer data was taken from another source. The study includes information about environmental performance and retrofits. Due to the fact that it's located in Montreal, it is applicable to Toronto. Since this was an initial study it is reported that, the biggest challenge to the implementation of natural gas absorption heat pumps into the North American market, is the lack of technology awareness and the relatively low level of knowledge on how to integrate it into space heating and domestic hot water systems.

In terms of CO_2 emissions, the study clarifies that what energy source primarily makes up the energy demand of the province is important before determining if natural gas absorption heat pumps produce less CO_2 emissions. In Canada, only provinces whose main electricity source is hydropower or nuclear power can claim that electrically driven heat pumps produce less GHG than natural gas absorption heat pumps in the heating mode. Indeed, the GHG emissions of electrically driven heat pumps in coal-dominated provinces are far greater than that of natural gas heat pumps.

Conclusions

According to the authors of the study, the results adequately met all the reliability and performance expectations. There was a 0.49 variation from manufacturer lab data and field data. After installing three water sourced gas absorption heat pumps, it was concluded that only 2 were needed to sufficiently meet the space heating requirements. If considering hot water needs, it is possible that more than 2 may be required. The 1.25 COP was stable despite the changes in ground temperature variation. The comparison of the emissions produced by the electric heat pump compared to a gas absorption heat pump must pay attention to the source of energy supply of that specific geographical location.

GAHP Case #4: State of the Art in Gas Driven Heat Pumps, Vaillant zeroTHERM + Solar Collectors (2013)[90]

Study Details	
Purpose	To examine 3 most common gas absorption heat pumps on the market
Location	Germany
Model	Vaillant zeroTHERM VAS 106/4 zeolite gas absorption heat pump; solar add on
Specifications[91,92]	Rated heat output range heating 1.5-10 kW Electrical power consumption max. 100 W Appliance width 772 mm Appliance height incl. flue outlet 1.700 mm Appliance depth 718 mm Transport weight (without casing) 160 kg Operating weight 175 kg *Model comes with a solar collector, which acts as the low temperature heat source and a water storage tank. In summer the solar collectors can provide domestic hot water. It is only intended for use with under floor heating systems. Although using the solar collector increases efficiency, it is possible to not it.
Parameters[89,92]	Tested by German ‘Initiative Gaswärmepumpe’ (IGWP): [Gas heat pump initiative] Solar circuit, temperature range: -20 to 80°C Primary circuit, temperate range: 5 to 127°C Manufacturer output temperature: 40°C. Field study output temperature: 28°C-55°C Under floor heating system in a single-family house, new-built/modern buildings with max 10 kW heating demand. Flexible indoor installation of zeroTHERM in basement, on floors or in the attic. Suitable roof for installations of solar collectors (min. 8 m^2). Floor heating or panel heating with flow temp. <40°C

Zeolites can be used as solar thermal collectors and for absorption refrigeration. Zeolites high heat of absorption and their ability to hydrate and dehydrate while preserving structural stability is exploited in the Vaillant zeroTHERM VAS 106/4 zeolite gas absorption heat pump[92]. The working agents of zeolite and water are non-toxic, non-combustible and environmentally friendly. The Vaillant system uses water as the coolant, zeolite as the adsorbent and consists of the heat pump itself, a solar collector that acts as the low temperature heat source and a water storage tank[93]. In summer the solar collectors can provide domestic hot water. It is only intended for use with under floor heating systems with maximum output temperature of 40°C[91]. Within the scope of the “Initiative für Gaswärmepumpen” (IGWP - Initiative for Gas Heat Pumps), a field trial was conducted over 29 sites in different geographical locations across Germany. The coverage of the installations was so that the heat pump can be analyzed in different situations and heating systems[93]. In locations with high levels of solar radiation the performance of the zeroTHERM heat pump system greatly improves. Vaillant zeolite heat pumps are able to provide an increase in efficiency of about 35% compared to a condensing boiler system[93]. Manufacture lab data and field data performance information consists of the zeroTHERM gas heat pump + solar thermal DHW. The field data is an example of the IGWP field study. From October 20-24th, 2011, 10 field test appliances were positioned all over Germany[93]. Data collected from there is used for the field study COP.

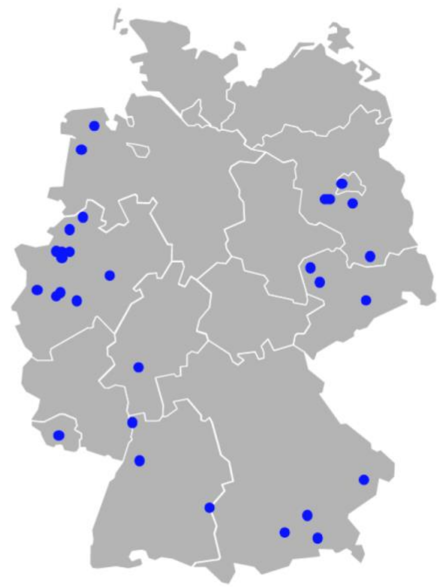


Figure 107: 29 Field Trial Appliances and 4 Laboratory Appliances of the zeroTHERM Vaillant in Germany

Table 104: Gas Calorific Value (GCV) Data Reported as COP for VAS 106/4 Zeolite Gas Absorption Heat Pump

Manufacture Lab Data	1.36*	
Field	At 45°C-55°C output temperature = 1.33*	At 28°C-35°C output temperature = 1.44*

*As aforementioned, manufacture lab data and field data performance information consists of the zeroTHERM gas heat pump + solar thermal DHW.

The Vaillant zeroTHERM VAS 106/4 zeolite gas absorption heat pump has information on environmental performance, temperature, cost and retrofit. The initial system sale price was around €16,000 (Euros) which is equivalent to CDN$21,734.49[92]. It is sold as a complete package with solar panels, solar water storage and solar pump ground[89]. It is recommended to install the zeroTHERM in a matched system, with bivalent solar storage tank for domestic hot water preparation, solar station and solar thermal collectors (flat or tubular)[93]. However it can also be integrated in an existing solar thermal system. Due to the compact design of the collectors and the flexible solar mounting systems for on- and in-roof installations, the zeroTHERM is easy installable and suitable for applications in both new build and retro fit. Although

Germany does not have a significantly high amount of sunlight days, it has become the world leader in solar power. To address the issue of this heat pump's applicability to the Toronto climate, it should be noted that on average, Ontario receives more sunlight than Germany. Therefore, if it can be used in Germany with success, a similar result can be predicted for Ontario as well.

Conclusions

The addition of the solar collector in this gas absorption heat pump increases efficiencies of performance. Since there is a negligible difference from the manufacture lab data and the field data, this technology is concluded to be reliable, robust and a smart option for a hybrid system. During the field study, it was concluded that the solar panels are of good use as there was found to be high solar radiation on the collectors[93]. When the system had to achieve an output temperate between 45°C-55°C, its COP was 1.338. However, then the system had to achieve an output temperature between 28°C-35°C it exceeded the manufacturer expectations and performed at a COP of 1.448. Therefore, costumer and manufacture expectations were completely met and in some cases exceeded.

GAHP Case #5: Buderus Luft-Wasser Gaswärmepumpe Logatherm GWPL38, Air Source (2013)[94]

Study Details	
Purpose	To significantly reduce the school's carbon footprint and simultaneously improve its overall heating efficiency by installing six Buderus Gas absorption heat pumps – GWPL38.
Location	North Hull, United Kingdom
Model	Buderus Gas absorption heat pump (GHAP) – GWPL 38 – Air source
Specifications[95]	Electricity consumption single unit: 1.09kW Max. gas consumption: 2.72m3/h Operating weight (single unit): 400kg Output single unit: 41.1kW Output cascade with two units: 82.2kW
Parameters	Tested at the new Endike Primary school located in North Hull, United Kingdom. Binks Building Services (BBS) (liased with Bosch commercial) managed installation, sourcing and procuring of the heating system. Study output temperatures: 35 °C - 50°C Manufacturer stated permissible ambient temperature: -20°C - 45°C Ideal for: schools, colleges, office developments, care homes, residential properties, leisure and sports facilities, where natural gas is by far the most popular source of energy. For installation outside on a flat roof or at ground level. Electricity consumption single unit: 1.09kW

The Endike Primary School in North Hull, United Kingdom has been on the same site for over 80 years, thus Endike Primary was selected for a development of an entirely new school with a significantly reduced carbon footprint as well as simultaneously enhanced overall heating efficiency by installing six Buderus Gas absorption heat pumps (model GWPL38), which draws energy from air. Sewell Group was the principal contractor on site who had to ensure the new building met the criteria of the BREEAM (Building Research Establishment Environmental Assessment Methodology) New Construction scheme. The BREEAM scheme is used to assess the environmental life cycle impacts of new non-domestic buildings. Binks Building Services (BBS) was appointed by Sewell Group to source, procure and manage the entire installation process of the heating system. BBS liaised with Bosch Commercial and agreed to install ix GWPL38 gas absorption heat pumps by Buderus. Based on the manufacturer GWPL38 GHAP has an efficiency of about 1.64 at 7°C and a heat output of about 38.3kW[95]. During the peak-freezing season (-7°C), the heat pump continues to work with an efficiency of about 1.25, with each single unit generating 31.5 kW of heating output. The efficiency was reported to be 1.25 at temperatures below freezing for both manufacturer and case study data. Based on the case study, the efficiency during peak heating season (7°C) is reported to be around 1.60.

Figure 108: New Endike Primary School Building where 6 GWPL38 Gas Absorption Heat Pumps have been installed

Table 105: Gas Utilization Efficiency (GUE) Data Reported as COP for GWLP38 GAHP

	COP	
Manufacturer Data	1.64 at 7°C	1.25 at -7°C
Case Study Data	1.60 at 7°C	1.25 at -7°C

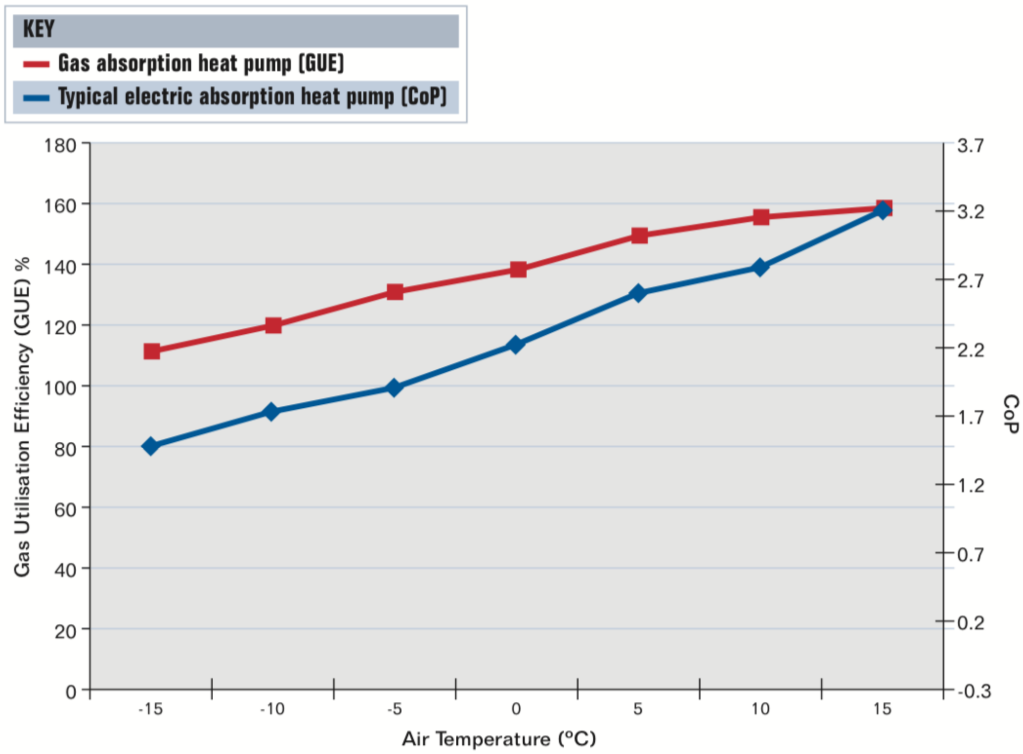


Figure 109: A Graphical Representation of COP Value in Accordance to GUE (%) Reported with Air Temperature

The GWPL38 GHAP manufacturer information and case study has information about emission and noise level and COP's at different temperatures. Its permissible ambient temperature of functioning is in the range -20°C to 45°C. -20°C is somewhat applicable to Toronto's winter weather conditions, but it should be noted that Toronto experiences some days in the winter where the temperature is below -20°C. It is in these harsher temperatures that the efficiency of this heat pump cannot be guaranteed. It should be noted that all information is based on what the manufacturer reported. No third party study on the GWPL38 GHAP was found. The heat pump draws energy from the air using advanced heat pump technology and a highly efficient yet low-NO_x condensing heat generator. Since gas is the primary energy source (direct point of use), rather than electricity, which is generated largely in coal or gas-fired power stations, the GAHP has a significantly smaller carbon footprint. They also cut running costs because gas is typically only a third of the price of electricity and the heat pump provides up to 65% additional heat by drawing in free energy from the surrounding air[95]. As far as energy consumption and carbon emission go, compared to conventional methods of providing heat to the buildings, GWPL38 GAHPs reduce these dramatically.

Conclusions

Buderus GWPL low-carbon gas absorption heat pumps deliver highly efficient, renewable heating solutions for commercial, industrial and residential applications. The case study performed was on a newly developed Endike Primary School located in North Hull, United Kingdom. The newly developed building encompasses six state of the art GWPL38 GHAP's manufactured by Buderus in conjunction with Bosch Thermotechnology Ltd. According to the Sewell Group, who appointed Bosch group to select the heating system selected the GWPL38 GHAP. GWPL38 is the perfect choice for new buildings or in existing buildings as a stand-alone solution or combined with a conventional boiler. It is ideal for schools, colleges, office developments, care homes, residential properties, leisure and sports facilities as well as process heat applications. As a renewable technology with NOx emissions qualifying for BREEAM, using a Buderus gas absorption heat pump helps achieve targets that renewable technologies requires.

GAHP Case #6: Air source gas absorption heat pump and gas condensing boilers, Remeha Fusion Hybrid (2014 & 2015)[96,97]

Study Details	
Purpose	To evaluate how newly manufactured gas absorption heat pump Remeha Fusion Hybrid performs at a care-home.
Location	Adderbury, Oxfordshire, UK
Model	Remeha Fusion Hybrid: Remeha Fusion gas absorption heat pumps (GAHPs) – air source and Remeha Quinta Pro gas condensing boilers
Specifications[98]	Three externally-sited 35kW Fusion GAHPs, Two Quinta Pro 45kW boilers on cascade Electrical output: 1.09kW
Parameters	Tested by manufacturer Remeha at Lake House, a care-home facility with 43 beds. Maximum return temperature of up to 55°C The Remeha Fusion continues to operate at temperatures down to -20°C and is still capable of functioning efficiently Ideal for: New and existing buildings, hotels, healthcare facilities, shopping centres and apartment blocks.

Due to the fact that this technology is quite recent, third party field study of the Remeha Fusion Hybrid is unavailable. The manufacturers have installed its first fusion hybrid at a care-home in UK. Hence all information is from the manufacturer and from the Modern Building Service paper journal. The existing boilers that fulfilled the heating demand at Lake House care home were replaced with gas absorption heat pumps supported by condensing boilers[97]. This system is the first hybrid model made by Remeha who is a well-known manufacturer of gas boilers. This technology delivers efficiencies of around 144%, which is 1.44 COP. The efficiency of heat pumps falls as ambient temperature falls, hence at temperatures of -7°C, the expected efficiency of this system is 120% or 1.20 COP[99].

Table 106: Gas Utilization Efficiency (GUE) Data Reported as COP for Remeha Fusion Hybrid

	COP
Manufacturer Data	1.44
Case Study Data	1.40

Since there is no published third party study on the Remeha Fusion, all information is based on what the manufacturer provided. The manufacturer states that when it comes to environmental performance this system ranks well. The air source gas absorption heat pump is for external use. A low noise brushless fan is fitted which keeps the environmental noise down to a minimum. Anti-vibration pads are available to reduce the transmission noises throughout the building. Remeha reports that after renovations and the installation of the Fusion Hybrid, CO_2 emissions will decrease around 20% per year and NOx emissions will decrease approximately 80% per year[11]. A similar case was found at Lake House care-home, where CO2 emissions were said to decrease 30% yearly[97]. Regarding retrofits, this heat pump uses outside air as a heat source instead of an expensive ground source. The manufacturer information does not mention other specific information on retrofits. The data says the system is capable of operating at temperatures down to -20°C[98]; however the COP at -20°C is not reported. -20°C is somewhat applicable to Toronto's winter weather conditions, but it should be noted that Toronto experiences some days in the winter where the temperature is below -20°C. It is in these harsher temperatures that the efficiency of the Fusion Hybrid cannot be guaranteed. The cost of installing a Fusion Hybrid was not provided, but the financial pay back was reported to be 4-5 years[97].

Conclusions

The Fusion Hybrid is a relatively new technology that appears to be a promising investment. The care home Lake House decided to replace its old existing boilers with three gas absorption heat pumps and Two Quinta Pro gas-fired condensing boilers[96]. This new system effectively lowers CO_2 and NOx emissions as well as providing reliable heating to the facility. Although only one published case study of the Fusion Hybrid model is found, it appears to meet manufacturer expectations. The variance in COP between manufacturer data and case study (also carried out by the manufacturer) is negligible.

Appendix D - Gas Engine Driven Heat Pump (GEDHP) Review

GEDHP Case #1: Natural-gas-driven heat pumps in the Netherlands – On field experiences and future perspective, Yanmar (2001)[100]

Study Details	
Purpose	To evaluate and perform field tests on different types and sizes of existing gas-driven heat pumps
Location	Groningen, The Netherlands
Model	Yanmar gas-driven heat pumps (GHP) – Eco Compact H1 Series - ANZP450H1
Specifications[2]	Heat output ranged from 8 kW to 13 kW Electricity power consumption in cooling: 0.90kW and heating: 0.84kW
Parameters	Tested by European natural gas supplier N.V. NederlandseGasunie and EnergieNed, Federation of Energy Companies in the Netherlands Outdoor Temperature:Cooling °C -10 - 43 Heating °C -20 - 35 Indoor Temperature:Cooling °C 20 - 30 Heating °C 15 - 30 Expected to be appealing: for heating and cooling of small office-buildings, bars, showrooms and alike and comprises a single outdoor unit and multiple indoor units.

For the purpose of this study a 5 HP (horse-power) Yanmar gas-engine heat pump supplied base-load heating and cooling to a large kitchen of a psychiatric institution. This type of heat pump can be utilized for heating and cooling needs of small office-buildings, bars, showrooms and more. The heat pump was rated at 18 kW heating and 14 kW cooling[86]. Depending on site and outdoor conditions, the heat output ranged from 8 kW to 13 kW with the corresponding COP ranging between 1.0 and 1.41. As shown in the performance table below the year-round COP was evaluated at 1.16.

Table 107: Coefficient of Performance (COP) Data for ANZP450H1

	COP
Manufacturer Lab Data	1.6*
Field Data	1.16

Calculated from manufacturer information[100]

Model Used ANZP450H1 (16 HP)

Rated Heating Capacity = 50.0 kW

Fuel Consumption (LHV – heating) = 30.7 kW

Power Consumption (Heating) = 0.84

$$COP = \frac{Rated\ Capacity\ (kW)}{Gas\ consumtion\ (kW) + Electricity\ Consumption\ (kW)} COP$$
$$= \frac{50.0\ kW}{30.7\ kW + 0.84\ kW} COP = 1.585 \approx \mathbf{1.6}$$

The cost of Yanmar gas-driven heat pumps (GHP) – Eco Compact H1 Series - ANZP450H1 is not stated in the study. Outdoor temperatures of -10 to 43°C for cooling and -20 to 35°C for heating are used[100]. This range of temperatures is adequate and appropriate to Toronto climate. However, it should be noted that there are some days of the winter when the temperate in Toronto is below -20°C, therefore the tested results may not hold for extreme cold days. The study mentions that investment and maintenance costs hamper large-scale implementation[86]. As such, further performance improvement and smart implementation, focused on a high yearly load-factor, is required for more favorable economics. However, due to the fact that they are small units it greatly improves retrofit possibilities in the large market of existing houses1. No specific data values on emissions were included in the data, however in the conclusions section it was found that engine driven heat pump technology had lower primary energy consumption and lower CO2 emissions compared to average emissions produced with electrically driven technologies (air and ground sourced heat pumps).

Conclusions

The main conclusion by EnergieNed is that introduction of this heat pump type into the Dutch market is feasible, preferably for base-load heating and cooling. The 5 HP (horse-power) Yanmar gas-engine heat pump is suitable for small buildings, office spaces, and large rooms such as the kitchen of the psychiatric institute. For it to be used in a larger setting, another model of Yanmar, one that has great horsepower is recommended.

GEDHP Case #2: Case-study on the application of building HVAC performance analysis and fault detection using ABCAT, Aisin Toyota Group (2012)[101]

Study Details	
Purpose	To analyze HVAC system underperformance due to constant, time-scaling performance degradation by comparing optimal systems to suboptimal ones
Location	Son, Netherlands
Model	Aisin Toyota Group Gas Engine Driven Heat Pump (Model not specified)
Specifications	Heat output ranged from 8 kW to 13 kW Electricity use not specified
Parameters	Tested by Eindhoven University of Technology and StruktonWorksphere (Masters student thesis).Office building tested: StruktonWorksphere, built in 2010.Expected to be state-of-the art climate system and with no degradation and HVAC performance of building was assumed to be quite optimal. 7 floors of office space, 400 kg/m^2 thermal mass. 4 gas-engine powered heat pumps for both heating and cooling purposes, source: ambient air, regular heat pump cycle. 71KW cooling, 84 KW heating each

Figure 108: The Strukton Worksphere Office Building where 4 Aisin Toyota Gas Absorption Heat Pumps have been installed

The Strukton Worksphere is a newly developed building in Son, Netherlands, where four Aisin engine driven gas heat pumps have been installed. The source used for these heat pumps is outside air and the heating temperature range is 35°C < total supply < 45°C.The heating COP is 1.5 while the cooling COP is 1.95[102].The reported COP from this case study is higher than the reported manufacture data. This must be interpreted with caution because the manufacturer data was reported with no specific model, as was this case study.

Table 108: Generation Efficiency Data Reported as COP for Aisin Gas Engine Driven Heat Pump

	Heating	Cooling
Manufacturer Data[102]	1.63	1.76
Field Data	1.5	1.95

The study lacked communication on ease of retrofit, as it did not provide any information about retrofitting opportunities or challenges with air gas engine driven heat pumps. The study did not include information on environmental performance, energy savings, and quantitative data on greenhouse gas emissions relative to conventional alternatives or any potential environmental hazards. It also did not mention the cost or the payback period. The reason for this can potentially be due to the fact that the focus of this study was on monitoring and fault detection of HVAC systems.

Conclusions

This study just refers to an Aisin Gas Engine Driven Heat Pump as the optimal HVAC system in an office building. The main part of the study is how to monitor degradation in a system. Hence there are no accurate and specific conclusions about how reliable or robust the Aisin GEDHP is. Based on the study, the Aisin engine heat pump at Strukton Worksphere exceeded expectation when it came to cooling. However, as aforementioned these results need to be interpreted with caution.

GEDHP Case #3: Gas Heat Pumps, Demonstration Project on Cinema CineMagnus (2013)[103]

Study Details	
Purpose	Demonstration Project: To show "praiseworthy" performance of gas heat pumps in practical situations
Location	Schagen, Netherlands
Model	Sanyo Engine Driven Heat Pump, three-pipe VRF
Specifications	Capactiy: 190 kW in total for heating and 170kW in total for cooling Use of electricity: Heating: 1.54kW Cooling: 1.35kW Width: 1800mm Height: 2248mm Depth: 1060mm
Parameters	3 gas engine heat pumps (3 pipe VRF system) installed at Cinema CineMagnus Approximately 1,700 m2 gross floor area Full heating capacity down to -21°C[104]

The installed system at Cinema CineMagnus is unique. Heat pumps are placed on the roof, eliminating the need for an engine room in the premises. A large injection and distribution plenum was created under the seats, which conditions the seats via the perforated central chair legs. The gas engine heat pumps regulate the temperature in the central plenum. The room is CO_2 controlled; 90% of the heat contained in the ventilation air is recovered. The system is linked up to the two cinemas and part of the foyer. If necessary it can continuously exchange heating and cooling between the specified areas. The three-pipe system enables mutual exchange of heat and cold between the areas within the building. The entire installation process was put into operation in 2006. Although the Cinema CineMagnus demonstration project had plenty of appropriate information, it lacked the COP numerical values of this case study. However, the manufacturer data of Sanyo engine driven three-pipe VRF was available.

Figure 111: Gas Engine Heat Pump Installed on the Roof

Table 109: COP from Manufacturer of Sanyo Engine Driven Heat Pump, three-pipe VRF

	Heating	Cooling
Manufacturer Data[104]	1.34	1.14

The demonstration was a summary of the project at Cinema CineMagnus, however the original study or further information was not found. The demonstration project did not include information about the COP, environmental performance such as CO_2 emissions reduction, ease of retrofit, or cost. It briefly mentioned the fact that the system installation was a little over the client's budget, but the client was satisfied with the advantages and future anticipated savings.

Conclusions

Since there is no COP data, it is inaccurate to form a conclusion about the inefficiency of the Sanyo heat pump. Although there is sufficient detail in describing the demonstration project, it fails to provide the COP information. Due to important information being omitted, this demonstration project is inconclusive.

GEDHP Case #4: East Meets West: Gas-Fired Heat Pumps, York split system (2011)[105]

Study Details	
Purpose	To evaluate performance of a York outdoor split system gas engine driven heating and cooling system with 3-ton capacity, in residences of 10 U.S cities with variety of climate conditions.
Location	10 different U.S. cities with variety of climate conditions York, Penn Chicago, Ill Wheaton, Ill Girard, Ohio Baltimore, Md Maplewood, N.J. Brooklyn, N.Y. Phoenix, Ariz Atlanta, Ga. Salt Lake City, Utah
Model	York outdoor split-system gas engine-driven heating/cooling system – 3 ton-capacity - Model: E2GE036N06401C
Specifications	HSPF – 14.0 and SEER – 15.0
Parameters	Tested at residences throughout ten different U.S cities with variety of climate conditions. Battelle Labs trained York dealers and installed York 3-ton capacity; split system Gas engine-driven heat pump units throughout the cities. Indoor Coil Temperature[106]: Heating: 10°C min, 27°C max Cooling: 14°C min, 22°C max Outdoor Coil Temperature: Heating: -23°C min, 24°C max Cooling: 10°C min, 46°C max Heating supply air temperature for the York test unit were 38°C to 46°C Sold mostly to the custom housing, replacement, and light commercial markets.

Gas Research Institute conducted the U.S Field study that used a York unit with 3-ton capacity, split system gas engine-driven heat pump developed by Battelle Laboratories. According to later investigation, study was done in 1995, even though an article was posted 2011. The gas heap pumps were installed in residences in ten different U.S. cities representing a wide range of climate conditions. The researchers recorded several parameters such as, gas and electricity consumption, indoor and outdoor temperatures and heat pump operating parameters. They later evaluated performances, defrosting and cycling, effects of extreme weather conditions, effectiveness of the variable speed control system, and reliability.

Table 110: Mean COPs Values Provided by the Manufacturer and U.S. Field Study for Heating and Cooling Seasons

	Heating	Cooling
Manufacturer Data	N/A	N/A
Field Data	1.35	1.05

The houses of the residences of the ten different cities were heated and cooled at a relatively fast rate due to speed modulation and accurate compressor sizing of the gas heat pump. They modulated down to lower speeds to maintain temperature and comfort levels. On average, the gas heat pumps cycled once an hour, providing more consistent comfort levels. Heating supply air temperature for the York test unit were 38°C to 46°C. In most summer months, the average humidity in each household was maintained at 50%. The measured mean heating season COP was about 1.35 and mean cooling seasonal COP was about 1.05. Based on these data retrieved from the field study, GRI estimated the energy cost savings to range from 20%-80% over a conventional electric heat pump and furnace/air conditioners. GRI also measured the Heating Seasonal Performance Factor (HSPF) to be around 14.0 and Seasonal Energy Efficiency Ratio (SEER) to be slightly above 15.0. HSPFs and SEERs exceed the minimum electric heat pump efficiency standards of the National Appliance Energy Conservation Act (NAECA) standards. Nevertheless, gas engine heat pumps, like electric heat pumps, use R-22 as a refrigerant, which are ozone-depleting chlorofluorocarbons. R-410a is also used in some cases, which has some environmentally damaging characteristics but since it is a hydro-fluorocarbon (HFC) it does not contribute to ozone depletion.

Conclusions

A conclusion about the 3-ton capacity outdoor split system gas engine driven heat pump cannot be synthesized because important information is missing. This product may be off the market for unknown reasons due to the fact that the model number: E2GE036N06401C is no longer in York's database. This needs to be investigated further. If it can be understood how these systems performed in USA and why they were taken off the market, it can lead to insight of its applicability to the Toronto residential market. . It is advised for interested parties to look into the research done by Gas Research Institute in the United States. Based on a conversation with the GTI, the database at GTI has 2 studies done on the engine driven split system and why it was removed from the market. The studies can be purchased and are titled "Field Test of the Fort San Fort Sam Houston Triathlon Gas Heat Pump" (gri/96/0043) and "1995 Cooling Season Summary of the San Antonio Triathlon Test GHP" (gri/96/0004).

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