COMPARATIVE LIFE CYCLE ASSESSMENT:

GROUND SOURCE HEAT PUMP SYSTEM VERSUS GAS FURNACE AND AIR CONDITIONER SYSTEM

By

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B.E.S., York University, Toronto, Canada, 2015

A Professional Project Paper presented to Ryerson University
in partial fulfillment of the requirement for the degree of

Master of Applied Science
in the Program of
Environmental Applied Science and Management

Toronto, Ontario, Canada, 2017

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ABSTRACT

Comparative Life Cycle Assessment: Ground Source Heat Pump System versus Furnace and Air Conditioner System

Master of Applied Science, 2017
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Ground source heat pump (GSHP) systems are an extremely efficient space heating and cooling technology. There is a large consensus throughout the literature that GSHP systems can reduce operational CO_2 emissions by up to 80% in comparison to natural gas furnace (GF) and air conditioner (AC) systems. The literature is limited; however, in regards to the specific environmental impacts associated with the systems, as well as the impacts that occur throughout the systems' entire life cycle. In this project, a comparative life cycle assessment was conducted to compare a GSHP system with a GF/AC system, examining 14 specific environmental impact categories. Results were consistent with the literature in regards to the operational stage; however the GSHP system displayed a significantly greater overall environmental impact. While these results are specific to the region of Ontario, Canada, they call into question the prevailing opinion that GSHPs are the more environmentally sustainable option.

ACKNOWLEDGEMENTS

I would like to express my sincere appreciation to my supervisor, Dr. Seth B. Dworkin, for giving me the opportunity to be a member of his research team at Ryerson University. Dr. Dworkin has been an incredible supervisor and has provided me with immense support and encouragement throughout my research term.

I would like to thank my colleagues in the Dworkin research group for their support and friendship throughout my research. I would also like to thank Dr. Cory Searcy for his helpful discussions throughout the year.

Lastly, I would like to thank my friends and family for their tremendous support, patience, and encouragement. Special thanks is extended to my parents, Sandra and Don, and to my closest friends.

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NOMENCLATURE

AC	Air Conditioner
AFUE	Annual Fuel Utilization Efficiency
AP	Acidification Potential
ASHP	Air Source Heat Pump
BTU	British Thermal Units
CO_2	Carbon Dioxide
COP	Coefficient of Performance
DALY	Disability Adjusted Life Years
EER	Energy Efficiency Ratio
EP	Eutrophication Potential
GF	Natural Gas Furnace
GHG	Greenhouse Gas
GJ	Gigajoule
GSHP	Ground Source Heat Pump
GWP	Global Warming Potential
HDPE	High Density Polyethylene
HVAC	Heating, Ventilation, and Air Conditioning
ILCD	International Life Cycle Data System
ISO	International Organization for Standardization
LEAP	Low-Income Energy Assistance Program
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
NEB	National Energy Board
NG	Natural Gas
NMVOC	Non-Methane Volatile Organic Compound
Mt	Megaton
NO_x	Nitrogen Oxides
ODP	Ozone Depletion Potential
OEB	Ontario Energy Board
PDF	Potentially Disappeared Fraction
PJ	Petajoule
PM	Particulate Matter
POF	Photochemical Ozone Formation
SEER	Seasonal Energy Efficiency Rating
SO_2	Sulfur Dioxide
TJ	Terajoule
VOC	Volatile Organic Compound
WSHP	Water Source Heat Pump

1.0 INTRODUCTION

1.1 Motivation

Ontario is the most highly populated province in Canada [1] and accordingly one of the largest energy consumers [2]. In 2015, Ontario developed a climate change strategy [3] in anticipation of the Paris Agreement resulting from the 21st Conference of the Parties to the United Nations Framework, also known as the Paris Climate Conference. The goal of the Paris Agreement is to ensure that all Parties, 153 countries, create a strategy to reduce their national greenhouse gas (GHG) emissions and minimize their impact on climate change [4]. Canada ratified the agreement and has declared a goal to reduce GHG emissions to 14% below 1990 levels by 2030 [5, 6]. Provincially, Ontario's climate change strategy a goal is to reduce GHG emission by 37% by 2030 based on 1990 levels [3]. With this goal, a climate change action plan [7] was established, a required under the 2016 Climate Change Mitigation and Low-carbon Economy Act. The climate change action plan details short-term energy reduction goals that Ontario plans to undertake from 2016 to 2020, and will be updated after this time. One of the goals in the action plan is to minimize emissions from fossil-fuel use in buildings and homes [7]. The buildings sector is categorized by Natural Resources Canada into residential, commercial, and institutional energy use [8, 9]. In total, residential, commercial, and institutional buildings consume approximately 56% of total provincial energy demand, which is expected to continue to increase with population and economic growth [8, 9].

The action plan suggests a number of ways in which reducing fossil-fuel use in buildings and homes could be possible. Many low-cost methods are suggested such as improved insulation, window replacements, and improved lighting efficiency. The plan also states that Ontario intends to offer funding and assistance to people interested in retrofitting detached homes, multi-residential buildings, schools, hospitals, universities, and colleges to replace existing heating and cooling systems with geothermal systems. The document very briefly describes geothermal technology as a heat pump that warms and cools buildings using the outside air, ground, or water [7]. However, the document does not describe the energy reduction or emission reducing potential of the geothermal technology nor any other actions suggested in the plan. For this reason, it is unclear to the reader what the relative potential each action has in relation to meeting Ontario's emission reduction goals. Studying potential energy reducing and GHG emission reducing heating, cooling, and air ventilation (HVAC) technologies is of significant importance for Ontario buildings because space heating and cooling accounts for 69% of residential energy consumption, and 64% of commercial and institutional energy consumption [8, 9].

Literature regarding geothermal technologies has determined that the most efficient geothermal system is the ground source heat pump (GSHP) system [10, 11, 12]. GSHP systems can reduce annual operational emissions by up to 88% in comparison to various methods of traditional HVAC systems [13]. Currently, Ontario's building heating and cooling relies predominantly on natural gas furnaces (GF) and electric air conditioning (AC) systems, respectively [8, 9, 14]. GSHP systems eliminate the need for two separate systems for heating and cooling needs, as the single system operates in both heating and cooling mode [13, 15, 16]. Relative to a GF and AC system, GSHP systems are approximately 3 to 5 times more efficient [11, 13, 17, 16, 18, 15]. In addition to significantly increased efficiency, GSHP systems also eliminate the use of natural gas and rely solely on small amounts of electricity. Due to the extremely low-carbon electricity mix in Ontario, GSHP systems would greatly reduce GHG emissions resulting from building heating and cooling.

Although GSHP systems are highly efficient, they remain underutilized due to large upfront costs of installation and poorly understood technology. Based on observations from the literature, another potential barrier associated with limited GSHP popularity is that their specific environmental benefits are unclear [13, 17, 19, 20]. The application of life cycle assessment (LCA) to compare a GSHP system with a GF and AC system would provide a complete comparative view of the environmental performance of each system. A LCA studies the potential environmental impacts that a product or system may have throughout its entire life cycle, from raw material extraction to end-of-life treatment [21, 22]. This research will enhance overall understanding of the environmental burdens and benefits of the two systems.

Although Ontario's climate change action plan encourages building retrofitting for GSHP technology, it does not discuss available government funding nor whether funding will be increased to support this proposed action. As capital cost is the most significant barrier to geothermal popularity, an increase in funding to building owners is necessary in order to meet the goals mentioned in the climate change strategy and action plan.

1.2 Objectives

The purpose of this thesis is to develop a foundation for a comparative life cycle assessment of ground-source heat pump systems, with a gas furnace and air conditioner system in order to achieve four objectives;

1. To create a LCA model that can be used as a specific guideline to compare the life cycle environmental impacts of GSHP systems versus GF/AC systems;
2. To conduct a case study using this model in order to:
    a. Identify specific environmental impact categories that the systems contribute to;
    b. Determine the energy savings potential of a GSHP retrofit in an Ontario building;

c. Determine GHG emission reductions in an Ontario building with a GSHP retrofit.

1.3 Outline of Document

Chapter 2 examines the current state of energy in Ontario, detail GSHP and GF/AC technology, and summarize the current life cycle assessment literature involving the two systems.

Chapter 3 describes the methods and their development to conduct the comparative LCA.

Chapter 4 provides the results and discussion of the LCA.

Chapter 5 draws conclusions as well as some final recommendations.

2.0 BACKGROUND INFORMATION AND STATE OF THE LITERATURE

This section will review existing literature regarding Ontario's energy outlook, GSHP systems, gas furnace and air conditioning systems. It will also provide a foundation for life cycle assessment, and review current literature surrounding the application of LCA to the two systems being studied.

2.1 Why Ontario?

In order to establish the importance of conducting this study in Ontario in particular, it is necessary to examine the current state of energy in Ontario in comparison to other provinces. Ontario is one of the highest energy consuming provinces in Canada, surpassed only slightly by Alberta [8, 9]. Figure 1 illustrates the electricity and natural gas use in petajoules (10^{15} joules) by province. ATL refers to the Atlantic Provinces; Newfoundland and Labrador, Prince Edward Island, Nova Scotia, and New Brunswick. Transportation fuel was not included in this analysis as it is not directly applicable to the heating and cooling industry.

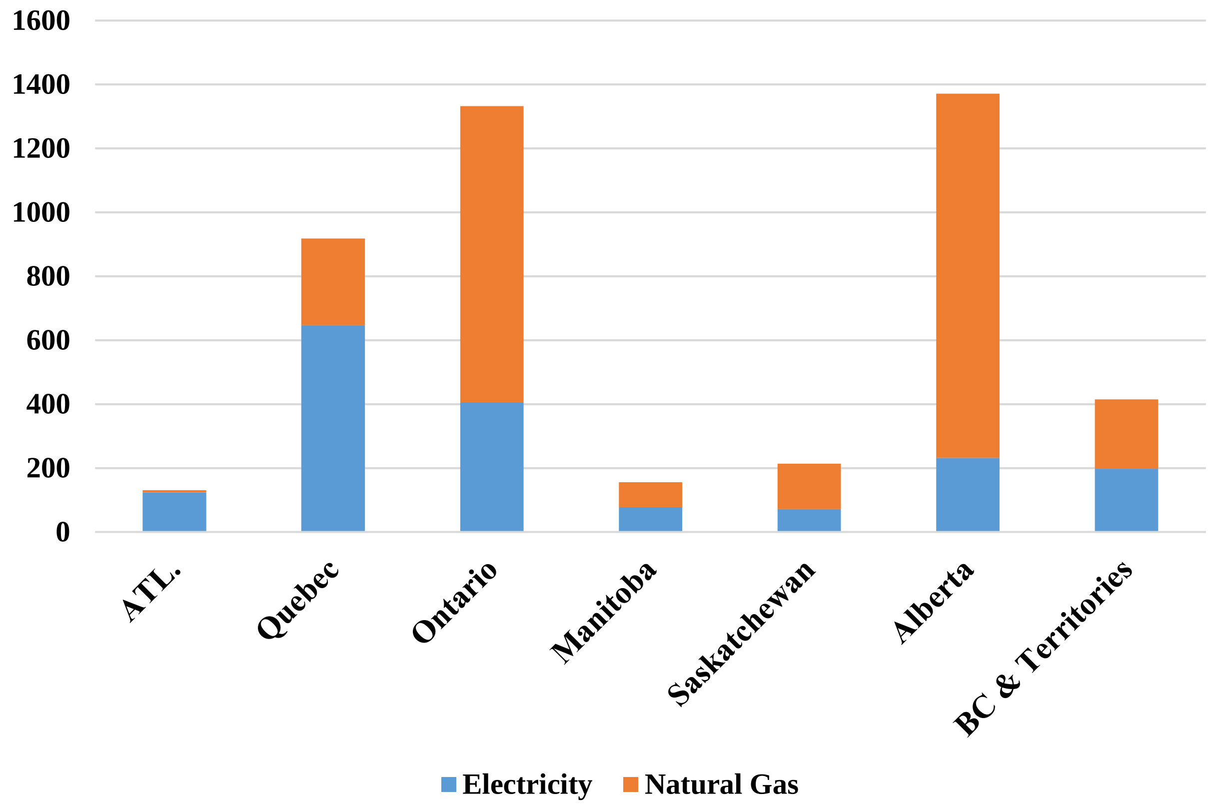

Figure 1: Electricity and natural gas use by province in Canada [8, 9].

As indicated by Figure 1, Quebec, Ontario, and Alberta are the top energy consumers in Canada. As the purpose of this study is to examine the potential reductions in energy use and GHG emissions that a GSHP system may have, it would appear that Alberta is the province in which this particular research should be focussed. As the GSHP system eliminates the need for natural gas heating and instead requires solely electricity to operate, the electricity portfolios of Quebec, Ontario, and Alberta must be assessed. As Figure 2 illustrates, Alberta's electricity portfolio has a 51% dependency on coal-fired generation, making it the most carbon intensive electricity mix of the three provinces.

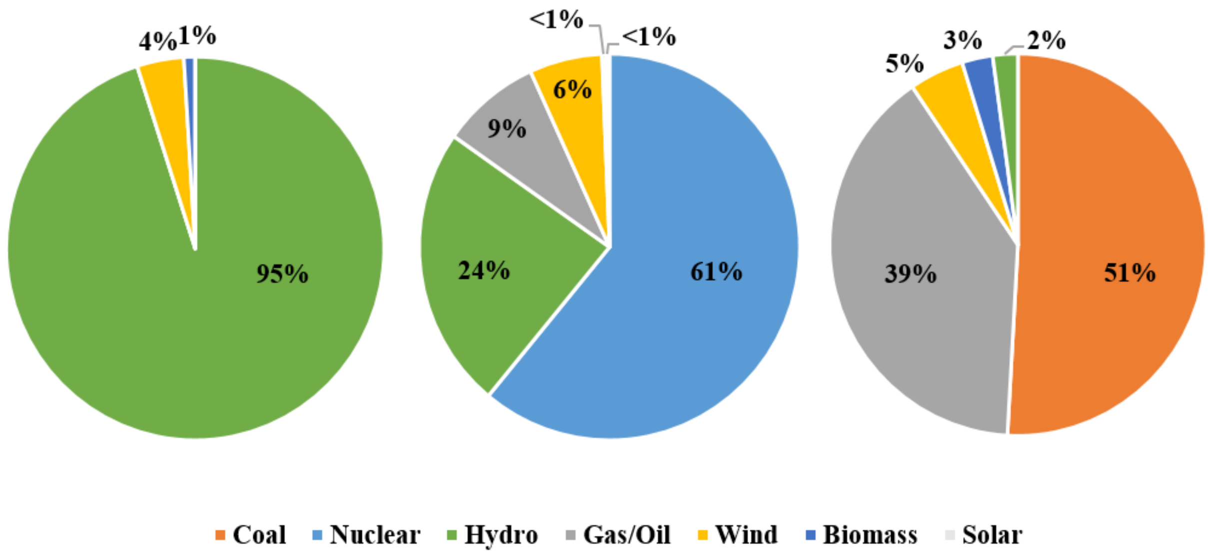

Figure 2: Electricity Mix for Quebec [23], Ontario [24], and Alberta [25]

As shown in Figure 3, roughly 89% of buildings in Alberta use natural gas heating systems. Given the current electricity mix in Alberta, a widespread switch from natural gas heating to GSHP systems would result in negligible GHG emission reductions or could potentially result in a slight increase in emissions. While significantly less energy would be required to operate GSHP systems as opposed to natural gas heating systems, the carbon intensity in Alberta is much higher than that of natural gas due to its coal content and therefore renders GSHP system promotion in the province unprofitable and unrewarding. Additionally, coal combustion produces a number of other harmful pollutants such as NO_x and SO_2 [26]. While NO_x emissions are also present for natural gas production, it is at a much lower level [26]. With Alberta eliminated from the potential scope of research, the next highest energy consumer is Ontario. Opposite to Alberta, Ontario has a very clean electricity mix with 91% low- or no-carbon sources. It can also be noted from Figure 3 that 74% of Ontario buildings utilize natural gas heating. This makes Ontario the perfect candidate for the setting for this study. While Figure 2 shows that Quebec has the cleanest electricity mix, Figure 3 shows that heating systems in the province are predominantly electric, such as baseboard heaters.

Widespread GSHP system installation in Quebec would result in a significant reduction in energy consumption; however would not significantly alter GHG emissions, as this is already very low and does not require immediate attention. Applying widespread GHSP system installation in Ontario would generate a significant reduction in both provincial energy use as well as provincial GHG emissions.

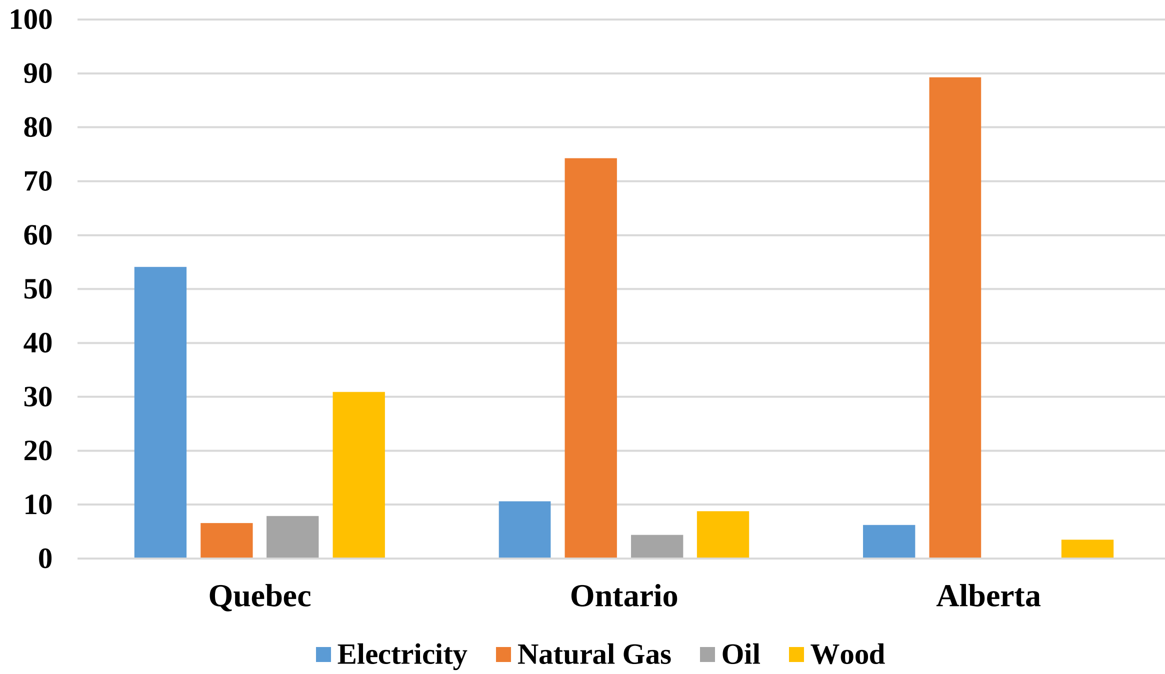

Figure 3: Percentage of Heating Types in Quebec, Ontario, and Alberta [8, 9].

2.2 Ontario's Energy Outlook

Ontario has a history of committing to huge GHG emission reduction goals. Most notably, the provincial phase out of coal-powered electricity is considered to be the largest GHG emission reduction action undertaken in North America to date [27]. This phase out was the primary action responsible for meeting and surpassing the 2007 Climate Change Action Plan goal of a 6% GHG emission reduction by 2014 compared to 1990 levels [3, 28, 29]. With the accomplishment of greening Ontario's electricity supply mix, the new 2016-2020 action plan focusses on reducing the demand for natural gas by replacing natural gas use with electricity where possible [7]. While the National Energy Board (NEB) has forecasted Canadian natural gas demand to remain relatively constant until 2040, the 2016 Ontario Climate Change Action Plan set a goal to eliminate natural gas heating in small buildings built from 2030 onward [7]. For pre-existing buildings, funding from the future cap and trade system is proposed to fund an increase in incentives and grants in order to make Ontario the easiest and most affordable jurisdiction in North America for retrofitting clean energy systems, including GSHP systems [7]. If successful, this plan has the potential to generate significant GHG emission reductions for Ontario.

Figure 4 displays types of heating systems used by the two building sectors in Ontario: the residential sector and the commercial and institutional sector. In both sectors, natural gas is the primary space heating method; 74% for residential buildings and 92% for commercial and institutional buildings [8, 9].

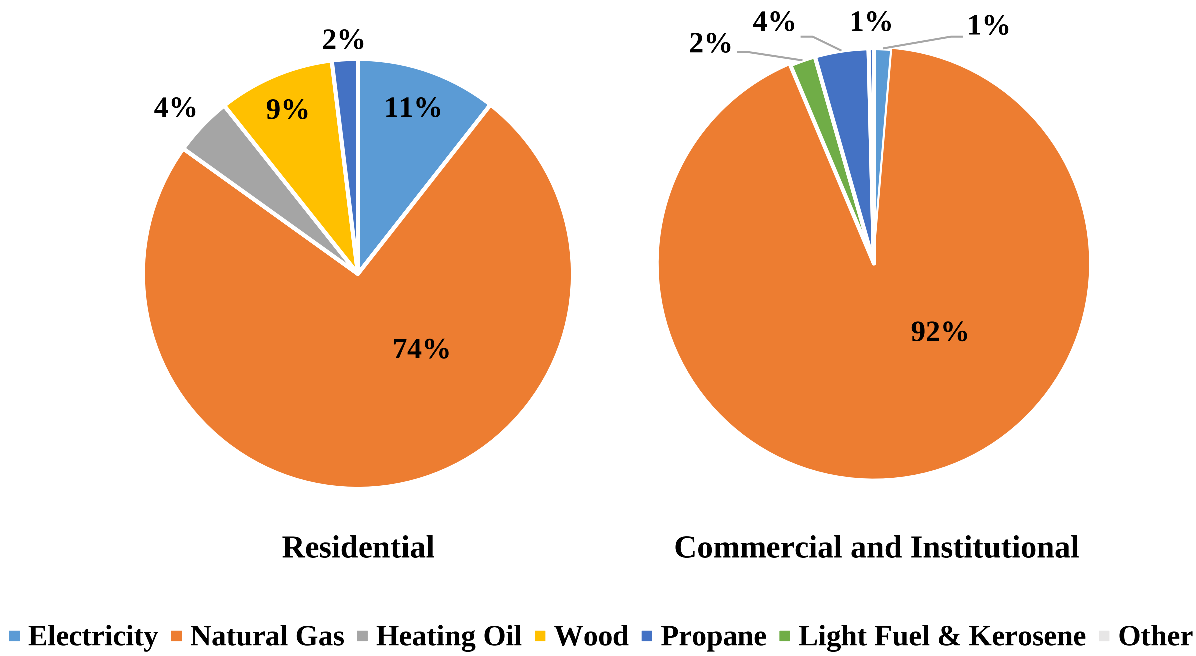

Figure 4: Heating Types in Residential, Commercial, and Institutional Ontario Buildings [8, 9]

Buildings types in the residential sector include single-detached homes, single-attached homes, and apartment buildings [9]. Buildings in the commercial and institutional sector include retail spaces, warehouses, cultural and public services buildings, offices, schools, colleges, universities, health care and social services, arts and entertainment, accommodations, and food services [8].

Table 1 summarizes the energy use for the entire residential, commercial, and institutional sectors using data from the Comprehensive Energy Use Database provided by Natural Resources Canada [8, 9]. The data presented in Table 1 is from 2014, as it is the most recent data currently available to the public. GHG emission data for electricity was not available; however as previously mentioned, Ontario's electricity mix is 91% carbon-free. Given the values from Figure 4 as well as the data in Table 1, it can be determined that 281.8 PJ of energy is consumed annually for natural gas heating in residential buildings, which accounts for approximately 16 Mt of CO_2e. In the commercial and institutional sector, 210.3 PJ of energy is consumed annually for natural gas space heating, emitting approximately 10.8 Mt of CO_2e. With these values, it can be determined that roughly 71% of total GHG emissions in the residential sector are attributed to natural gas space heating and 84% respectively in the commercial and institutional sector. These calculations validate the immense potential that clean-energy heating systems such as GSHP systems can have on Ontario's building sector.

Table 1: Residential, Commercial, and Institutional Energy Use and GHG Emission Summary

Residential, Commercial, and Institutional Energy Use and GHG Emission Summary								
	Residential Sector [9]				**Commercial & Institutional Sector** [8]			
	Energy		**GHG Emissions**		**Energy**		**GHG Emissions**	
End-Use	**PJ**	**%**	**Mt CO_2e**	**%**	**PJ**	**%**	**Mt CO_2e**	**%**
Space Heating	380.8	67	16.2	75	228.6	59	11.2	87
Space Cooling	10.3	2	0	0	17.8	5	0.1	1
Water Heating	116.9	21	5.3	24	30.7	8	1.5	11
Lighting	14	2	0	0	37.9	10	0	0
Appliances	49.2	9	0.2	1	-	-	-	-
Other*	-	-	-	-	70	18	0.2	1
TOTAL	**571.2**	**100**	**22.4**	**100**	**384.9**	**100**	**12.9**	**100**
→Electricity	118.1	20	-	-	124.8	32	-	-
→Natural Gas	391.3	69	19.1	88	219.6	63	11.7	91
→Other**	61.9	11	2.6	12	19.3	5	1.2	9
Energy Intensity	0.74 GJ/m^2				1.32 GJ/m^2			
GHG Intensity	38 tonne CO_2e/TJ				33.6 tonne CO_2e/TJ			

*Other end-use sources for commercial and institutional buildings are auxiliary equipment, auxiliary motors, and street lighting **Other energy sources for residential buildings are heating oil, wood, and propane, and other energy sources for commercial and institutional buildings are light fuel oil, kerosene, heavy fuel oil, steam, and propane.

Table 1 identifies the energy intensity as well as the GHG intensity of both sectors. Energy intensity refers to the total amount of energy used per total floor space requiring energy. In the residential sector, energy intensity has decreased from 1.11 GJ/m^2 in 1990 to 0.74 GJ/m^2 in 2014 [9]. Although total floor space in the residential sector has increased from 480 million m^2 in 1990 to 774 million m^2 in 2014, total energy consumption has only increased from 532 PJ in 1990 to 571 PJ in 2014 [9]. This data can infer that energy use in residential buildings has become more efficient.

In the commercial and institutional sector, energy intensity is the same in 2014 as it was in 1990, 1.32 GJ/m^2, although it did fluctuate in the interim. Total energy use has increased from 256 PJ in 1990 to 385 PJ in 2014. Total floor space increased from 190 million m^2 in 1990 to 289 million m^2 in 2014. As energy intensity is a measure of energy use per floor space, 1990 and 2014 values are the same because total energy use and total floor space both increased by factor of 1.5.

GHG intensity is the total mass of emissions per total energy used. Residential GHG intensity has increased from 34 tonne CO_2e/TJ in 1990 to 38 tonne CO_2e/TJ in 2014. Although the phase out of coal decreased the GHG intensity of the electricity supply mix, the majority of energy consumption is of natural gas. Demand for natural gas is at its record peak for the residential sector, resulting in a higher GHG intensity. The GHG intensity for the commercial and institutional sector has decreased from 35.7 tonne CO_2e/TJ in 1990 to 33.6 tonne CO_2e/TJ in 2014. This decrease can be attributed to an increased percentage of electricity use, which has a lower GHG intensity than natural gas.

Based on the figures and table above, it is evident that space heating is the primary energy sink in buildings, while space cooling is the least significant. As the GSHP system to be studied operates in both heating and cooling mode, it is valuable to briefly examine the current use of cooling systems in Ontario buildings. Figure 5 summarizes the space cooling systems in Ontario buildings. Air conditioning is utilized in 79% of residential buildings, of which 17% are single room AC units and 83% are central AC systems [9]. Approximately 69% of commercial and institutional buildings have air conditioning, of which 78% operate central AC systems, and 22% rely on single room AC units [30]. Buildings with no AC systems are typically those constructed prior to 1990 [30].

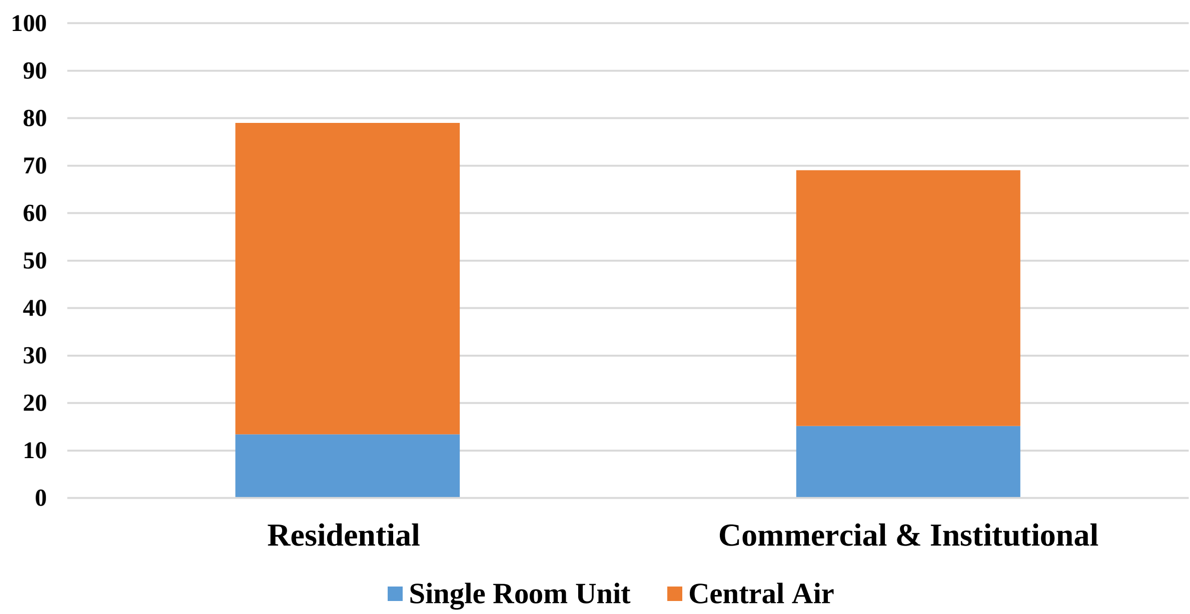

Figure 5: Percentage of Cooling Types used in Residential, Commercial & Institutional Buildings in Ontario [8,9]

One of the reasons Ontario buildings favour natural gas heating over other electric systems is that Ontario has the highest electricity costs of all the provinces [31]. This presents a barrier when promoting GSHP systems, as they require electricity to operate. The climate change action plan outlines some strategies in place to combat this potential issue. In January of 2016, the Electricity Support Program was launched, which provides monthly discounts on electricity bills for Ontario's low-income households [7]. Additionally, the Ontario Low-Income Energy

Assistance Program (LEAP) provides emergency financial assistance grants to cover the full payment of energy bills for households in extreme need [7]. The Ontario Energy Board (OEB) describes low-income as a factor of both household income as well as individuals living in the home. An income of $28,000 is considered low-income regardless of the number of individuals living in the household. $28,000-39,000 for 3 or more individuals, $39,000-48,000 for 5 or more, and $48,000-52,000 for 7 or more [32].

The action plan briefly outlines how a portion of the profits from the future cap and trade program will work toward minimizing costs of HVAC retrofits for building owners. Approximately $1.8 billion per year is expected to be generated from the program, which is to be located in a new financial entity called the *Green Bank*. One of the functions of the Green Bank is to work to reduce emissions produced by the building sector by financing retrofits for new, energy efficient technologies such as GSHP systems. The Green Bank will assist building owners in finding available government grants and incentives and assist with securing flexible low-interest loans for the remaining balance if required. In addition to financial assistance, the Green Bank plans to offer individuals free consultations to calculate their payback period and return on investment for large GHG-reducing projects such as GSHP system installations.

2.3 Ground Source Heat Pump System

Ground source heat pump systems operate both in heating and cooling mode, utilizing the ground as a heat source as well as a heat sink to provide space conditioning [33]. Using the ground as a heat source allows the system to operate at a much greater efficiency than that of traditional HVAC systems because it uses electricity to move heat as opposed to burning fuel to create heat.

The first heat pump was built in 1855 by Peter Ritter von Rittinger, based on the theoretical writings of Lord Kelvin [34, 35]. At this point in history, it was understood that the heat pump could be used for both building heating and cooling; however the pump was only able to use air from the external atmosphere to provide heat to the building. The first known use of the ground as a heat source for the heat pump was not until 1912, when the geothermal heat pump was patented by Swiss engineer, Heinrich Zoelly [10]. For decades, the heat pump was not considered to be a valuable device, as other heating methods remained much more simplistic and inexpensive. Many complications arose with system design, which halted any further installations. After the oil crisis in the 1970s, ground source heat pump research gained momentum, solving many of the problems previously experienced [10]. Further development of new materials and continual research in system design has led to the extremely efficient system that is presently available. After over a century of research, GSHP systems are still not a commonly used HVAC system because of their high upfront installation costs, as well as the general lack of public awareness and understanding of the system [36]. Currently, GSHP systems are used in less than 1% of Ontario buildings [8, 9].

2.3.1 Open Loop

Open loop GSHP systems, also known as water source heat pump (WSHP) systems, interact directly with the ground using groundwater or surface water, such as lakes or ponds [12]. The water with which the system interacts acts as a heat exchange medium. To heat a building, the water is extracted and passed through the heat pump, which absorbs the heat from the water and then discharges it back to its original source. The three common designs for open systems are extraction wells, extraction and reinjection wells, and surface water systems. The most common of the three is the extraction and reinjection wells [12, 33]. In an extraction and reinjection system, there are commonly two water wells. As shown in Figure 6, one well is used to extract water, the other to reinject it after the heat pump has absorbed its heat.

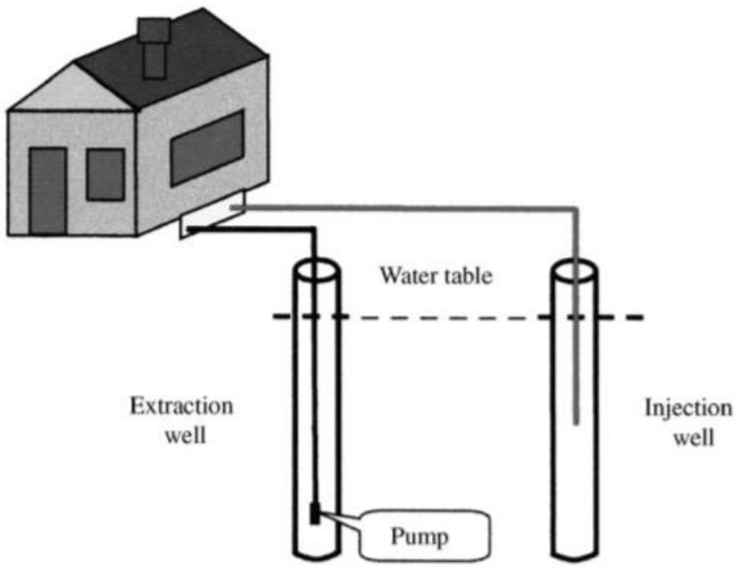

Figure 6: Open Loop Extraction and Rejection Well GSHP System. (Reproduced from [12])

Open loop systems have many advantages: the water temperature remains relatively constant depending on the source; they require less drilling than most closed loop designs; open loop designs are quite simple; and simpler designs result in a cheaper initial cost than most closed loop systems [12, 15, 16]. The disadvantages of open loop systems raise environmental concerns. The allowable volume of water that can be extracted for use can be limited by local water resource regulations. Additionally, the heat exchanger between the well and the heat pump is subject to corrosion, which results in issues of water contamination as well as increased system maintenance [12].

In a closed loop system, the heat transfer fluid is enclosed in a circulating loop and has no direct contact with the ground. Closed loop systems are the most common, and therefore will be discussed in greater detail in the following sections.

2.3.2 Closed Loop

Closed loop GSHP systems comprise three main components; the ground loop piping, the heat pump, and the distribution system [10, 12]

2.3.2.1 Ground Loop Piping

The ground loop is an arrangement of high density polyethylene (HDPE) pipes that are buried in the ground outside of the building and connect to the heat pump within the building. The pipes contain a solution of water and glycol that works as a heat transfer fluid. The GSHP does not use energy to create heat, rather it uses the ground loop piping to move heat from the ground and into the home and vice versa. During the winter months, the fluid in the ground loop absorbs the heat from the ground and delivers it to the heat pump to heat the building. During the summer months, the heat is expelled from the building and into the fluid, where it dissipates into the ground. The design of the ground loop varies based on land availability, soil quality, and the heating and cooling load requirements of the building. The three main designs of the ground loop pipes are referred to as horizontal, “slinky”, and vertical.

The horizontal ground loop design, illustrated in Figure 7, is installed in shallow trenches, typically no more than 5 meters in depth. The HDPE pipes are can be installed in a number of patterns, depending on the land availability and the load requirements of the building. To supply a higher load requirement, more length of pipe will be required. There are two primary advantages associated with the horizontal design. It is relatively inexpensive to install in comparison to the vertical design due to the shallow depths. Additionally, given sufficient land space, there is some flexibility in the layout of the ground loop piping. The main disadvantages of this design is that it requires abundant ground area, and the shallow ground depths are subject to seasonal variations in ground temperature [12, 15, 16].

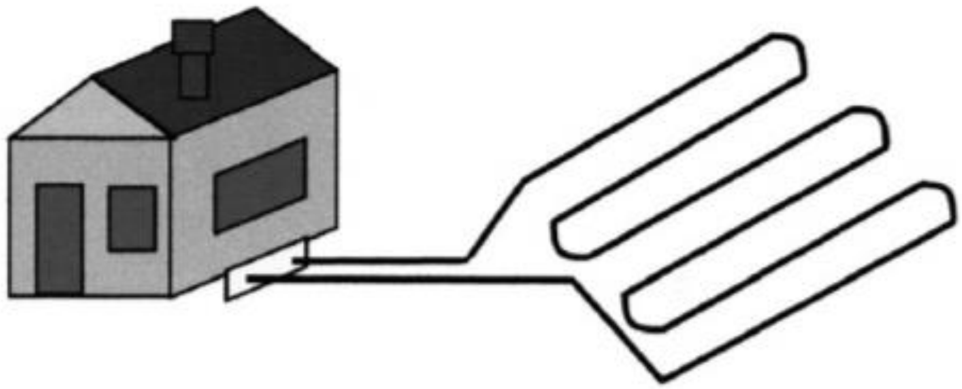

Figure 7: Horizontal Ground Loop Orientation. (Reproduced from [12])

The slinky ground loop design is also buried in shallow trenches of up to 5 meters in depth; however the pipes are laid in a spiral formation (Fig. 8). The purpose of this design is to have a greater length of pipe in a smaller area [12]. The main advantage of the slinky design is that it requires less space than the horizontal designs, which also makes the slinky orientation the cheapest to install. The disadvantages of the slinky design are that it still requires fairly significant land area, and it is exposed to seasonal variation in temperature due to the shallow depths [12].

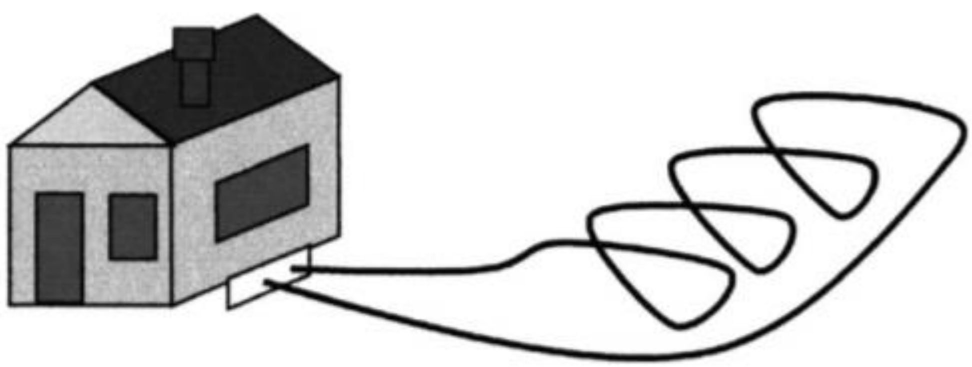

Figure 8: Slinky Ground Loop Orientation. (Reproduced from [12])

The vertical ground loop design (Fig. 9) is constructed by drilling a hole, called a borehole, typically about 150 meters in depth and 5 inches diameter [12]. The number of boreholes and their depth depend on the energy required to meet the heating and cooling load demands of the building as well as the soil conditions. The ground loop piping is inserted in the shape of a "U" into the borehole. The borehole is then filled with grout, which acts as a heat conductor between the piping and the soil. The advantage of this ground loop design is that it requires minimal land space, which makes it ideal for urban settings [12]. In addition, the ground temperature is stable at depths greater than 10 m, which allows the system to operate at much greater efficiency that the previously mentioned ground loop designs [12]. The disadvantage of this system is that it is the most expensive to install due to the drilling depths.

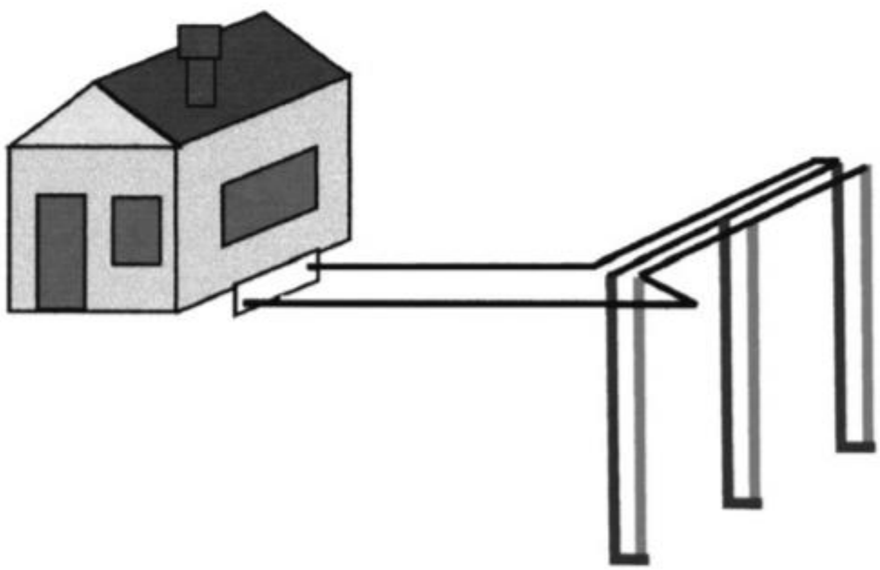

Figure 9: Vertical, or Borehole, Ground Loop Orientation. (Reproduced from [12])

Figure 10 illustrates the average fluctuation in ground temperature for a Central Ontario city at various depths in relation to fluctuations in ambient air temperature. As shown, at depths below 7 meters, ground temperature remains constant. GSHP systems operate most efficiently when ground temperature is constant [12]. Below 7 meters, ground temperature is warmer than the ambient outdoor air temperature in the winter, and respectively cooler in the summer. When the ground temperature is closer to the desired indoor temperature, less work is required by the heat pump [12]. As previously mentioned, the horizontal and slinky ground loop designs are typically installed at a depth of 5 meters. From Figure 10, it can be observed that seasonal fluctuation in ground temperature is minimal at 5 meters in depth; however it still has a negative impact on the efficiency of the systems.

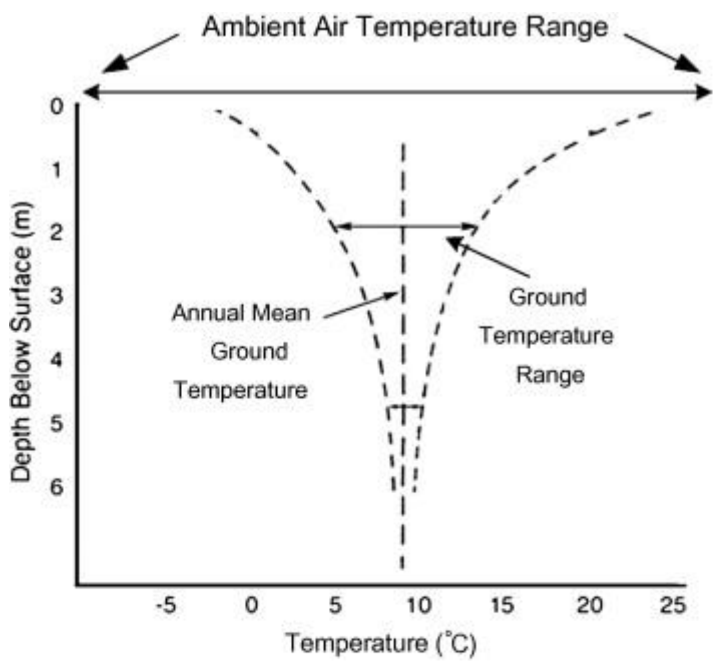

Figure 10: Ground temperature fluctuation in relation to depth and ambient air temperature.

(Reproduced from [12])

2.3.2.2 Heat Pump

The heat pump is required to provide adequate heating to the building, as the heat directly from the ground loop is at too low a temperature for direct use. The heat pump operates on a vapour compression cycle. In heating mode, the glycol solution within the ground loop piping travels to the heat pump, which contains a refrigerant. The heat from the glycol solution is transferred to the refrigerant, which causes it to heat up and become a vapour. The vapour is then compressed, causing it to increase in temperature and pressure. Finally, the hot gas flows through the coils of a condenser. The distribution system collects the heat from the condenser coils and distributes the heat throughout the home. The gas that remains in the condenser has lost its heat and moves to the expansion valve where the temperature and pressure decreases. The refrigerant then recommences the cycle. In cooling mode, the direction of the refrigerant flow is reversed and the refrigerant picks up heat from the building and transfers it to the antifreeze solution, where it dissipates into the ground [12]. Figure 11 illustrates the cycle in which the refrigerant flows to heat and cool the building. In heating mode, the refrigerant flow is reversed, depicted by a change in direction of the arrows.

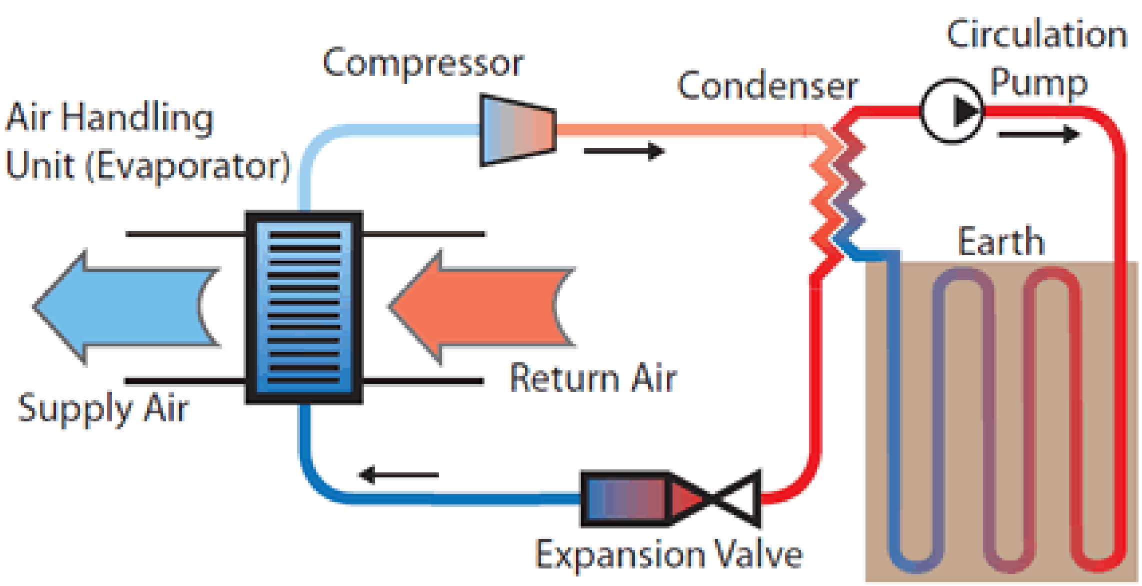

Figure 11: Heat pump in cooling mode. (Reproduced from [37])

2.3.2.3 Distribution System

The distribution system delivers the heat from the heat pump throughout the home. This can be done through ductwork or through radiant in-floor heating. When utilizing a ductwork distribution system, air blows over the coils of the condenser in the heat pump, collecting the heat from the hot gas within the condenser. The now hot air is sent throughout the duct system by the blower. For radiant in-floor heating, the heat from the condenser is given to a tank of water. This hot water travels through the in-floor piping system that heats the home, also called water-to-water heating [12]. Ductwork, also called water-to-air heating, is the most common distribution system [12].

2.4 Gas Furnace and Air Conditioner

The three components of this system are the natural gas furnace, the air conditioner, and the ductwork distribution system.

The furnace contains a small combustion chamber, a heat exchanger, and a blower. In the combustion chamber, a small spark ignites a mixture of natural gas and air. The heat exchanger sits on top of the combustion chamber, collecting the heat from the combustion process. Once the desired temperature is reached, the blower is activated and forces the cool air collected from the vents of the building to blow over the heat exchanger, collecting its heat. The hot air then travels through the ductwork of the building to provide heating. Carbon monoxide and small amounts of unburned natural gas remain as combustion by-products and are released into the atmosphere through an exhaust pipe. Furnace efficiency is referred to as the annual fuel utilization efficiency (AFUE). Gas furnaces in Canada are required to have a minimum efficiency of 90% [38], meaning that for one unit of fuel supplied to the furnace, 0.9 units of heating is supplied to the building.

As previously mentioned, air conditioning systems are present in 79% and 69% of residential sector buildings and commercial and institutional buildings respectively. The air conditioner runs on electricity alone. The unit is located outside of the building so that it can expel the warm air from inside the building to the outdoors. It operates the same way the heat pump does during the cooling cycle; however, instead of expelling the unwanted heat into the soil, it is released into the atmosphere. The air conditioning efficiency is often measured by the energy efficiency ratio (EER), which refers to the ratio of the cooling generated in British thermal units (BTU) to Watts of electricity required to operate the AC unit, or the seasonal energy efficiency ratio (SEER), which is the measurement of the cooling efficiency over the entire cooling season. The higher the EER or SEER value, the more efficient the unit [39]. To be ENERGY STAR certified, central air conditioning systems must have a minimum SEER rating of 12. 5 [39].

2.5 Life Cycle Assessment

Life cycle assessment is a valuable environmental management tool used to determine the potential environmental impacts of a product or system throughout its entire life cycle [21, 22]. Life cycle assessment is a valuable environmental management tool used to determine the potential environmental impacts of a product or system throughout its entire life cycle. The International Organization for Standardization (ISO) published a set of LCA performance standards in 1998 due to the growing concern for the environmental impacts associated with product manufacturing and use [21, 22]. A life cycle assessment has four phases as mandated by ISO: goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and interpretation. The inclusion of each phase in an LCA study is mandatory, and consists of a number of required subsections. The manner in which each phase is carried out is not specified and is at the discretion of the researcher.

The life cycle of a system is typically broken down into five stages: manufacturing, transportation, installation, operation, and end of life treatment. This is often referred to a “cradle-to-grave” assessment. When examining current literature comparing the environmental impacts of GSHP systems and GF/AC systems, two key knowledge gaps are noticeable. First, a large number of related studies discuss the environmental impact of each system in terms of CO_2 emissions only.

These studies are usually not LCA studies, as LCAs typically examine a greater range of environmental impacts. While CO_2 is a commonly understood substance relating to climate change, there are many other emissions associated with both systems that have specific and individual environmental impacts. Second, the majority of existing studies address the operational stages of each system only, as it is the part of the life cycle that is the most important to building owners. There are significant environment impacts associated with the life cycle of the two HVAC systems beginning with the raw material extraction for manufacturing. Neglecting to analyze all but one stage of the life cycle could potentially result in ignoring 4/5 of the associated impacts of the respective systems.

Table 2 displays a number of studies that will be considered in this section, what type of study was conducted and which stages of the life cycle were covered in the study.

Table 2: Summary of literature studying GSHP system impacts.

Study	Region	System(s) Studied	Environmental Impact(s)	M	T	I	O	E
Blumsack *et al.* [40]	Pennsylvania	GSHP, GF, AC	CO_2, SO_2, NO_x				X	
Blum *et al* [41]	Germany	GSHP, Oil Boiler	CO_2				X	
Bristow & Kennedy [42]	Toronto, ON, Canada	GSHP	CO_2				X	
Bayer *et al.* [17]	Europe	GSHP	CO_2				X	
Self *et al.* [12]	Alberta, Ontario, Nova Scotia (Canada)	GSHP, ASHP, electric heat, GF	CO_2				X	
Carvalho *et al.* [11]	Portugal	GSHP	CO_2				X	
Michopoulos *et al.* [43]	Cyprus	GSHP, Oil Boiler	CO_2				X	
Saner *et al.* [13]	Europe	GSHP	Climate change, ODP, AP, EP, human toxicity, POF, PM, terrestrial, freshwater/ marine ecotoxicity, ionizing radiation, agricultural/urban/ natural land occupation, and water/metal/fossil depletion	X	X	X	X	X
Greening and Azapagic [20]	UK	ASHP, GSHP, WSHP NG Boiler	Abiotic depletion potential, AP, EP, freshwater/marine ecotoxicity, GWP, human/terrestrial toxicity, ODP, and POF	X	X	X	X	X
Rodriguez, Bangueses, and Castro [44]	Spain	GSHP, Oil Boiler	Carcinogen, respiratory inorganics, ionizing radiation, ODP, aquatic/terrestrial ecotoxicity, AP, land use, EP, GWP, non-renewable energy, minerals	X	X	X	X	X
Huang & Mauerhofer [45]	Shanghai, China	GSHP	GWP, AP, and EP	X		X	X	X
Hong *et al.* [19]	Seoul, Korea	GSHP	RDP, GWP, ODP, AP, EP, and POCP	X			X	
Koroneos & Nanaki [18]		GSHP	Greenhouse effect, ODP, AP, EP, carcinogenesis, winter smog, heavy metals	X	X		X	

M=manufacturing, T=transportation, I=installation, O=operation, and E=end-of-life.

Table 3 includes all studies mentioned in Table 2, detailing the systems and buildings examined in the study, the primary findings, and the software used when applicable.

Table 3: Detailed summary of GSHP studies

Reference	System(s) Studied	Building/ Scenario	Significant Finding(s)
Blumsack *et al.* [40]	GSHP, GF, AC	Residential home	GSHP decreased CO_2 by 62%, increased SO_2 by 3% and increased NO_x 1%
Blum *et al.* [41]	GSHP	Residential Southwest Germany	GSHP reduced CO_2 by 64%.
Bristow & Kennedy [42]	PV/wind/solar air & water heating, GSHP	Residential & commercial building	GSHP had most significant energy & CO_2 savings of all renewable options
Bayer *et al.* [17]	GSHP	Residential Sector	80% coal causes increase in GHG emissions
Self *et al.* [12]	GSHP, ASHP, electric, GF	Residential building	CO_2 emissions reduced by 76% for Ontario
Carvalho *et al.* [11]	GSHP	Residential sector	GSHP will reduce heating energy by 60% & reduce CO_2 by 90% by 2050
Michopoulos *et al.* (2016) [43]	GSHP Oil-Boiler	Single-family & Multi-residential	GSHP increased CO_2 emissions for single-family & decrease for multi-residential
Saner *et al.* [13]	GSHP	200 m^2 house	34% resource depletion, 43% human health, & 23% ecosystem quality
Greening & Azapagic [20]	ASHP,GSHP, WSHP, NG Boiler	Residential building	GSHP has 36% less CO_2 emissions but overall 73% higher env impact than NG boiler
Rodriguez, Bangueses & Castro [44]	GSHP Oil Boiler	800 m^2 building	GSHP ½ human health but doubled ecosystem quality impact
Huang & Mauerhofer [45]	GSHP	10 residential (800-1500m^2) 10 commercial (2000-3000m^2)	40% GHG emission reduction
Hong *et al.* [19]	GSHP	University Dormitory (26,298 m^2)	Material manufacturing has greatest impact, most sensitive to borehole length
Koroneos & Nanaki [18]	GSHP	Pylaia Town Hall (1350m^2)	73% of total impact is acidification

Bayer *et al.* [17] calculated the CO_2 emission savings of GSHP systems in the residential sector of 19 countries in Europe [17]. The overall results of the study determined that if all 19 countries replaced all heating systems, primarily natural gas furnaces, with GSHP systems, a collective 30% CO_2 reduction would be realized. Results for the Czech Republic and Denmark determined that a nation-wide conversion to GSHP systems would reduce CO_2 emissions by less than 1% due to high dependence on coal-powered electricity. Results for Poland displayed an increase in emissions with GSHP system use, as coal constitutes 80% of the Polish electricity system. Sweden showed the most potential of all countries studied, as its electricity mix is generated mostly from nuclear and hydropower. Based on the results of this study, the authors determined that greening electricity supply is of primary importance before widespread conversion to GSHP systems can be environmentally sound.

Following this research, Carvalho *et al.* [11] calculated the potential reduction in CO_2 emissions for GSHP systems in Europe using the estimated future electricity mix [11]. By 2050, the average electricity mix in Europe is expected to be generated from a minimum of 30% renewable sources. Once this has been accomplished, Carvalho *et al.* estimate that replacing all existing HVAC systems with GSHP systems will reduce space heating energy consumption by 60% and reduce CO_2 emissions by 90%.

Blum *et al.* [41] studied the potential CO_2 savings of GSHP systems compared to conventional HVAC systems in Germany's residential sector [41]. Results determined that a GSHP system had the potential to reduce CO_2 emissions by 64%. These results are not consistent with those of Bayer *et al.*, which stating that only 0.2% annual CO_2 savings was achieved in Germany [17]. The electricity mix in Germany during the time of these studies contained approximately 53% fossil fuel based generation [17]. The discrepancies between these results are unusual because both studies focussed on the residential sectors; however, there could have been a difference in emission intensity used in CO_2 calculations.

In Cyprus, a country with a similar electricity mix to Germany, a study was conducted by Michopoulos *et al.* [43] which examined the operational energy and CO_2 emission reduction potential of a GSHP system compared to oil-fired boilers in single-family dwellings and multi-residential buildings [43]. Results determined that energy reduction in the single-family home was only 1-23% across study areas; however, it increased CO_2 emissions by 16-24% compared to the oil-fired boiler in every case study. Results for the multi-residential building showed 18-36% reduction in energy use across the study areas. In 4 cases, the multi-residential buildings displayed results of 6-10% less CO_2 emissions than the oil boiler, with the exclusion of a 4% increase in CO_2 emissions in 1 case.

Blumsack *et al.* [40] discovered more positive results when studying the environmental benefits of a GSHP system in a residential home in Pennsylvania [40]. The study determined that the GSHP system was 42% more efficient than the NG furnace for space heating and hot water heating and 43% more efficient than the electric AC unit for space cooling. The environmental impacts were calculated based on CO_2, SO_2, and NO_x emissions. Results determined that replacing the NG furnace and electric AC system with a GSHP system decreased annual CO_2 emissions by 62%; however SO_2 and NO_x emissions were both increased by 3% and 1% respectively.

Self *et al.* [12] examined GSHP systems in terms of their economic and environmental feasibility in comparison to conventional HVAC systems [12]. The compared annual heating costs, annual fuel use, emission intensity, and CO_2 emissions for 5 heating systems; GSHP, ASHP, electric baseboard heating, a mid-efficiency NG furnace, and a high-efficiency NG furnace. Results were presented for the Canadian provinces of Alberta, Ontario, and Nova Scotia. Annual heating costs were 48% cheaper and CO_2 emissions were 80% less for GSHP system operation in Ontario compared to Alberta and Nova Scotia. Compared to the NG furnace, annual fuel costs reduced by 69%, 61%, and 46% for Ontario, Nova Scotia, and Alberta respectively. CO_2 emissions reduced by 76% for Ontario, but actually increased by 26% for Nova Scotia and 31% for Alberta. These increases are due to Nova Scotia and Alberta relying on coal-fired electricity while Ontario's electricity mix is highly renewable. With these results, it was concluded that electricity rates must be low and electricity mix must have a high renewable content for the GSHP system to be both economically and environmentally advantageous in comparison to NG heating.

Bristow and Kennedy [42] examined renewable technologies such as photovoltaic and wind electricity generation, solar air and water heating, and GSHP systems to determine which had the greatest potential for reducing building energy use, and CO_2 emissions [42]. The study was conducted in Toronto, Ontario, and included residential, small business, and commercial building types. It concluded that the GSHP system had the most significant energy and CO_2 savings. A financial analysis determined that the GSHP system was also the best investment for every building type studied as it had the shortest payback period of all the technologies considered.

Many other studies also examined the financial aspects of the GSHP system. Michopoulos *et al.* [43] estimated that the initial cost for a GSHP system and an NG furnace for an average single-family home in Cyprus ranges from $15,000-$18,000 and $11,500-$12,700 (CAD) respectively [43]. Lu *et al.* [46] calculated that a GSHP system for a typical 1400 ft^2-1750 ft^2 residential home in Australia with 2-3 bedrooms would cost $31,000 [46]. It is agreed upon throughout the literature that although capital costs fluctuate depending on the region, the ground loop drilling and installation is the largest expense for GSHP systems [43, 40, 46].

Table 4 provides a summary of capital cost [47], fuel use [12], operating costs [47], and CO_2 emissions [12] for GSHP, electric baseboard, natural gas and AC systems in Ontario. The capital costs of the systems were assumed to be for a 1,700 ft^2 residential detached home [47].

Table 4: Cost, fuel use, and CO_2 emission summary for a GSHP system, electric baseboard & AC system, and NG/AC system in Ontario

Heating System	GHG Intensity (kg CO_2/kWh)	Annual Fuel Use (kWh)	CO_2 Emissions (kg)	Capital Cost ($)	Annual Cost ($)	Present Worth ($)
GSHP (COP 4)	0.188	6080	1143	23,000	713	37,260
Electric Baseboard (1) & AC	0.188	22280	4188	9,000	2,175	52,500
Natural Gas Furnace (0.97) & AC	0.190	24655	4684	11,000	1,408	39,160

**Present worth assumes a life cycle of 20 years.*

Although the aforementioned studies provide valuable knowledge to the field of GSHP research, if the goal of the study is to understand the environmental performance of the system, more than CO_2 emissions must be analyzed. Greening and Azapagic [20] solidify this argument with their results from a LCA comparing GSHP, ASHP, and WSHP systems with a tradition gas boiler system in the UK [20]. The study, acknowledging that most literature reviews consider CO_2 only, examined 10 environmental impact categories; abiotic depletion potential, acidification potential (AP), eutrophication potential (EP), freshwater and marine aquatic ecotoxicity, global warming potential (GWP), human and terrestrial toxicity potential, ozone depleting potential (ODP), and photochemical oxidation formation (POF). Results determined that the overall environmental impacts for the ASHP system were 82% higher than those of the gas boiler on average. The interesting and most valuable result from this study is that the GSHP and WSHP systems both reduced CO_2 emissions by 36% compared to the gas boiler; however the impact on abiotic resource depletion and POF increased by 44% and 37% respectively. The environmental categories in which the GSHP and WSHP systems created a larger impact resulted in the systems having an overall environmental impact that was 73% higher than the gas boiler. The operational stage of every system contributed the most to their overall environmental impact, therefore it was concluded that replacing gas boilers with any of the heat pump systems would not be a sustainable option for the UK given the current fossil-fuel-based electricity mix.

Saner *et al.* [13] recognize that the sustainability of GSHP systems is strictly dependent upon the renewable content of the electricity supply [13]. Additionally, it is acknowledged that more than CO_2 must be considered in environmental evaluations of GSHP systems. A complete cradle-to-grave LCA was conducted examining 18 environmental impact categories; climate change, ODP, terrestrial AP, freshwater and marine EP, human toxicity, POF, PM, terrestrial, freshwater, and marine ecotoxicity, ionizing radiation, agricultural, urban, and natural land occupation, and water, metal, and fossil depletion. The 18 impact categories were further characterized into their overall effect on human health, resource depletion, and ecosystem quality. Results indicated that the electricity use for operation dominated all environmental impact categories except for ozone depleting potential, in which refrigerant manufacturing was the primary contributor. The final results determined that the overall impact of the GSHP system can be broken down into 34% resource depletion, 43% human health, and 23% ecosystem quality. The overall impact was broken down into components of the system. Manufacturing of the heat pump contributed to less than 1% of the total impact of the system, the ground loop contributed 4.5%, transportation less than 1%, refrigerant manufacturing and use 6%, and 87% for operational electricity. The study also conducted a sensitivity analysis for worst case scenarios and determined that leakage of heat carrier fluid had no change in total emissions, heat pump refrigerant leakage had very small increase in CO_2, and decreased COP resulted in increased impacts of climate change, fossil depletion, PM formation, and freshwater ecotoxicity.

Rodriguez *et al.* [44] came to similar conclusions as Saner *et al.* when comparing a conventional fuel boiler system to a GSHP system in a nursery school in Galicia, Spain [44]. Using LCA, the systems' environmental impacts were studied from cradle to grave, concluding that the operational stage of the GSHP system's life cycle contributed to 92% of its total environmental impact. 15 environmental impact categories were considered, further classified into impacts on human health, ecosystem quality, climate change, and resources. Compared to the boiler system, the GSHP system reduced human health impacts by 60%, climate change by 54%, and resources by 35%; however it increased impacts on ecosystem quality by 37%. Overall, the GSHP system had roughly half the impact than the boiler system.

Koroneos and Nanaki [18] gathered some different results when conducting a LCA on the Town Hall building of Pylaia in Thessaloniki, Greece [18]. This study examined the entire cradle-to-grave life cycle of the GSHP system currently in place. Values were calculated for CO_2, SO_2 CO, NO_x, HC, PM, and HCFC-22, which were further classified into their relative impacts on the greenhouse effect, ODP, AP, EP, carcinogenesis, winter smog, and heavy metals. In contrast to Saner *et al.* and Rodriguez, Bangueses, and Castro, Koroneos and Nanaki concluded that raw material extraction, rather than operational electricity use, was the primary contributor to the systems' life cycle environmental impacts, emitting 79% of total CO_2, 81% of total SO_2, and 45% of total NO_x. Results showed that 73% of the system's total environmental impact is associated with acidification, 14% with the greenhouse effect, and 10% with eutrophication. There is a need for further research to clarify these inconsistencies that still exist in the literature.

Hong *et al.* [19] conducted a sensitivity analysis to determine which system design factors have the greatest influence on the overall environmental impact of GSHP systems [19]. The LCA examined borehole length, borehole spacing, borehole diameter, grout thermal conductivity, u-pipe diameter, and u-pipe position on the material manufacturing and the operational stages of the life cycle. The results of the study determined that the manufacturing of materials produced the greatest environmental impact, consistent with Korneos and Nanaki, and that borehole length was the most influential component of the system. Factors associated with the U-pipe had the least impact. The environmental impact categories included in this study were resource depleting potential (RDP), GWP, ODP, AP, EP, and POF. RDP was determined to be the most significant impact category. It was determined that RDP impact was most sensitive to borehole length, and that an increase in length from 50 m to 150 m increases resource depletion by 33%.

Huang and Mauerhofer [45] differed slightly in their research by calculating the economic valuation of the environmental impacts associated with GSHP systems [45]. The study examined 10 residential buildings and 10 commercial buildings all varying in size and occupancy. Results determined that 40% GHG emission reduction is possible for all cases studied. The primary environmental impacts associated were GWP, AP, and EP. Economic valuation of the environmental impacts determined that impacts during the production process would cost 15.84 RMB/m^2 to remediate and 5 RMB/m^2 during operation, which is equivalent to 2.94 CAD/m^2 and 0.93 CAD/m^2 respectively. It was estimated that the GSHP system had a payback period of 4 years, which is extended to 4.29 years when remediation costs included.

2.6 Summary

Natural gas and air conditioning systems are currently the most common HVAC system being used in Ontario buildings. Natural gas remains the dominant source of energy in buildings, although the Ontario electricity mix is less carbon-intensive. With the GHG reduction goals laid out in the Climate Change Action Plan, it is evident that the Ontario building sector must significantly reduce natural gas consumption. The most effective way to drastically reduce natural gas consumption in buildings is to replace natural gas furnaces with electric GSHP systems. GSHP systems have the potential to reduce fuel use and CO_2 emissions by 75% compared to NG/AC systems.

The main knowledge gaps that still exist in the literature, however, is that specific environmental impacts caused during the life cycle of the GF/AC and GSHP systems are not deeply understood. Current literature predominantly examines CO_2 emissions only when comparing the two systems. There have been a number of studies examining the life cycle of the GSHP alone; however, the comparative results must be considered in order to make a thoroughly informed conclusion as to which system has the lesser overall environmental impact. Furthermore, there is no research that compares the NG/AC system with the GSHP system in a region with a 91% renewable electricity mix such as Ontario. This is important research, as it examines the immense potential that a cleaner electricity system has in conjunction with highly efficient HVAC technology.

This study will address the knowledge gaps identified by performing a comparative LCA of a GF/AC and GSHP system in an Ontario residential home. A selection of 16 specific environmental impacts will be addressed, further detailed in the next section.

3.0 METHODS

As previously discussed, a life cycle assessment is broken down into four phases; the goal and scope definition, inventory analysis, impact assessment, and interpretation. This section will follow the methodological framework of ISO 14040/14044 [21, 22], detailing the development and construction of the LCA comparing the GSHP with the GF/AC HVAC systems.

3.1 Goal and Scope Definition

Goal and scope definition is the first phase of a life cycle assessment study. The goal definition determines the purpose of the study, while the scope definition process defines the boundaries of the systems being studied. The goal and scope phase therefore provide the initial plan for conducting the next phase of the LCA, the life cycle inventory phase.

3.1.1 Goal Definition

When defining the goal of the study, ISO 14040/44 requires the following statements; intended application of the study, reason for carrying out the study, the intended audience to whom the results will be communicated, and whether the results will be disclosed to the public [21, 22].

The intended application of this study is to evaluate and compare the life cycle environmental impacts of GSHP and GF/AC systems. The reason for carrying out the study is to address current knowledge gaps; no comparative LCA of GSHP and GF/AC systems have been conducted in Ontario and the LCA literature comparing the two systems lack specific environmental impact analysis. The intended audience for this study are stakeholders of the promotion of GSHP systems in Ontario, including industry and government representatives as well as building owners. The results of this study are intended to be disclosed to the public.

3.1.2 Scope Definition

The scope of the study must be clearly described in adequate detail, in order to provide a framework upon which the following phases of the LCA will be based. ISO standards require the scope definition to state the systems to be studied, their function(s), the functional unit of the study, the system boundaries, chosen life cycle impact assessment methodology, interpretation to be used, and any assumptions made [21, 22].

The systems to be studied are a GSHP system and a GF/AC system. Each system will be studied using a simulated 2000 ft^2 single detached home located in Toronto, Ontario. Using eQuest, a building energy simulation program [48], it was determined that the building has a heating load of 9.4 kW (31,905 Btu/hr) and a cooling load of 6.5 kW (22,136 Btu/hr) per year. For heat pump sizing, general industry standards recommend 1 ton per 12,000 Btu/hr. These heating and cooling loads therefore require a 3 ton heat pump. A vertical ground loop design was chosen for this study, as it is the most efficient option and land space availability in Toronto is typically minimal. The total required length of the borehole was determined using a software called HGS, which allows the user to design HVAC systems for optimal efficiency [49]. HGS uses the method proposed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) to determine borehole length. By inputting building heating and cooling load requirements, it was determined that 497 ft of borehole length is required to support the system, which is rounded to 500 ft for simplicity and consistency with industry practices.

The GSHP system operates at a COP of 4, which is an average efficiency rating for the vertical design. The GF/AC system being studied includes a 55,000 BTU/hr natural gas furnace and a 2 ton central air conditioning unit. The size of the furnace was estimated based on square footage of the house and the assumption that it was built after 1990. The furnace has an AFUE of

0.9, a minimum efficiency required for furnaces in Canada. The size of the central air conditioner was determined by an industry rule of thumb of 1 ton per 1000 ft^2 of cooling area. The AC has a SEER of 13, which meets the minimum requirement of 12.5 for ENERGY STAR certified central air conditioning systems. Both the GSHP and GF/AC systems will utilize identical ductwork distribution systems, which will therefore be omitted from the comparison.

The function of both systems is to provide heating and cooling to an identical building. ISO requires LCA studies to be based upon a chosen functional unit. The importance of this functional unit is that it provides a reference to which comparisons between the two systems shall be based and quantified. From the studies reviewed in the previous section, Table 5 displays those that stated a functional unit. It can be observed that three of the four functional units included in the table examine heating only [13, 20, 44]. Only two of the four functional units refer to an extended time period that would reflect the operational stage of the life cycle [13, 44]. The functional unit chosen for this study is maintaining building temperature at 20 ˚C during winter months (September-May) and 24 ˚C during summer months (June-August) for 20 years. The reason this functional unit was chosen is because it ensures consistent temperatures within which the systems must operate, and it also includes the duration of the entire operational stage.

Table 5: Functional units chosen in past LCA studies examining heating and cooling systems

Reference	Functional Unit
Saner *et al.* [13]	Produced heat of GSHP over 20 years
Greening and Azapagic [20]	1 kWh of thermal energy for domestic space heating
Rodriguez, Bangueses, & Castro [44]	Supplied heat energy to meet building needs for 10 years
Koroneos and Nanaki [18]	1 kW of installed power

The GSHP system boundary and the GF/AC system boundary are illustrated in Figure 12 and Figure 13, respectively. The blue boxes, representing each stage of the life cycle, contain the components to be analyzed at each stage. The green arrows above each life cycle stage displays the inputs to be considered, while the orange boxes below are the outputs considered. For the GSHP system, the following assumptions are made: for end-of-life treatment, the grout and ground loop piping were left in the ground, the metal and refrigerant from the heat pump was recycled, and the glycol solution was pumped out of the ground loop [13].

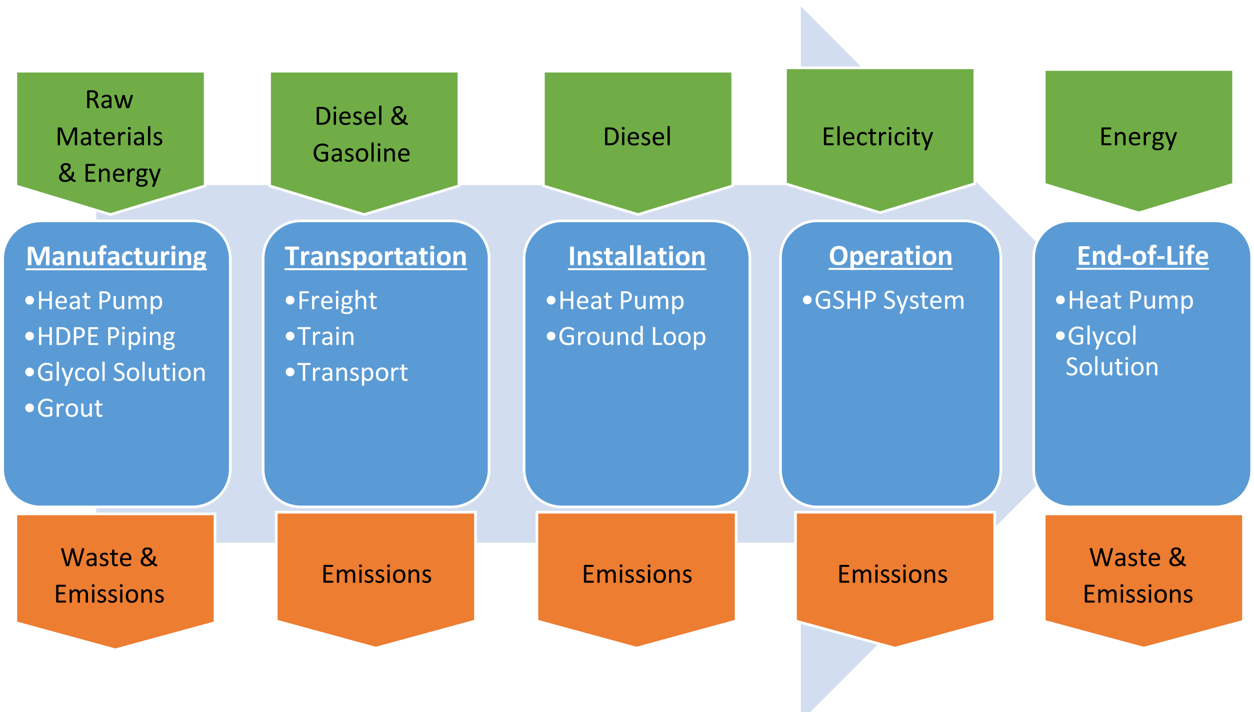

Figure 12: Ground Source Heat Pump System Boundary

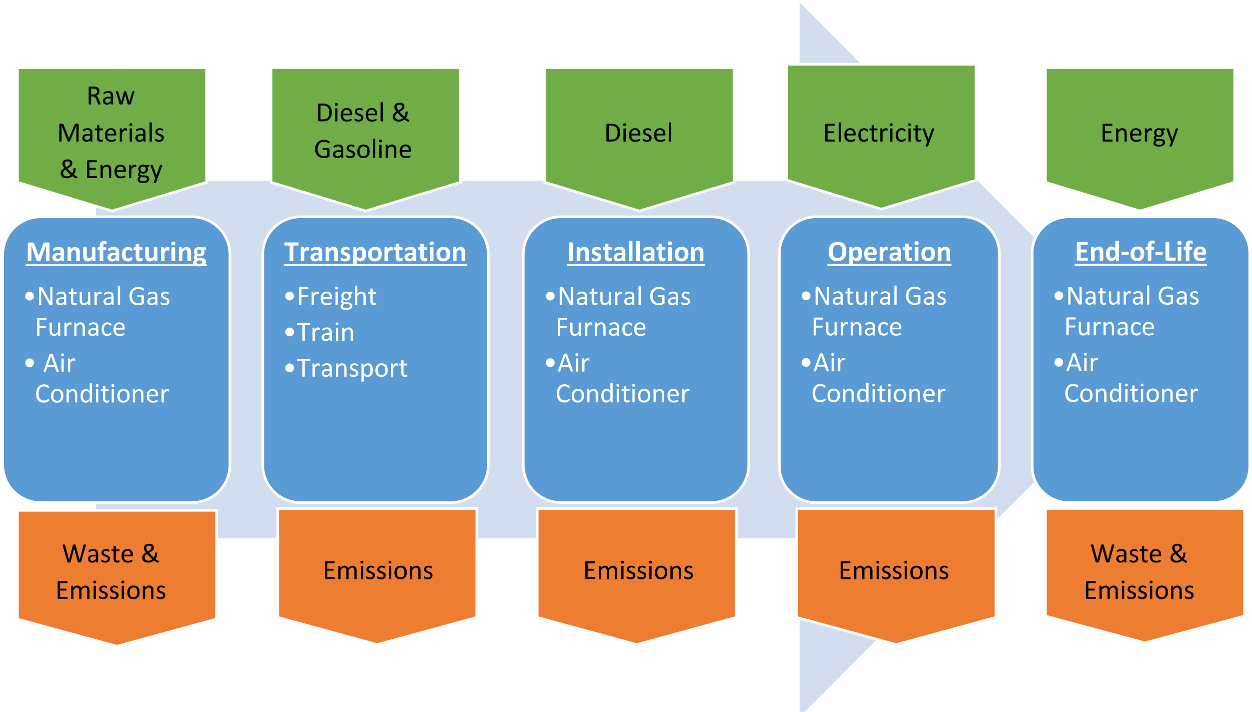

Figure 13: Gas furnace and air conditioner system boundary

Greater detail regarding product models and sizing for the materials and systems included in this study are provided in Table 6. Saner *et al.* [13] conducted a LCA on a GSHP system for a 2150 ft^2 residential home. For the 2000 ft^2 home being considered for this study, the GSHP system utilized by Saner *et al.* would be appropriate. Shah *et al.* [50] conducted a LCA on various fossil fuel-based HVAC systems. The building examined by Shah *et al.* was a 1950 ft^2 residential detached home, nearly identical to the 2000 ft^2 home being considered for this study. Since 2008, when the Shah *et al.* study was published, a minimum AFUE requirement of 90% for natural gas furnaces was developed in Canada. The natural gas furnace chosen by Shah *et al.* (model 58DLA) operated an AFUE of 80%. The model chosen for this study is the newer version of the 58DLA, called the 59SP2, which operates at an AFUE of 92%. Carrier Corporation was chosen as the manufacturer, as it is one of the most popular and well-known HVAC product manufacturers. The air conditioner system that was fitted for the Shah *et al.* home (24ARC3) is no longer being manufactured, as it no longer meets minimum efficiency requirements. As previously stated, to be ENERGY STAR certified, central air conditioning systems must have a minimum SEER rating of 12.5. For this reason, the 24ABB3 central air conditioner by Carrier Corporation was chosen for this study, as it has a SEER rating of 13. The glycol solution circulated in the ground loop piping is propylene glycol assumed to be produced by Dow Chemical Company. CanPipe was chosen to supply the grout to fill the borehole, as there is a Toronto location, which would minimize transportation related impacts. It was assumed that the HDPE ground loop piping was manufactured by the Tianjin Junxing Pipe Group, located in Tianjin, China. ¾" SDR-11 ASTM D3035 HDPE is the pipe chosen for this study, as it is the most common in GSHP system installation.

Table 6: Systems and materials assumed manufacturing details

System or Material	**Manufacturer**	**Manufacturing Location**
Heat Pump [13] - Model GP	Carrier Corporation	Nuevo Leon, Mexico
Ground Loop Piping [13] - 3/4" SDR-11 ASTM D3035 HDPE	Tianjin Junxing Pipe Group	Tianjin, China
Glycol Solution [13] - Propylene glycol	Dow Chemical Company	Michigan, USA
Grout [13] - Bentonite	CanPipe	Ontario, Canada
Natural Gas Furnace [50] - Model 59SP2	Carrier Corporation	Nuevo Leon, Mexico
Air Conditioner [50] - Model 24ABB3	Carrier Corporation	Nuevo Leon, Mexico

3.2 Life Cycle Inventory Analysis

Data for the inventory analysis was collected for each life cycle stage. The following subsections list all considerations for the study and describe how the data was obtained or calculated.

3.2.1 Manufacturing

For the manufacturing stage of the LCA, a list of materials required for the production of each system and their components was acquired. The data for the heat pump component of the GSHP system was obtained from Saner *et al.* [13]. The data for the natural gas furnace and the air conditioner was obtained from Shah *et al.* [50]. The mass of ground loop piping, glycol, and grout was determined using volume calculations from the determined borehole length as well as available manufacturing information. The HDPE ground loop piping is installed into the borehole in a U-shape, which means the doubled borehole length will equate to the total pipe length. With a total borehole length of 500 ft, the required length of piping will be 1000 ft. The HDPE ground loop pipes weigh approximately 58.97 g/ft, which equates to a total of 29.49 kg of required piping. With a total inner volume of 0.017 m^3, the piping is filled with a glycol solution containing 25% propylene glycol and 75% water. With a mass of 1.04 g/cm^3, the total mass of propylene glycol filling 25% of the volume of the ground loop pipes is 4.38 kg. The industry standard for borehole diameter is 5 in. The grout fills the entire volume of the borehole, less the volume displaced by the piping. The total borehole volume of 1.93 m^3, less the total piping volume of 0.026 m^3, results in a required volume of 1.9 m^3 of grout.

Table 7 summarizes the materials required to manufacture the components of each system. The materials required for GSHP system components reflect the calculations previously made. The GSHP system assessed by Saner *et al.* [13] is similar to that considered in this study. The mass of the intermediate materials for all components of the GSHP system listed are taken from Saner *et al* [13]. The intermediate materials required for the manufacturing of the natural gas furnace and air conditioner were acquired from Shah *et al* [50]. As stated previously, the furnace and AC examined by Shah *et al* [50] is now out of date; however, the material composition remains similar.

Table 7: Raw materials required for system component manufacturing.

System Component	**Material**	**Weight (kg)**
Heat Pump [13]	Refrigerant, R-134a	6.69
	Elastomer	10
	Copper	22
	Polyvinylchloride	1
	Low-alloyed steel	20
	Reinforcing steel	108
	Lubricating oil	1.7
Ground Loop [13]	Polyethylene, LDPE granulate	204
	Ethylene glycol	119.8
	EDTA (ethylenediaminetetraacetic acid)	1.23
	Potassium hydroxide	1.23
Grout [13]	Bentonite	209
Natural Gas Furnace [50]	Steel	46
	Galvanized steel	18
	Aluminum	9
	Copper	3
Air Conditioner [50]	Steel	78
	Galvanized Steel	35
	Copper	17
	Aluminum	17
	Refrigerant, R-22	6

3.2.2 Transportation

Using the manufacturing location information from Table 6, the estimated transportation methods and distances for the components of each system can be determined. This section refers only to the delivery of the components listed to the site.

Table 8: Transportation data for system components.

System Component	Transportation Method	Distance Travelled (km)
Heat Pump	Train Truck	3000 100
Ground Loop	Ocean freight Truck	10,000 100
Glycol	Truck	700
Grout	Truck	30
Natural Gas Furnace	Train Truck	3000 100
Air Conditioner	Train Truck	3000 100

3.2.3 Installation

The natural gas and air conditioner system has a very simple installation process with a negligible impact. It is assumed that the home already has access and an existing connection to natural gas as well as electricity. The installation requirements for the GF/AC system are negligible and will be excluded from this study. The GSHP system requires a much more substantial and impactful installation process.

The first step in GSHP system installation is drilling the borehole. The transportation required to deliver the necessary machinery and equipment to the home will be included in this section. This section must also include the process of filling the completed borehole with grout.

3.2.4 Operation

As previously stated, eQuest was used to determine that the home's annual heating and cooling loads are 31,905 Btu/hr and 22,136 Btu/hr respectively. The annual energy consumption for each system can be calculated by dividing the heating and cooling loads by the efficiency of the system. The natural gas furnace has an AFUE of 0.9, the air conditioner has a SEER of 13, and the GSHP system has a COP of 3.8 for heating and a SEER of 17 for cooling.

Table 9: Annual and 20-year heating and cooling requirements of GF/AC and GSHP systems.

System	**Cooling (Btu/hr)**	**Heating (Btu/hr)**	**20-Year Life Span (Btu/hr)**
GF/AC	5,811.5	35,450	825,230
GSHP	4,445	7,976	248,420

3.2.5 End-of-Life

Consistent with Greening and Azapagic [20], it is assumed that for end-of-life treatment, the metals within the furnace, air conditioner, and heat pump and the refrigerant in the air conditioner and heat pump were all recycled. Consistent with Saner *et al.* [13], it was also assumed that the grout and ground loop piping was left in the ground and the glycol solution was pumped out of the ground loop.

3.3 Life Cycle Impact Assessment

ISO 14040/44 requirements for this phase of the LCA are vague and unspecific. ISO standards require a clear identification of the chosen impact categories, category indicators, characterization models, and endpoint categories, however, these standards not identify or require any specific impact categories, indicators, methods, or endpoint categories to be used. The chosen impact categories represent the environmental impacts that will be considered in the LCA. Each impact category has a category indicator, which can be any measurable environmental mechanism related to that environmental impact. The characterization model is the conversion of LCI results into common units and the aggregation of the results within the impact category. Endpoint categories reflect the damage that the impact categories may cause. For this reason, many LCIA models and methods exist. Each LCIA method has its own set of impact categories, indicators, and characterization methods, although many have overlapping or similar qualities. Collectively over 90 impact categories have been suggested for use in LCA literature [51]. It has been argued in the literature that LCA studies ought to have a standardized list of impact categories to ensure more accurate comparisons [12]. Table 10 displays the studies examined in the previous section, the LCIA methodologies employed, and the LCA software used. It can be seen from the studies that utilized existing LCIA methodologies that they each used a different method. Owsianiak *et al.* [52] conducted three identical studies using IMPACT 2002+, ReCiPe 2008, and ILCD 2009 to compare the LCIA results. ILCD is not listed in Table 10; however, it refers to the LCIA method recommended by the International Reference Life Cycle Data System. It was determined that the three methods all pointed to the same general conclusions. For impact categories relating to toxic impacts, ionizing radiation, land use, and resource depletion, results varied between all three methodologies. All other 10-15 impact categories studied displayed minimal variation.

Table 10: LCIA methodology and LCA software used in current literature.

Study	**LCIA Methodology**	**LCA Software**
Saner *et al.* [13]	ReCiPe 2008	SimaPro
Greening and Azapagic [20]	CML 2 Baseline 2001	GaBi
Rodriguez, Bangueses, and Castro [44]	IMPACT 2002+	Not stated
Huang & Mauerhofer [45]	Not stated	GaBi
Hong *et al.* [19]	Not stated	Not stated
Koroneos and Nanaki [18]	Not stated	SimaPro

There are also a number of software programs available to model a product or system and examine its life cycle environmental impacts. Of the two listed in Table 10, the software that will be used for this study is GaBi [53]. GaBi allows the user to model the entire life cycle of a product or system. With access to immense databases that GaBi provides, the user has access to pre-existing materials, energy, and emission data. Alternatively, the program allows the user to create new project-specific inputs and outputs if required. The software is able to simulate the life cycle of the product or system and calculate its life cycle environmental impacts. With all else equal, GaBi was chosen over SimaPro because it provides fully funded licenses to researchers.

For the LCIA methodology, ReCiPe 1.08 was chosen, which examines a list of 16 impact categories and 3 endpoint categories. These categories encompass the most significant potential impacts associated with human and environmental health. Table 11 lists the impact categories to be examined, the associated category indicator, and the characterization method. The table also lists the endpoint category or categories associated with each impact category. The endpoint categories chosen for this study are damage to human health, ecosystem quality, and resource availability.

Table 11: Impact categories, category indicators, characterization methods, and associated endpoint categories.

Impact Category	**Category Indicator**	**Categorization Factor**	**Unit**	**Endpoint**
Climate Change	Increased radiative forcing	GWP	kg CO_2 eq	Human Health & Ecosystem Quality
Ozone Depletion	Decreased stratospheric ozone	ODP	kg CFC11 eq	Human Health
Human Toxicity	Increased human illness	Cancer & Non-cancer Illlnesses	kg 1,4-DB eq	Human Health
Particulate Matter Formation	Increased respiratory human illness	Air Quality	kg PM_{10} eq	Human Health
Ionizing Radiation (human)	Increased environmental contamination	Cancer	kg U235 eq	Human Health
Photochemical Ozone Formation	Increased tropospheric ozone	Acute and Chronic Illness	kg NMVOC	Human Health
Terrestrial Acidification	Decreased pH of soil	Accumulated Exceedance	kg SO_2 eq	Ecosystem Quality
Eutrophication (freshwater)	Increased N	Accumulated Exceedance	kg P eq	Ecosystem Quality
Eutrophication (marine)	Increased P	Accumulated Exceedance	kg N eq	Ecosystem Quality
Ecotoxicity (freshwater)	Increased environmental contamination	Biodiversity Loss	kg 1,4DB eq	Ecosystem Quality
Ecotoxicity (marine)	Increased environmental contamination	Biodiversity Loss	kg 1,4DB eq	Ecosystem Quality
Ecotoxicity (terrestrial)	Increased environmental contamination	Biodiversity Loss	kg 1,4DB eq	Ecosystem Quality
Water Depletion	Scarcity	Displaced Quantity	m^3	Resource Availability
Metal Depletion	Scarcity	Displaced Quantity	kg Fe eq	Resource Availability
Fossil Depletion	Scarcity	Displaced Quantity	kg oil eq	Resource Availability
Agricultural Land Occupation	Scarcity	Displaced Quantity	m^2	Resource Availability

Climate change is a very common impact category in LCA literature, and is often referred to as global warming [13, 18, 19, 20, 44, 45]. LCA studies calculate the impact on climate change or global warming using the characterization method called Global Warming Potential (GWP). GWP quantifies the category indicator of integrated infrared radiative forcing increase of a GHG over a time period of 20, 100, or 500 years, measured in kg CO_2-eq [54]. The ReCiPe 1.08 method uses GWP100 (GWP over 100 years) [55], which is consistent with the timeframe that the Kyoto Protocol and the Paris Agreement uses to measure GWP. This is a universally accepted category indicator, as the Intergovernmental Panel on Climate Change (IPCC) developed a standardized list of GWP of all GHGs that is publicly available [56]. Figure 14 illustrates the cause and effect chain of climate change as an impact category and how it contributes to the human health and ecosystem quality endpoint categories. Using the ReCiPe method, the impact of climate change on human health is associated with estimated heat stress, malnutrition, infectious diseases, and flooding. Overall damage of these effects to human health is measured in disability-adjusted life years (DALY), where one DALY refers to the loss of one year of healthy life due to disease and/or disability [57]. The effects of climate change on ecosystem quality is associated with decreasing biodiversity caused by changing biomes, which is measured in Potentially Disappeared Fraction (PDF) of species. PDF is the rate of species loss in specified area of land or volume of water per year, and is therefore often referred to in the unit ‘species/year’.

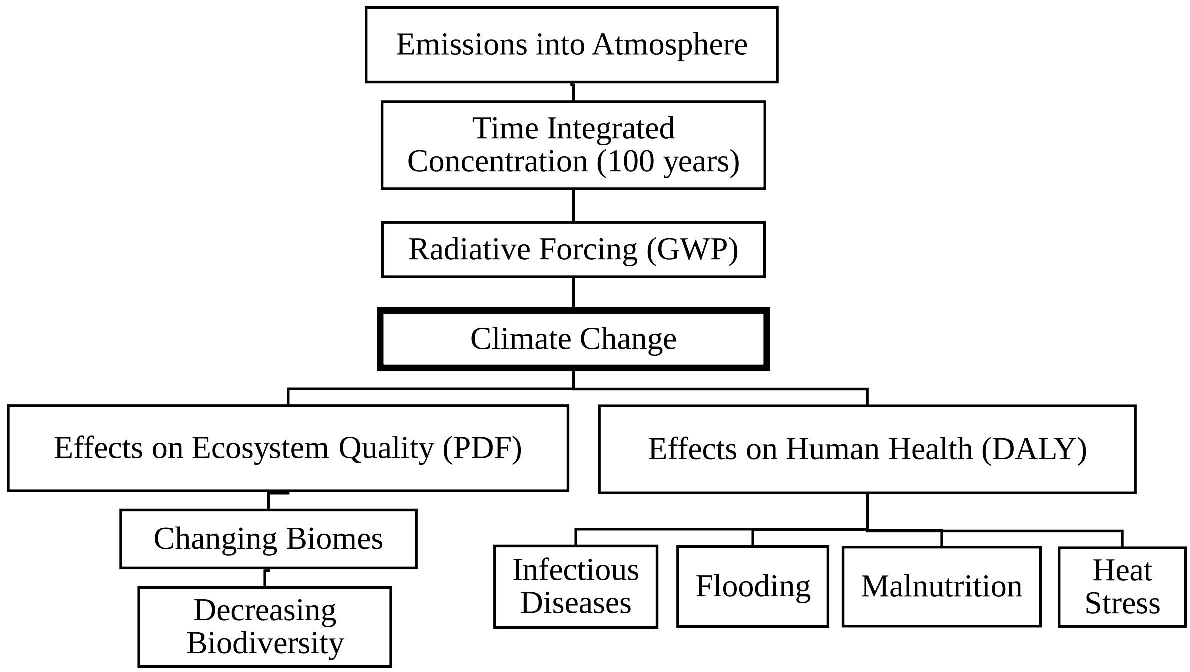

Figure 14: Climate Change cause and effect chain. (Reproduced from [55])

Ozone depletion is another common impact category, sometimes referred to as 'stratospheric' ozone depletion. LCA studies calculate ozone depletion using the characterization method called ozone depletion potential (ODP). ODP measures the category indicator of a decrease in stratospheric ozone concentration caused by the cumulative effect of a substance, relative to the impact of CFC-11 or R-11, over an infinite time period [55, 58, 59]. ODPs of ozone depleting substances are published by the World Meteorological Organization (WMO), and are quantified in kg CFC-11 eq [59]. Ozone depleting substances, generally described as halocarbons, contain chlorine, fluorine, bromine, carbon, and hydrogen. When these substances are emitted, UV radiation in the stratosphere breaks up the molecules into chlorine or bromine, depending on the molecular composition and structure of the substance, which breaks up ozone [60]. The cause and effect chain from impact category to the endpoint category of human health is shown in Figure 15. Overall impact on human health is measured in DALY, which examines skin cancer and cataract caused by an increase UV-B exposure due to decreased ozone concentration [55, 58]. There is currently insufficient literature to determine effects of ozone depletion on ecosystem quality.

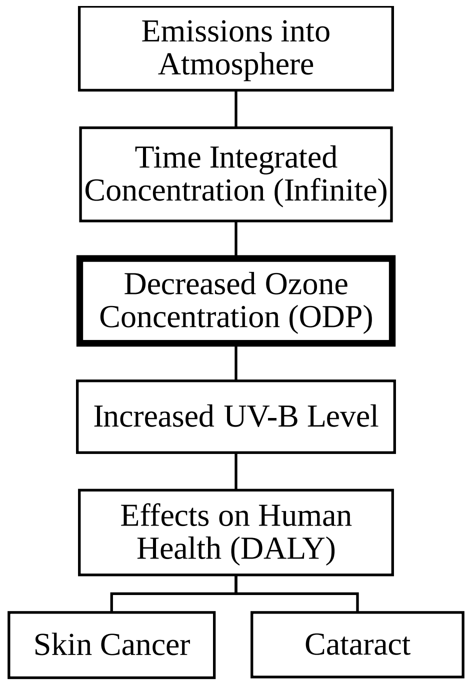

Figure 15: Ozone Depletion cause and effect chain. (Reproduced from [55])

The ReCipe LCIA method examines human toxicity in terms of carcinogens and non-carcinogens. Human toxicity is measured by examining the fate of waste and emissions in the environment, the potential channels of human exposure, and the associated toxicological response, measured in kg 1,4-dichlorobenzene (kg 1,4-DB eq). Figure 16 illustrates the cause and effect chain of substances entering the environment and their effect on human health. Toxic substances can come into contact with humans through emissions to the air, water, and soil. These substances can then be injected or inhaled by humans, which causes negative health impacts such as various cancers or non-cancer diseases.

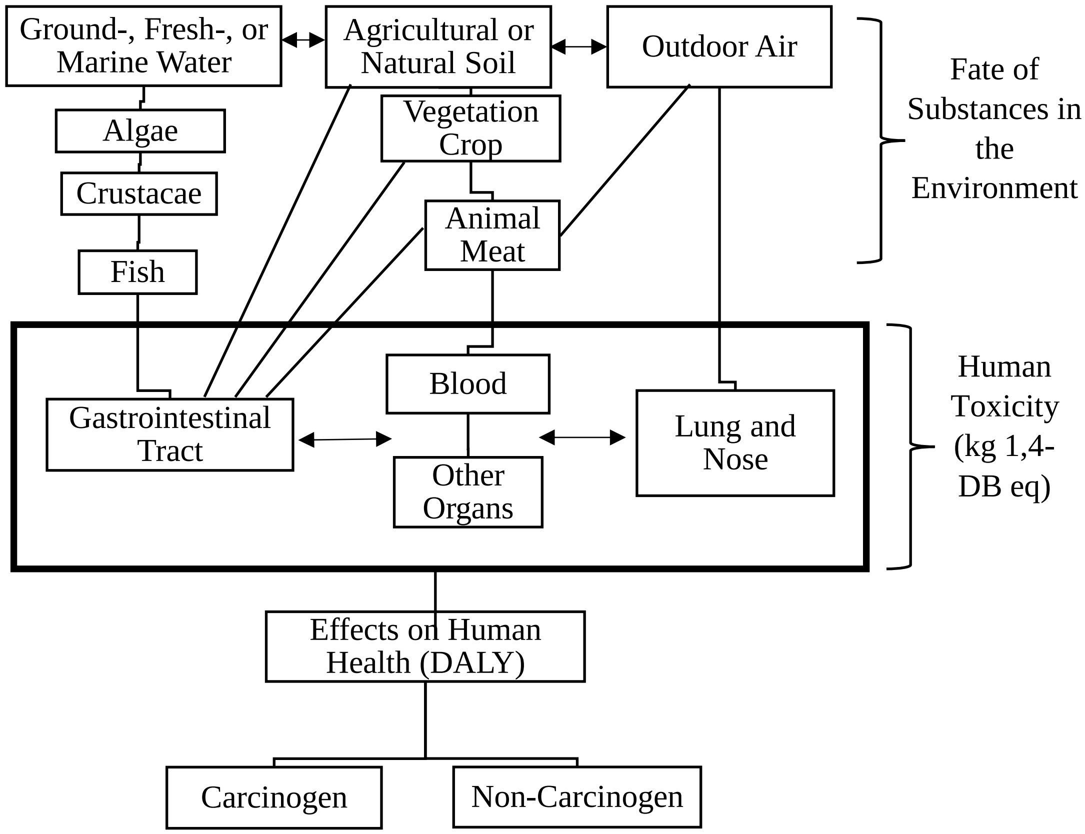

Figure 16: Human Toxicity cause and effect chain. (Reproduced from [55])

Particulate matter air pollution is another important impact category when calculating pollution impacts on human health [55, 61]. Particulate matter includes aerosols, smoke, fumes, ash, and dust. The ReCiPe method calculates both primary PM as well as secondary PM, which is created by chemical reactions in the atmosphere of SO_2 and NO_x emissions, in terms of PM_{10} [55]. The endpoint category associated with particulate matter and respiratory inorganics is human health, measured in DALY. Health effects considered to be caused by PM_{10} includes chronic bronchitis, asthma, lower respiratory infections, chronic cough, and congestive heart failure [55]. There is insufficient literature regarding calculation of PM_{10} impacts on ecosystems.

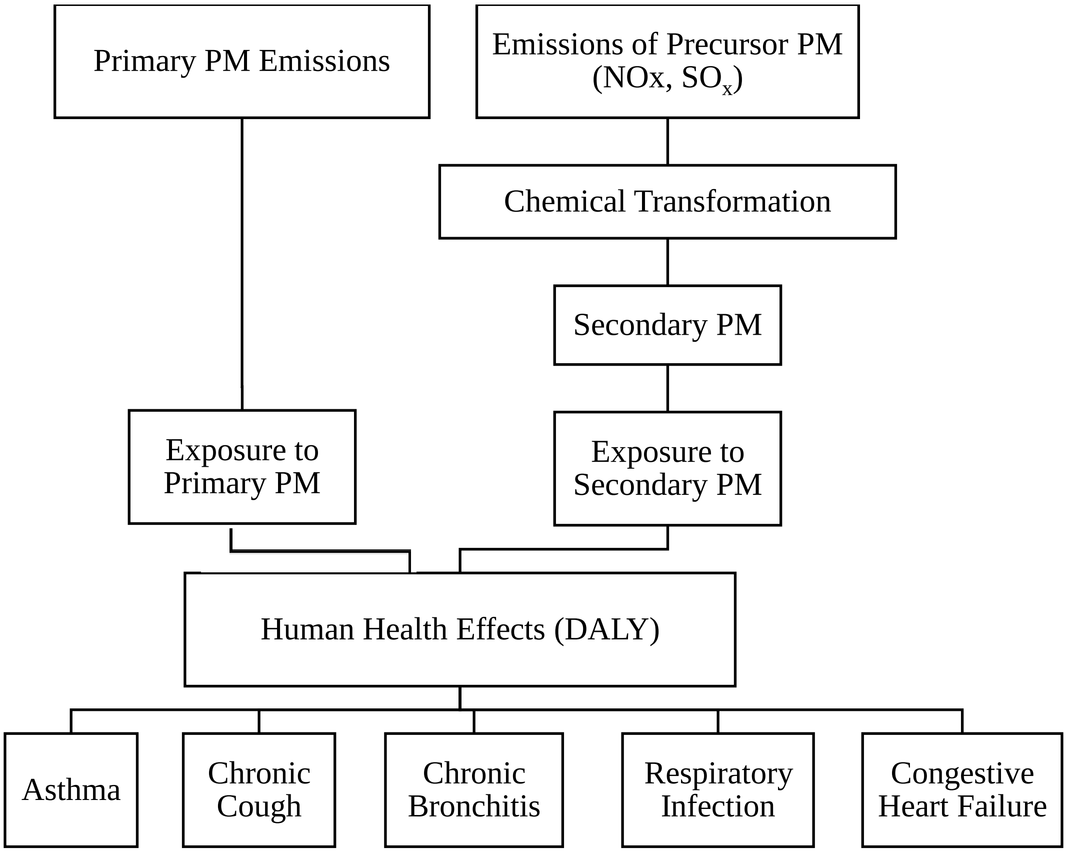

Figure 17: Particulate Matter Formation cause and effect chain. (Reproduced from [55])

Ionizing radiation is measured in terms of kg U235-eq. This impact category examines the release of radioactive material to the environment. The cause and effect chain for ionizing radiation to its endpoint of human health is very similar to that of the human toxicity impact categories, seen in Figure 16, although it only considers carcinogens as having human health impact. Additionally, the impact category of ionizing radiation examines the release of radioactive material into the environment as opposed to the emissions examined in the human toxicity impact category. The effects of ionizing radiation on human health is recorded in DALY.

The photochemical ozone formation impact category measures the increase in ozone formation due to the emissions of non-methane volatile organic compounds (kg NMVOC). Tropospheric ozone is created when VOCs, NO_x, or CO react in the atmosphere in the presence of sunlight. The only endpoint category considered is human health, measured in DALY, which examines both acute and chronic effects. The cause and effect chain of tropospheric ozone creation on human health is shown in Figure 18.

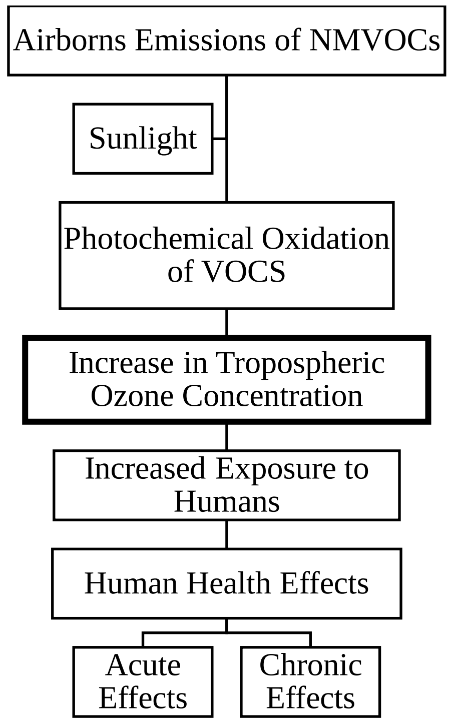

Figure 18: Photochemical ozone formation cause and effect chain. (Reproduced from [55])

Terrestrial acidification is an impact category that measures the change in soil due to the deposition of acidifying nutrients such as NO_x and SO_2 [55]. This process results in a decline in soil pH as well as an increase in dissolved aluminum in the soil. The category indicator for acidification is accumulated exceedance (AE). AE is the excess deposition of a substance in an ecosystem above its critical load in a given space. AE is calculated by adding up the reduction required to achieve non-exceedance. GaBi quantifies this by calculating substances in equivalence to kg SO_2 eq. The endpoint category considered for terrestrial acidification is ecosystem quality, as it causes a significant decline in soil fertility, and therefore is measured in PDF of species.

Figure 19 displays the complex journey of acidifying nutrients in the environment and their eventual impact on ecosystem quality.

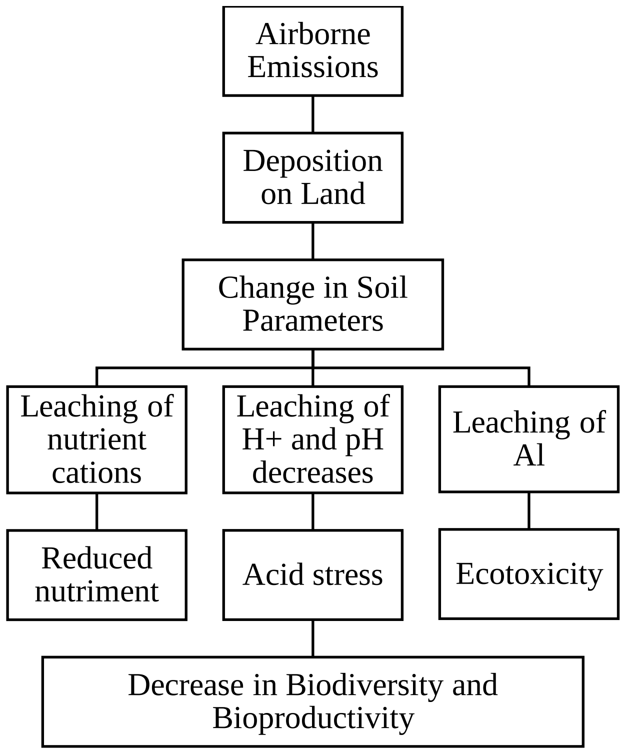

Figure 19: Terrestrial Acidification cause and effect chain. (Reproduced from [55])

The ReCiPe LCIA method separates eutrophication into two separate impact categories; freshwater and marine water. Aquatic eutrophication is the negative effect of excessive nutrient content in the water, namely phosphorus and nitrogen. Freshwater eutrophication is measured in terms of phosphorous-compound emissions only (kg P eq), and marine eutrophication is measured in nitrogen only (kg N eq). These two eutrophication-based impact categories are both related to the endpoint category of ecosystem quality, measured by PDF of species. Figure 20 illustrates the cause and effect chain of terrestrial, freshwater, and marine eutrophication.

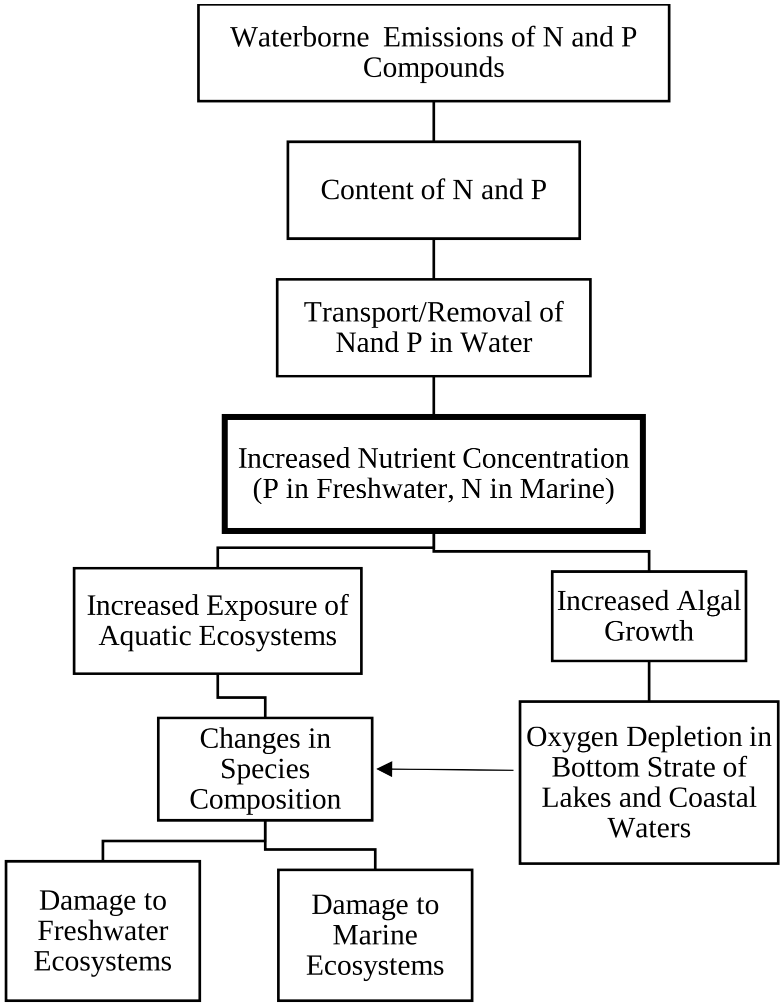

Figure 20: Eutrophication cause and effect chain. (Reproduced from [55])

The ReCiPe method separates ecotoxicity in to three independent categories: freshwater, marine, and terrestrial. Ecotoxicity is very similar to the impact category of human toxicity; however, the endpoint category associated is ecosystem quality, measured in PDF of species. These impact categories examines the contamination of marine water, freshwater, groundwater, and soil due to emissions, and the associated impact on species and their relative ecosystems. Figure 21 illustrates the complex cause and effect change of ecotoxicity. The arrows at the top of the figure represent the incoming emissions affecting the environment.

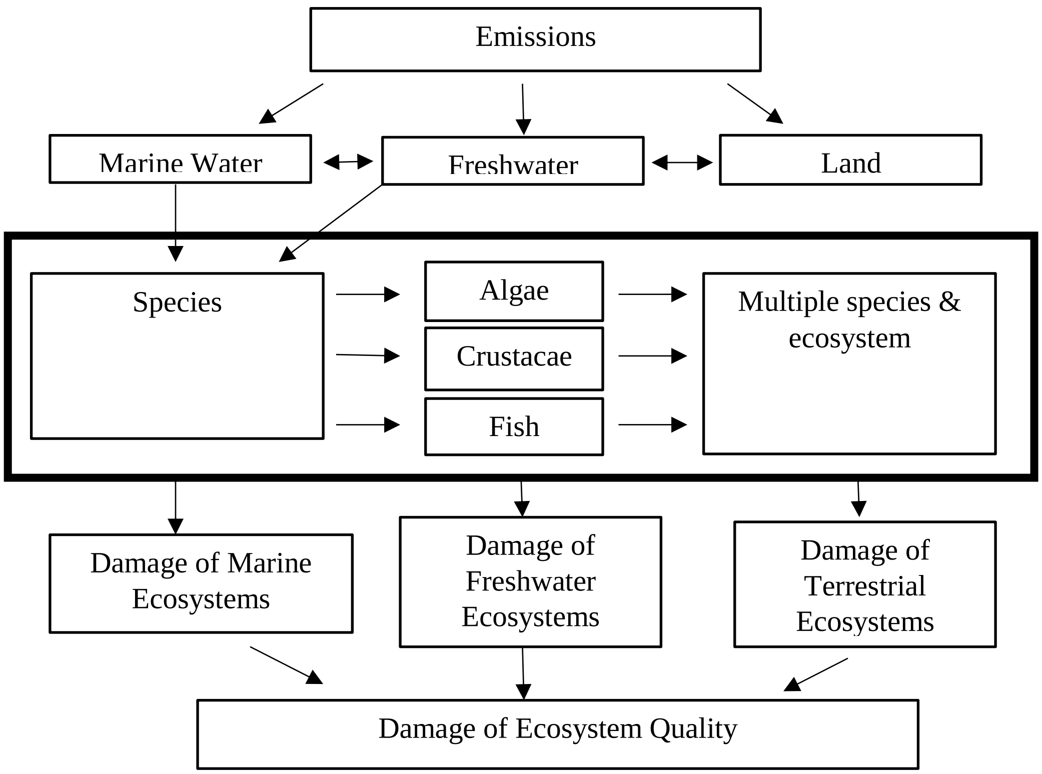

Figure 21: Ecotoxicity cause and effect chain. (Reproduced from [55])

Resource depletion is separated into four impact categories; water, fossil, and metal depletion, as well as agricultural land occupation. Water depletion is simply measured in terms of m^3 of water used throughout the systems' life cycle that is no longer available. Metal depletion is measured in kg Fe eq depleted throughout the systems life cycle. Fossil depletion is measured in kg oil eq, and agricultural land occupation is measured in m^2.

3.3.1 GaBi Software

As mentioned, GaBi is software used to facilitate LCAs [53]. It provides the user with an immense database containing information including but not limited to materials, products, and systems use and manufacturing, various transportation methods, fuel and energy production and use. This database allows the user to input all components included in the scope of an assessment and create a model that illustrates the use of these components. The user is able to connect the manufacturing, transportation, installation, use, and disposal processes of the product or system being modelled. Once the model is complete, the user is able to simulate the environmental impact of the product or system based on the chosen methodology.

As mentioned, this study will be using the ReCiPe method. Using this method, GaBi calculates the 16 environmental impact categories based on the items included in the model by the user. These calculations are made using conservation of mass and unit conversion equations, which convert the emission and resource use data included in the model into the units associated with each of the impact categories. The units are then further converted into the associated endpoint category units. Table 12 summarizes the approximate conversion factor of each impact category to its associated endpoint category. As shown, the ozone depletion impact category is calculated using a number of different values representing different subgroups of ozone depleting substances. For all zero values, the midpoint categories are not considered in the final overall impact of the systems.

Table 12: Summary of Conversion Factors for Impact Category to Endpoint Category (Reproduced from [62])

Impact Category	Unit	Human Health (DALY)	Ecosystem Quality (PDF)	Resource Depletion (US$)
Climate Change	kg CO_2 eq	1.40×10^{-6}	8.73×10^{-6}	
Ozone Depletion	kg CFC11 eq	CFC 1.76×10^{-3} CCL_4 3.30×10^{-3} CH_3CCl_3 4.41×10^{-3} Halons 2.64×10^{-3} HCFCs 3.65×10^{-3} CH3Br 4.72×10^{-3}		
Human Toxicity	kg 1,4-DB eq	7.0×10^{-7}		
PM Formation	kg PM_{10} eq	2.6×10^{-4}		
Ionizing Radiation	kg U235 eq	1.64×10^{-8}		
Photochemical Ozone Formation	kg NMVOC	3.9×10^{-8}		
Terrestrial Acidification	kg SO_2 eq		1.52×10^{-9}	
Eutrophication (freshwater)	kg P eq		4.44×10^{-8}	
Eutrophication (marine)	kg N eq		0	
Ecotoxicity (freshwater)	kg 1,4-DB eq		8.61×10^{-10}	
Ecotoxicity (marine)	kg 1,4-DB eq		1.76×10^{-10}	
Ecotoxicity (terrestrial)	kg 1,4-DB eq		1.51×10^{-7}	
Water Depletion				0
Metal Depletion				0.0715
Fossil Depletion				0.165
Agricultural Land Occupation				1.969×10^{-8}

The ReCiPe method in GaBi provides the user with the option to use the Individualist (I) method, the Hierarchist (H) method, or the Egalitarian (E) method. The conversion factors in Table 12 are used by the 'Hierarchist' version, which is the most commonly used of the three because it uses a 100-year time frame when calculating impacts, such as GWP. The individualist version is based on a short-term time frame of 20 years, while the egalitarian time frame is 500 years. As stated previously, to be consistent with the Kyoto Protocol and the Paris Agreement, the 100-year time frame will be used.

One of the main strengths of this software is the vast availability of data included in the database. Almost any material can be found in the database with multiple options from which to choose. The software allows the user to choose the option most appropriate for their work by providing the date in which the data was acquired, and whether the data is based on industry reporting, academic sources, calculations, or assumptions. It is important to note that this database is called the US Life Cycle Inventory database, and was developed in 1990 by the US National Renewable Energy Laboratory (NREL) [63]. A potential weakness of the software is that if a material or product is not included in the database, the user must create their own process. While the products or materials already available in the dataset have extremely detailed existing input and output data, anything created by the user may be simplified, resulting in an incomplete or less accurate model. All data used for this study was acquired from the existing database.

3.4 Interpretation

ISO standards require the interpretation phase of the LCA to present the findings from the LCIA, reach conclusions, explain any limitations experienced throughout the study, and provide recommendations [21, 22]. The following results and discussion section will represent the interpretation stage of the life cycle assessment.

4.0 RESULTS & DISCUSSION

Using the data provided in the life cycle inventory analysis (3.2), each system component was modeled using GaBi. As seen in Figure 22, galvanized steel, steel, copper, and aluminum are the primary raw materials required to manufacture the natural gas furnace. From the manufacturer, which was assumed to be the Carrier Corporation facility in Nuevo Leon, Mexico, the GF travels approximately 3000 km by rail transport, and 100 km by truck. It was assumed that the rail transport system is electrified as opposed to diesel. The electricity mix applied to rail transport was a mix of the Eastern States through which it was expected to travel. After the rail transport, the GF travels another estimated 100 km in a diesel 40 tonne transport truck. Finally, the GF enters the operational stage of its life cycle, consuming a total of 748.6 MJ (709,000 Btu) thougout its 20-year life cycle. The end-of-life stage of the GF would require recycling of the metals. Insufficient data was available using GaBi to model an accurate representation of this life cycle stage. To maintain consistency, the end-of-life stage was omitted from each model. This was not expected to have a change in the overall outcome of the results.

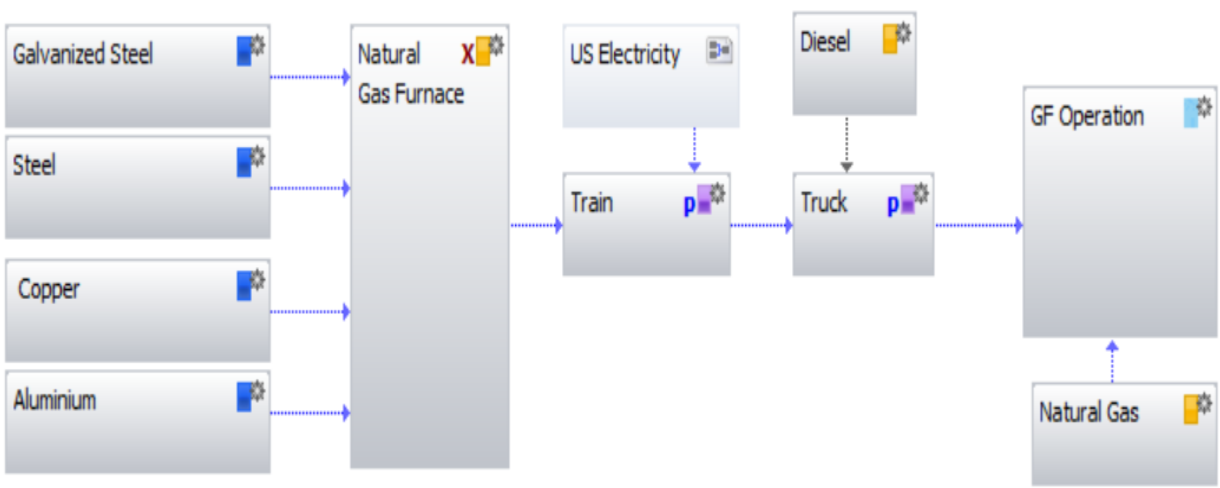

Figure 22: Natural Gas Furnace Life Cycle Model in GaBi

The air conditioner begins its life cycle with the raw materials of galvanized steel, steel, copper, aluminum, and refrigerant. The AC was assumed to be produced by the same manufacturer as the GF, Carrier Corporation; the two components have an identical transportation stage. The 20-year operational stage of the AC will require 122.7 MJ (116,230 Btu) of Ontario electricity. Ontario's electricity mix can be referenced in Figure 2. Figure 23 illustrates the AC model produced in GaBi. As stated, the end-of-life stage was not modelled; however, it would include the recycling of the metals as well as the refrigerant within the AC unit. The refrigerant is not seen in the model's illustration; however, it lies within the AC manufacturing stage.

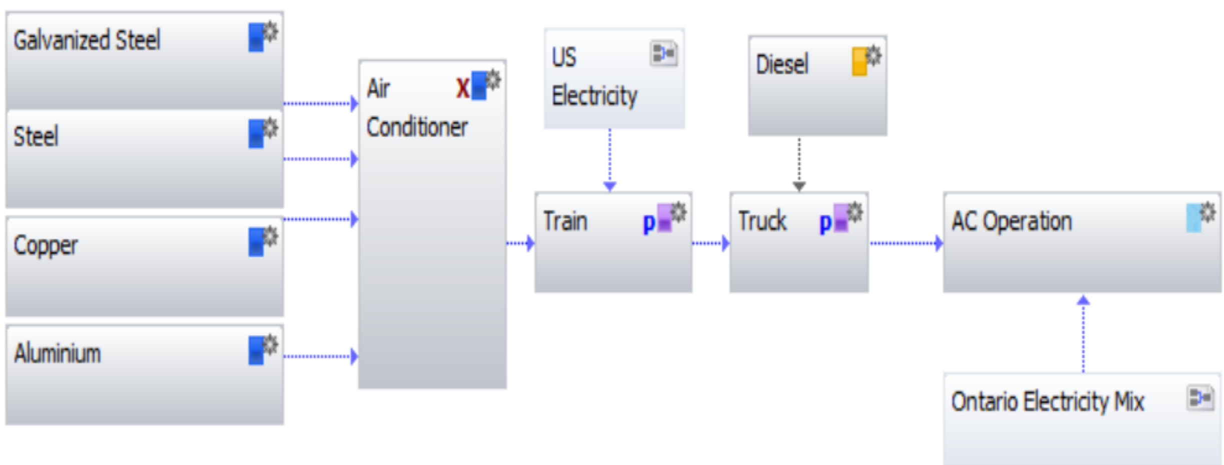

Figure 23: Air Conditioner Life Cycle Model in GaBi

The life cycle model of the heat pump for the GSHP system can be seen in Figure 24. The raw materials that enter the manufacturing process are elastomer, copper, polyvinylchloride, low-alloyed steel, reinforcing steel, and lubricating oil. The transportation stage of the heat pump's life cycle is identical to the GF and AC because the heat pump was also assumed to be manufactured by Carrier Corporation. The operational stage of the heat pump requires 262.3 MJ (248,423 Btu) of Ontario electricity.

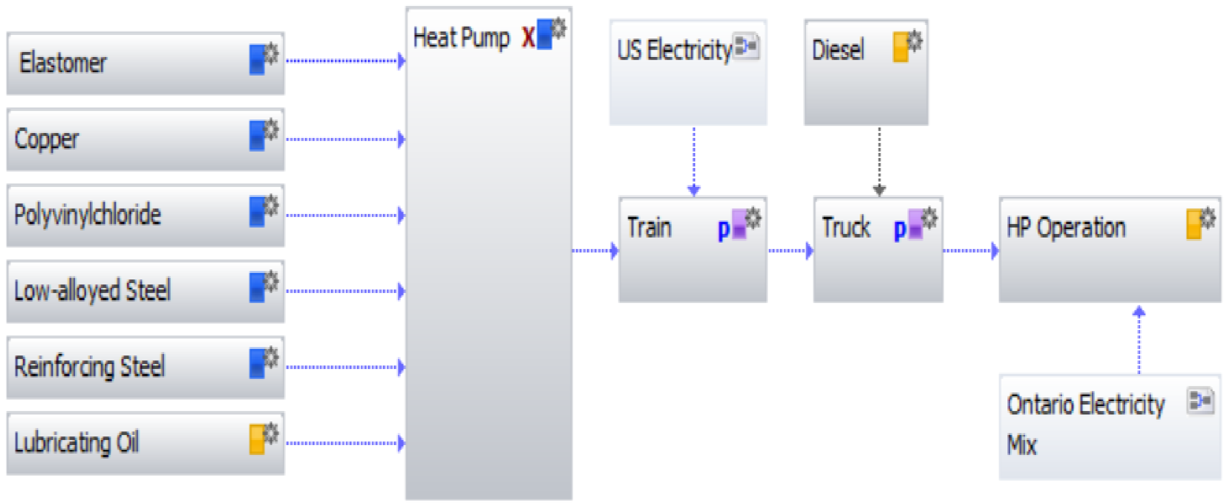

Figure 24: Heat Pump Life Cycle Model in GaBi

The HDPE ground loop pipes are manufactured by melting and shaping HDPE resin pellets, produced through the polymerization of ethylene. As seen in Figure 24, ethylene begins the life cycle, which produces the HDPE pellets needed to manufacture the ground loop piping. In the previous three models (the dataset in which the raw materials were selected), the energy required for manufacturing was included. For the ground loop model, the ethylene and HDPE resin processes include their required energy; however, the addition of an electricity source was needed to represent the energy required for the melting and forming of the pellets into piping. It was assumed that the piping was manufactured by Tianjin Junxing Pipe Group in China. The piping is transported via ocean freight for an estimated 10,000 km, running on heavy fuel oil. Next, the piping is transported via 40 tonne, diesel transport truck, identical to that in the other models, for 100 km. The operation stage of the ground loop piping neither requires inputs nor produces outputs. At the end of the life cycle, it is assumed that the pipes are left buried in the ground with no recycling or treatments.

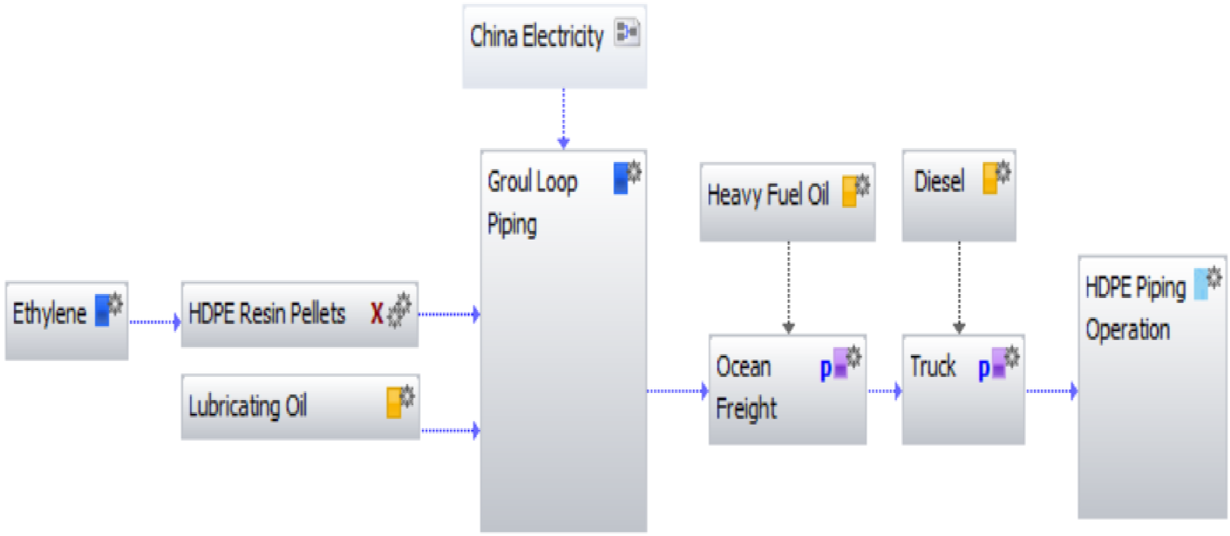

Figure 25: Ground Loop Life Cycle Model in GaBi

Propylene glycol is modelled in Figure 25, which is the glycol component in the glycol/water mixture solution circulated in the ground loop piping. The primary raw materials required for the manufacturing of propylene glycol are propylene oxide, methanol, and sodium hydroxide. The raw materials undergo a chemical reaction, in which electricity and natural gas are needed. It was assumed that the glycol was produced by Dow Chemical Company, located in Michigan, USA. During the operational stage of the life cycle, the glycol requires no further inputs and generates no further outputs. At the end-of-life stage, the glycol solution can be pumped out of the ground loop pipes. The solution is safe for disposal into the drain of the building and does not require treatment prior to disposal.

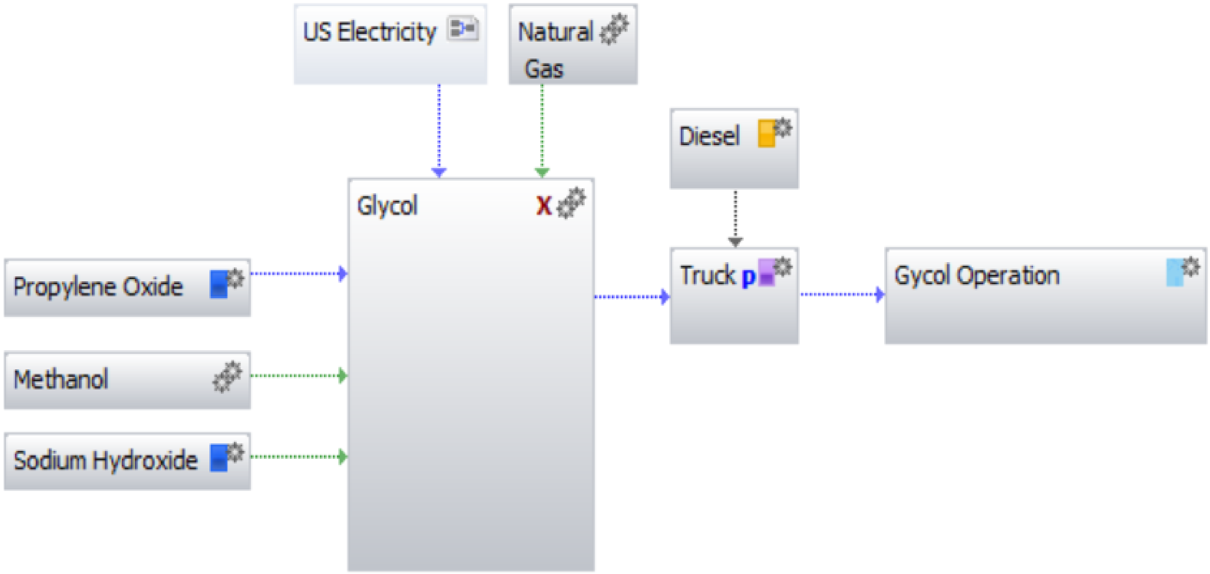

Figure 26: Propylene Glycol Life Cycle Model in GaBi

The life cycle model of the grout required to fill the borehole of the GSHP system is shown in Figure 26. The raw material composition of the grout is 9.5 parts cement to 0.5 parts bentonite. The bentonite is not shown in the image as it is nested within the grout manufacturing. Cement is shown on its own as it has a manufacturing process of its own. The assumed manufacturer for the grout was CanPipes, which has a location in Toronto, Ontario. For this reason, the grout was assumed to be transported 30 km. The grout was assumed to be left buried in the ground at the end of its life cycle.

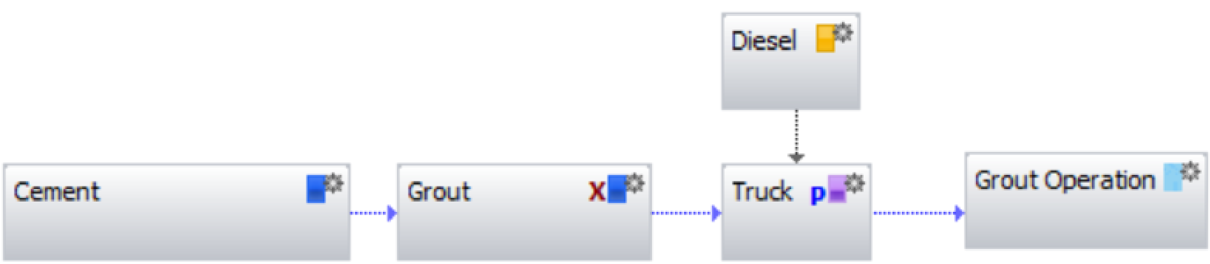

Figure 27: Grout Life Cycle Model in GaBi

The ReCiPe 1.08 LCIA method was applied to the models to determine their environmental impacts on the 16 categories examined. The results presented in Table 13 overview some unexpected findings. For a detailed view of the data used to create Table 13, see Appendix A and B.

Table 13: Summary of Life Cycle Environmental Performance of the GF/AC and GSHP Systems.

Impact Category	GF	AC	Total GF/AC System	Heat Pump	Ground Loop	Glycol	Grout	Borehole	Total GSHP System
Climate Change (kg CO_2-eq)	203.551	379.433	582.98	390.305	688.276	95.3	857	21.4	2052.281
Ozone Depletion (kg CFC-11 eq)	1.08 $x10^{-6}$	6.07 $x10^{-6}$	7.15 $x10^{-6}$	6.37 $x10^{-7}$	6.42 $x10^{-10}$	3.76 $x10^{-8}$	4.17 $x10^{-5}$	4.12$x10^{-10}$	4.24$x10^{-5}$
Human Toxicity (kg 1,4-DB eq)	94.860	170.045	264.9	71.739	114.681	1.817	11.974	1.03	201.241
Particulate Matter Formation (kg PM_{10} eq)	0.327	0.619	0.946	0.511	2.231	0.075	0.645	0.016	3.477
Ionizing Radiation (kg U235 eq)	4.312	15.944	20.256	21.932	4.098	10.732	2.161	0.125	39.049
Photochemical Ozone Formation (kg NMVOC)	0.534	0.970	1.504	0.953	1.764	0.158	2.101	0.044	5.019
Terrestrial Acidification (kg SO_2 eq)	0.683	1.328	2.011	1.407	22.673	0.292	2.038	0.441	6.455
Freshwater Eutrophication (kg P-eq)	3.4 $x10^{-4}$	6.3 $x10^{-4}$	9.74 $x10^{-4}$	1.71 $x10^{-3}$	2.737 $x10^{-4}$	5.36 $x10^{-5}$	1.73 $x10^{-4}$	2.38 $x10^{-4}$	0.002
Eutrophication – Marine (kg N-eq)	0.023	0.041	0.064	1.23 $x10^{-4}$	0.067	0.006	0.074	0.011	0.158
Freshwater Ecotoxicity (kg 1,4-DB eq)	0.121	0.199	0.3203	0.8099	0.075	0.018	0.021	0.010	0.9339
Marine Ecotoxicity (kg 1,4-DB eq)	0.953	1.77	2.728	1.960	0.814	0.012	0.060	0.014	2.846
Terrestrial Ecotoxicity (kg 1,4-DB eq)	0.052	0.103	0.155	0.1208	0.052	9.89 $x10^{-4}$	0.016	5.64 $x10^{-5}$	0.190
Water Depletion (m^3)	250.938	845.583	1096.52	1273.096	786.464	57.417	1.585	3.16	2118.562
Metal Depletion (kg Fe-eq)	683.731	1270	1951.261	1392.591	2.932	0.267	6.865	0.088	1402.655
Fossil Depletion (kg oil-eq)	72.925	104.520	176.977	109.178	221.773	27.8	79.597	14.5	438.708
Agricultural Land Occupation (m^2)	1.493	2.595	4.088	1.7494	12.384	0.362	0.16	1.09	12.384

As seen in Table 12, in all but two impact categories the GSHP system had a greater negative environmental impact than the GF/AC system. Although it is important for this study to compare the impacts of the two systems, it is also important to examine the magnitude of these impacts. From Table 12, it can be seen that for the impact categories of ozone depletion, freshwater and marine eutrophication, and freshwater and terrestrial ecotoxicity, the values associated with each category are very small. For example, when looking at the ozone depletion row, the GSHP system impact is six times greater than that of the GF/AC system; however, the values are so small that they are both insignificant regardless of which is greater than the other. This detail is important to consider when observing the following figures in this section.

It is also important to reiterate that the scope of this study involved only one residential home. While some of the values previously identified are insignificant to this particular work, if the scope of the study were to be expanded to include residential, commercial, and institutional buildings across Ontario, these values may not remain insignificant.

In order to gain a better understanding of the environmental impacts at each stage of the life cycle, it is valuable to display the comparable results of the GF/AC system and the GSHP system at each stage of their life cycles. The effects of the manufacturing stage of the life cycle on the 16 impact categories are displayed in Figure 28.

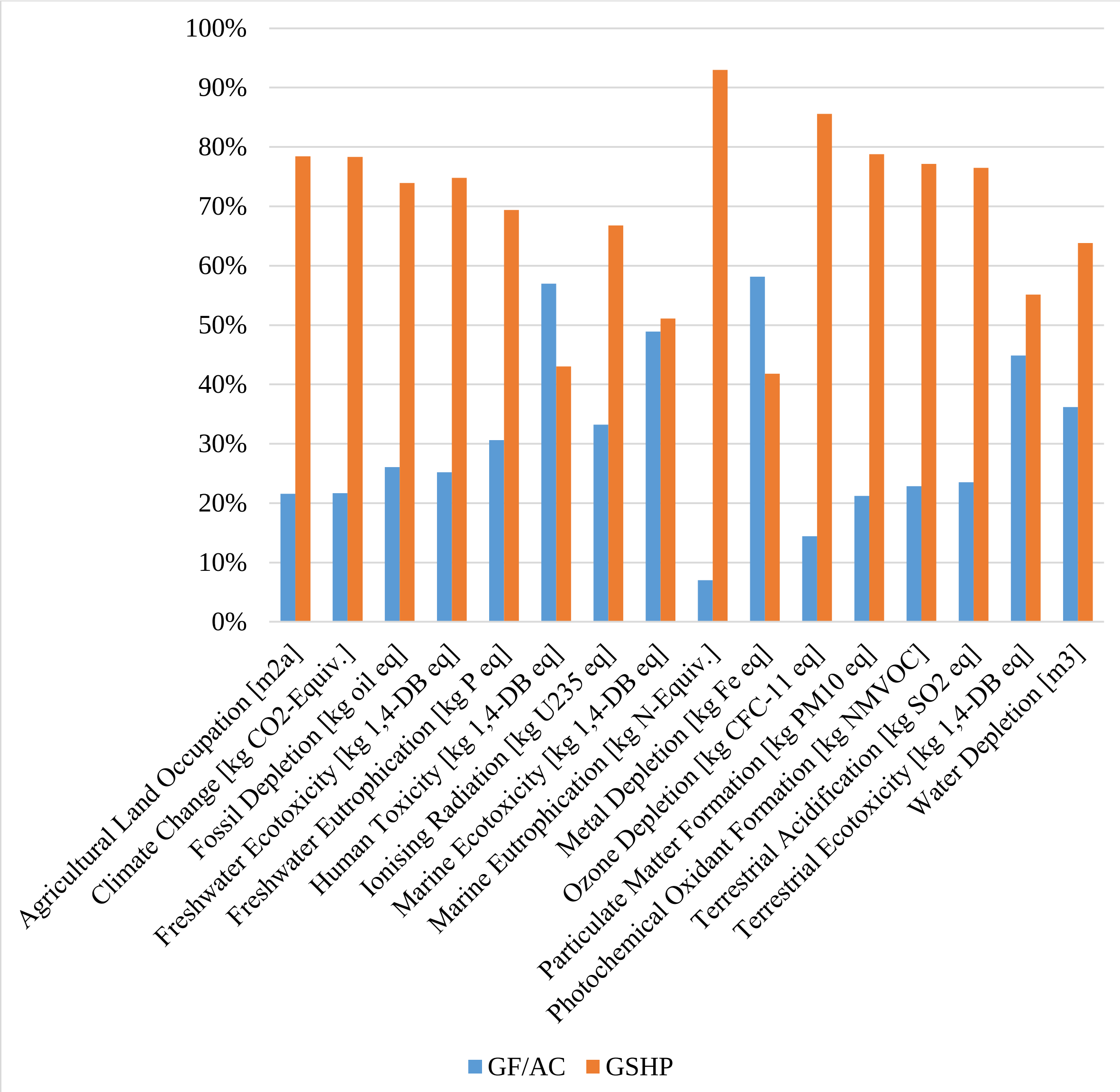

Figure 28: Manufacturing Life Cycle Stage – GF/AC vs GSHP system

Figure 28 shows that the GSHP system has a higher impact in all but two categories throughout the manufacturing life cycle stage. Figure 29 examines the manufacturing impacts of each system component. Grout manufacturing has the highest impact on ozone depletion, which was mostly linked to the cement manufacturing within the grout model (Figure 27). The GF and AC components combined have the greatest impact on metal depletion and human toxicity, while the heat pump from the GSHP system has the most significant impact on freshwater eutrophication and freshwater ecotoxicity.

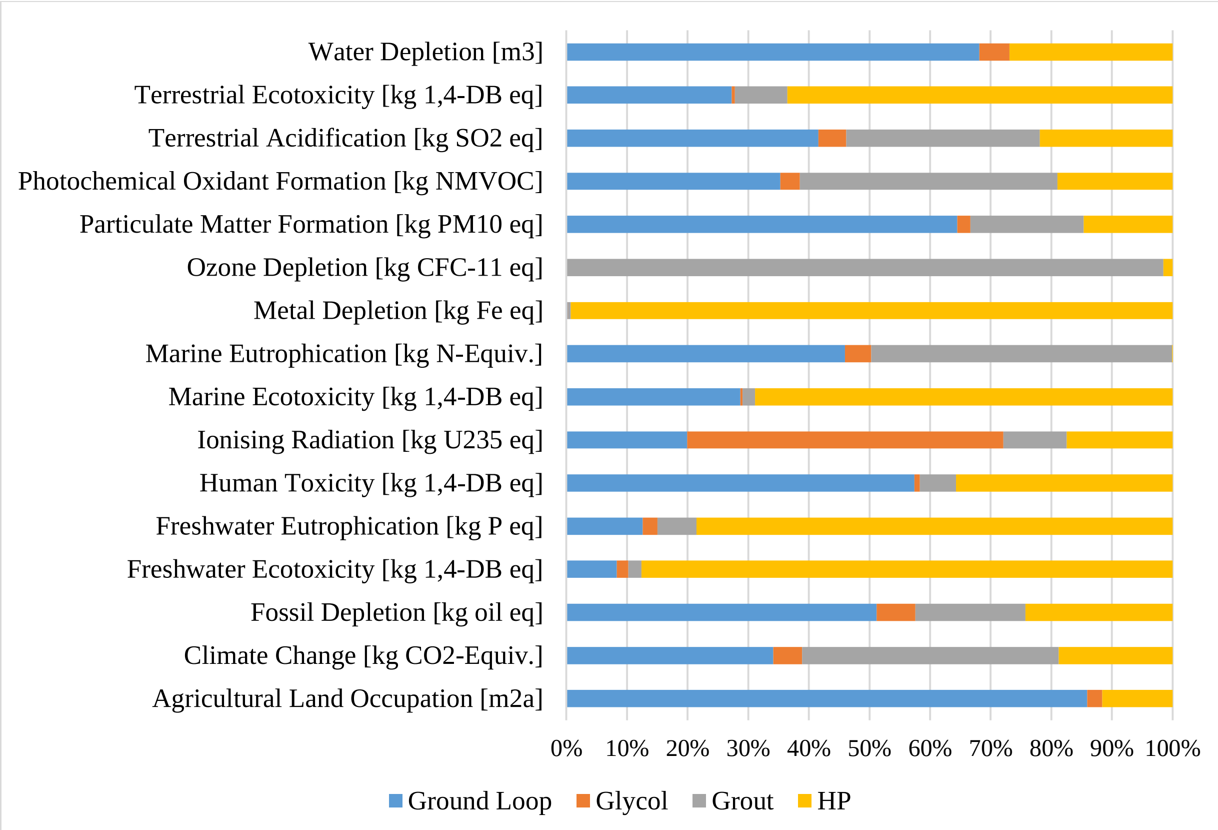

Figure 29: Manufacturing Life Cycle Stage – GSHP System Components

Figure 30 illustrates the comparative environmental impacts of the GF and the AC. The AC had a consistently higher impact than the GF in most impact categories; however it had a more substantial increase in the ozone depletion category due to the manufacturing and use of the refrigerant.

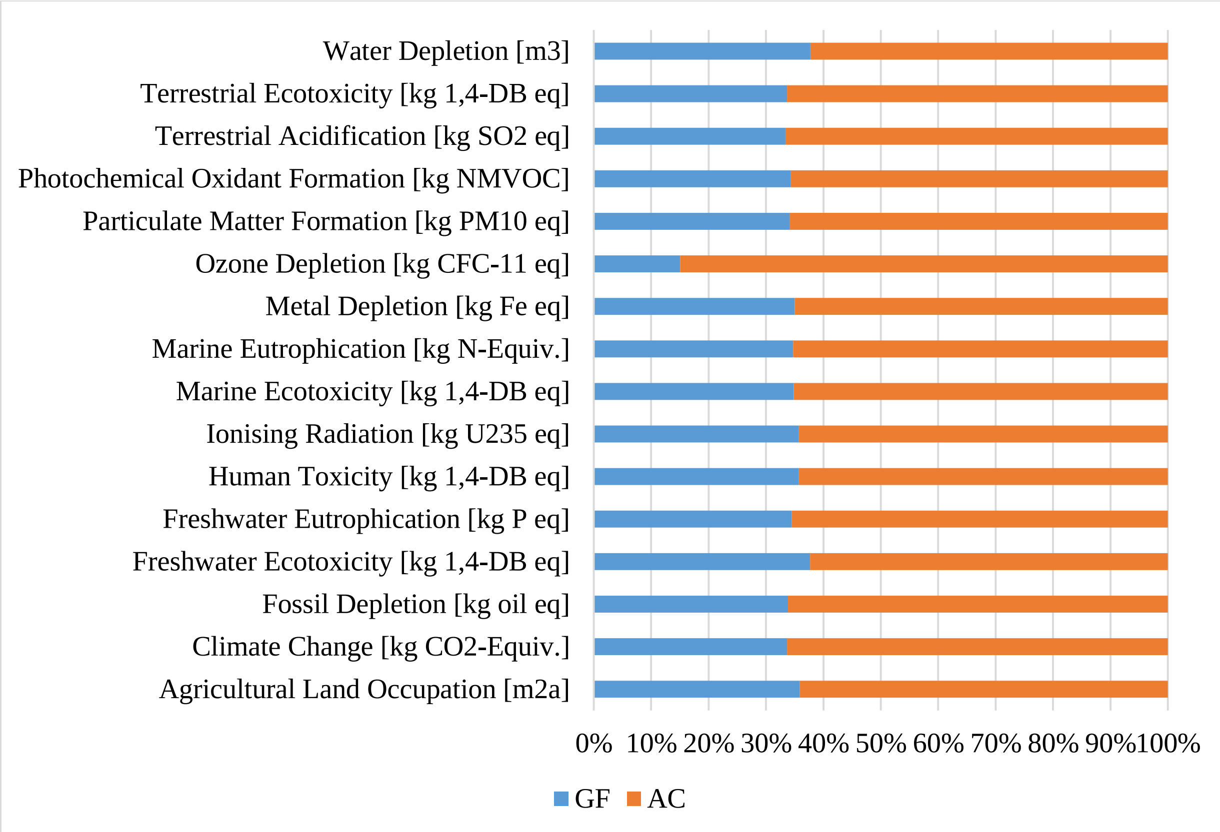

Figure 30: Manufacturing Life Cycle Stage - GF/AC System Components

The transportation life cycle stage for the GF and the AC system components were exactly the same. While the HP had an identical transportation stage as the GF and AC, the GSHP system requires the transportation of the ground loop, glycol, and grout as well. For this reason, the GSHP system has a slightly higher overall impact in the transportation stage, as seen in Figure 31.

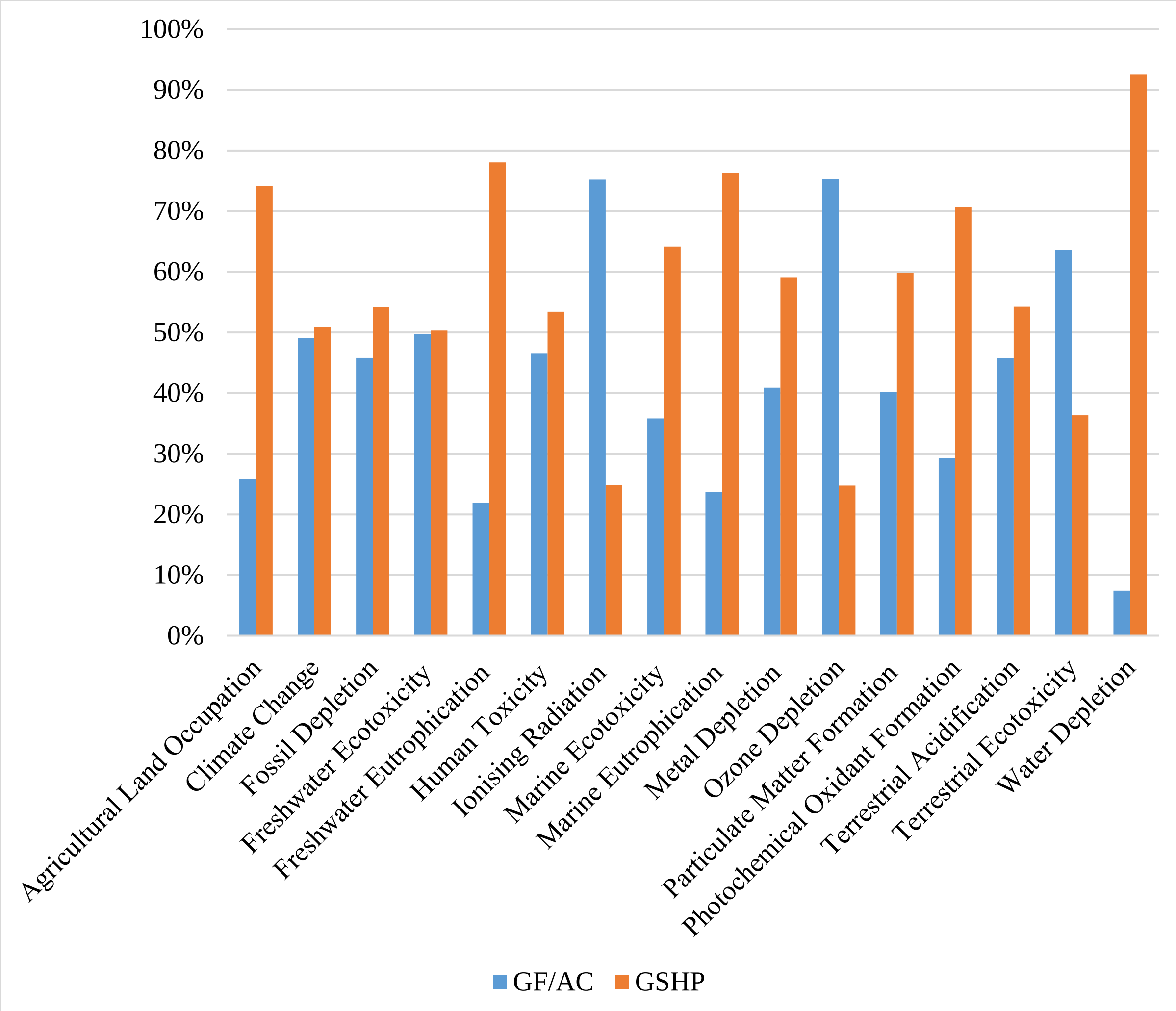

Figure 31: Transportation Life Cycle Stage – GF/AC vs GSHP system

For the installation stage of the life cycle, the GF/AC was not included. It was assumed that both the GF/AC system as well as the GSHP system would require an identical delivery service to the home owner, and therefore was not necessary to include in the assessment. Once the GF/AC system is delivered to the home, the installation process does not require any additional material or energy inputs. The GSHP system, however, requires the drilling of a borehole to function. As shown in Figure 32, the most significant impacts from the GSHP system at the installation stage are climate change and fossil fuel depletion, which is the result of the use of diesel throughout the drilling process.

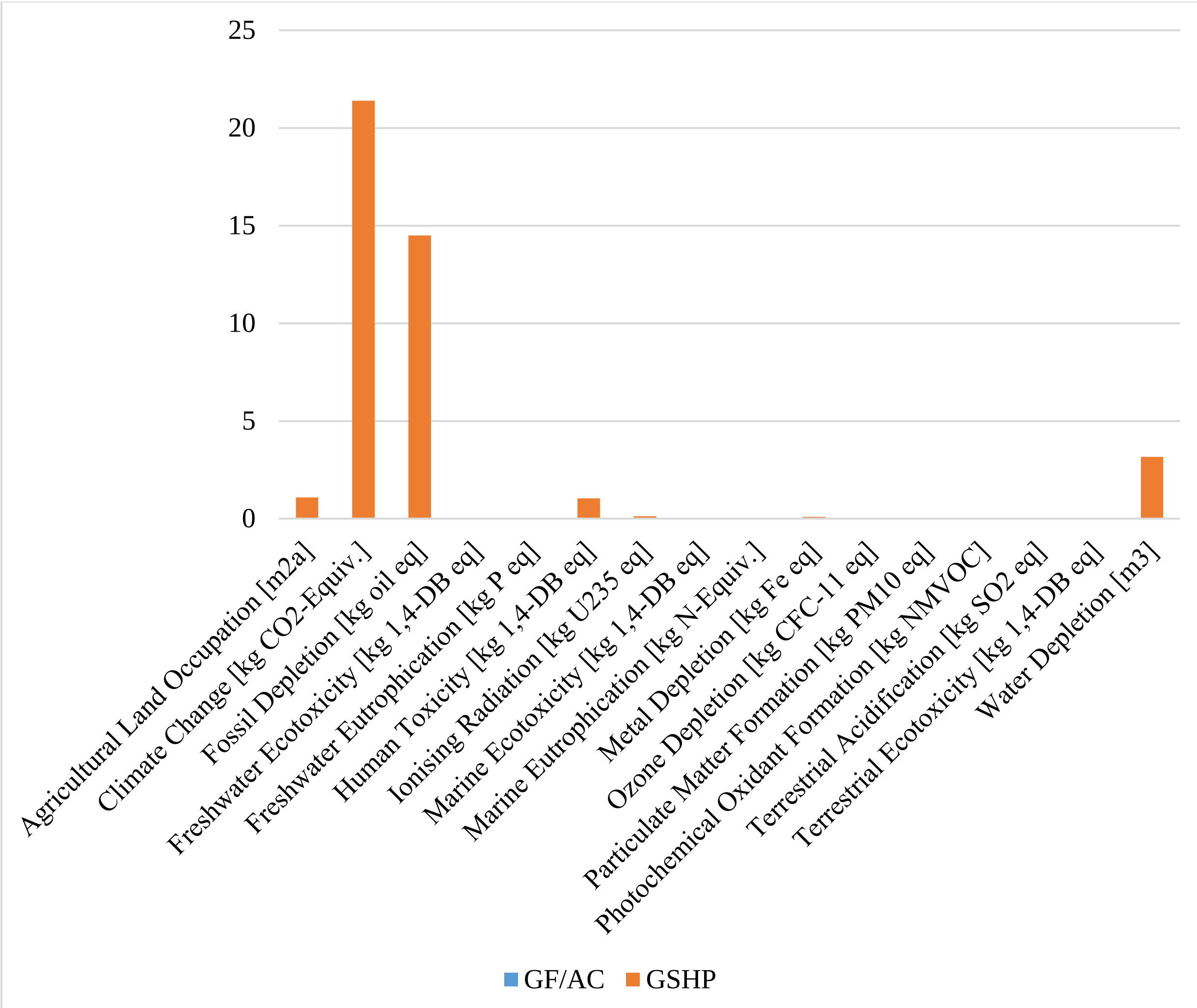

Figure 32: Installation Life Cycle Stage – GSHP system

Although climate change and fossil fuel depletion impacts were most significant to the installation stage, it can be seen in Figure 33 that the borehole installation has very little impact on the overall impacts of the system.

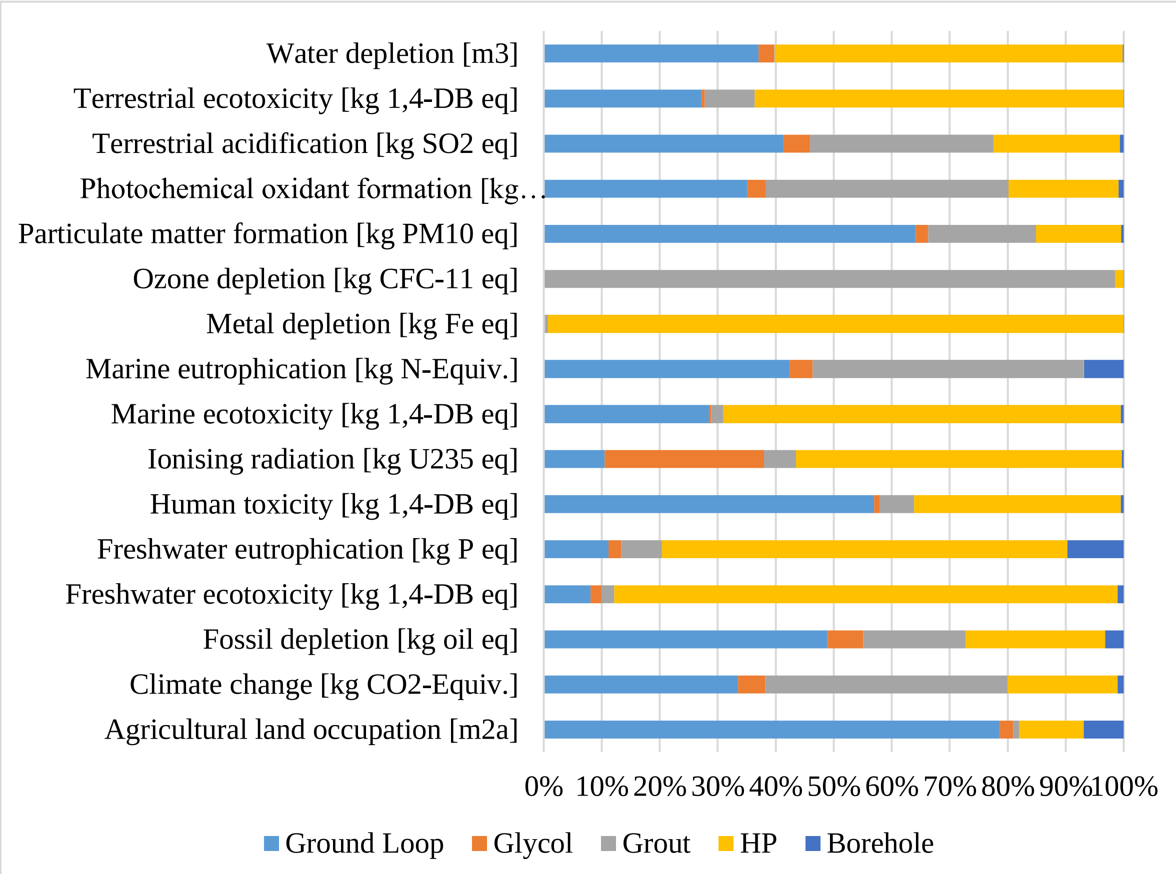

Figure 33: GSHP Complete Life Cycle Assessment of Components

Figure 33 examines the relative impact that the GF/AC and GSHP systems have on each environmental impact category throughout the operational stage of the life cycle. The results for the operational stage of the life cycle were fairly consistent with three of the studies identified in section 2.5, Table 3. It can be observed in Figure 34 that the GF/AC system was responsible for 70% of the total climate change impact category, which is measured in kg CO_2e. When comparing the GSHP system with a natural gas boiler, Blumsack *et al.* [40] found that the GSHP system reduced CO_2 emissions by 62%. Blum *et al.* [41] found that GSHP systems typically reduced CO_2 emissions by 64% in comparison to conventional HVAC systems. The findings in Figure 31 are most consistent with the work of Self *et al.* [12], who determined that CO_2 emissions could be reduced by up to 76% in Ontario by replacing GF/AC systems with GSHP systems. It is also valuable to note that the GF/AC system has a higher impact than the GSHP system in 9 of the 14 impact categories for the operational stage, and most significantly with in the land occupation, climate change, fossil fuel depletion, photochemical ozone formation, terrestrial acidification, and particulate matter formation.

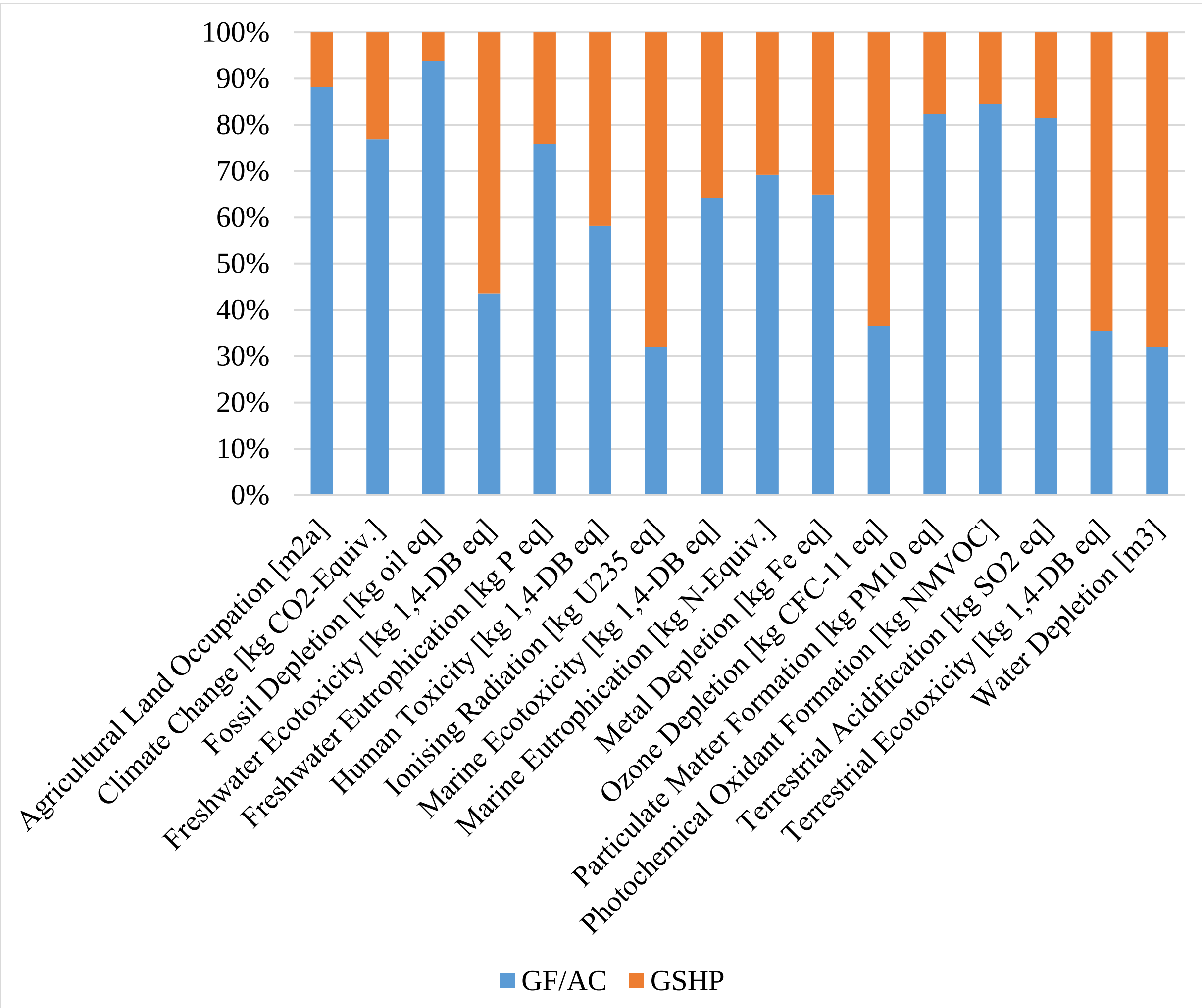

Figure 34: Operational Life Cycle Stage – GF/AC vs. GSHP system

The ReCiPe 1.08 LCIA method allows the user to compartmentalize the environmental impact categories into three endpoint categories, also known as damage categories. The damage categories measured were human health, ecosystem quality, and resource depletion. The purpose of these endpoint categories is to infer a conclusion as to which system has the lesser environmental impact.

Table 14 displays the values for impact category expressed in the units of their associated endpoint category. For example, the human toxicity impact category is expressed in DALY, which is the unit used to measure damage to the human health endpoint category. Again, it is important to note that although the values for this particular study are extremely small, these results present the relative impact of each system. Extrapolating to consider the large number of buildings across Ontario, the values could become more significant and representative of the environmental impact of wide-spread GSHP system utilization.

Table 14: Impact Categories Classified in Endpoint Category Units – GF/AC vs GSHP System

Impact Categories Expressed in Endpoint Category Units	**GF**	**AC**	**Total GF/AC System**	**Heat Pump**	**Ground Loop**	**Glycol**	**Grout**	**Borehole**	**Total GSHP System**
Agricultural land occupation [PDF]	2.94×10^{-8}	5.11×10^{-8}	8.05×10^{-8}	3.45×10^{-8}	2.44×10^{-7}	7.12×10^{-9}	3.15×10^{-9}	2.15×10^{-8}	3.102×10^{-7}
Climate change Ecosystems [PDF]	1.61×10^{-6}	3.01×10^{-6}	4.62×10^{-6}	3.1×10^{-6}	5.46×10^{-6}	7.55×10^{-7}	6.8×10^{-6}	1.69×10^{-7}	1.628×10^{-5}
Climate change Human Health [DALY]	2.85×10^{-4}	5.31×10^{-4}	8.16×10^{-4}	5.46×10^{-4}	9.64×10^{-4}	1.33×10^{-4}	0.0012	2.99×10^{-5}	0.00287
Fossil depletion [$]	12.033	17.2	29.2	18.015	36.6	4.59	13.2	2.4	74.805
Freshwater ecotoxicity [PDF]	1.03×10^{-10}	1.69×10^{-10}	2.72×10^{-10}	6.99×10^{-10}	6.43×10^{-11}	1.48×10^{-11}	1.75×10^{-11}	8.14×10^{-12}	8.041×10^{-10}
Freshwater eutrophication [PDF]	1.51×10^{-11}	2.82×10^{-11}	4.33×10^{-11}	7.6×10^{-11}	1.22×10^{-8}	2.38×10^{-12}	7.67×10^{-12}	1.06×10^{-11}	1.089×10^{-10}
Human toxicity [DALY]	6.54×10^{-5}	1.17×10^{-4}	1.82×10^{-4}	4.94×10^{-5}	7.98×10^{-5}	1.26×10^{-6}	8.27×10^{-6}	6.94×10^{-7}	1.390×10^{-4}
Ionising radiation [DALY]	7.07×10^{-8}	2.61×10^{-7}	3.32×10^{-7}	3.61×10^{-7}	6.72×10^{-8}	1.76×10^{-7}	3.55×10^{-8}	2.05×10^{-9}	6.416×10^{-7}
Marine ecotoxicity [PDF]	1.68×10^{-10}	3.12×10^{-10}	4.80×10^{-10}	3.45×10^{-10}	1.43×10^{-10}	2.08×10^{-12}	1.04×10^{-11}	2.44×10^{-12}	5.034×10^{-10}
Metal depletion [$]	48.850	90.6	139.45	99.727	0.210	0.019	0.491	0.0063	100.454
Ozone depletion [DALY]	1.91×10^{-9}	1.08×10^{-8}	1.27×10^{-8}	2.09×10^{-9}	1.31×10^{-12}	6.64×10^{-11}	1.01×10^{-7}	7.27×10^{-13}	1.032×10^{-7}
Particulate matter formation [DALY]	8.50×10^{-5}	1.61×10^{-4}	2.46×10^{-4}	1.33×10^{-4}	5.80×10^{-4}	1.94×10^{-5}	1.68×10^{-4}	4.05×10^{-6}	9.043×10^{-4}
Photochemical oxidant formation [DALY]	2.08×10^{-8}	3.78×10^{-8}	5.86×10^{-8}	3.72×10^{-8}	6.88×10^{-8}	6.16×10^{-9}	8.2×10^{-8}	1.7×10^{-9}	1.958×10^{-7}
Terrestrial acidification [PDF]	3.96×10^{-9}	7.70×10^{-9}	1.17×10^{-8}	8.16×10^{-9}	1.55×10^{-8}	1.69×10^{-9}	1.18×10^{-8}	2.56×10^{-10}	3.740×10^{-8}
Terrestrial ecotoxicity [PDF]	7.92×10^{-9}	1.56×10^{-8}	2.35×10^{-8}	1.83×10^{-8}	7.81×10^{-9}	1.49×10^{-10}	2.51×10^{-9}	8.51×10^{-12}	2.876×10^{-8}

The final set of results, presented in Figures 35-37, show that the GSHP system has a greater negative impact in each of the endpoint categories examined in comparison to the GF/AC system. The GSHP system has a significantly greater negative impact on human health and ecosystem quality throughout its entire life cycle. More precisely, the GSHP system quadrupled the GF/AC impact on human health, as seen in Figure 35. The actual impact on human health caused over the life cycle of the GSHP system is 0.0054 DALY. As this unit of measurement for this category is the daily adjusted life year, this value can be expressed as the equivalent to approximately 2 days of healthy life lost due to disease and/or disability caused by the impacts of the GSHP system. In comparison, the GF/AC system impact can be simplified as approximately 11 hours of healthy life lost due to disease and/or disability.

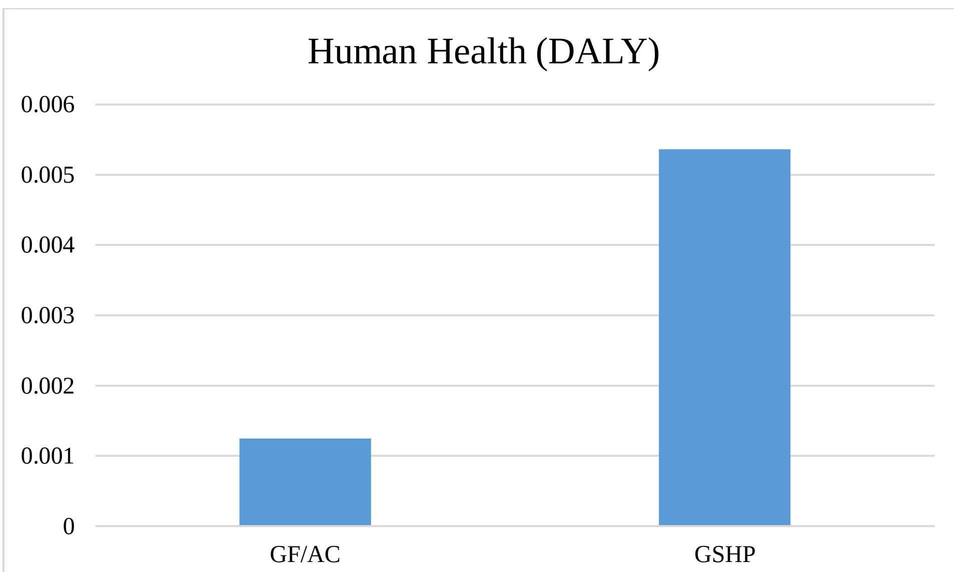

Figure 35: Overall Human Health Impact - GF/AC vs GSHP System

Figure 36 illustrates the overall relative impact of the GF/AC system and the GSHP system on ecosystem quality, measured in potentially disappeared fraction (PDF). The results for this study show that the GSHP system has the potential to cause a rate of 0.005 species/year to disappear. The GF/AC system results display a rate of 4.7×10^{-6} species/year to disappear.

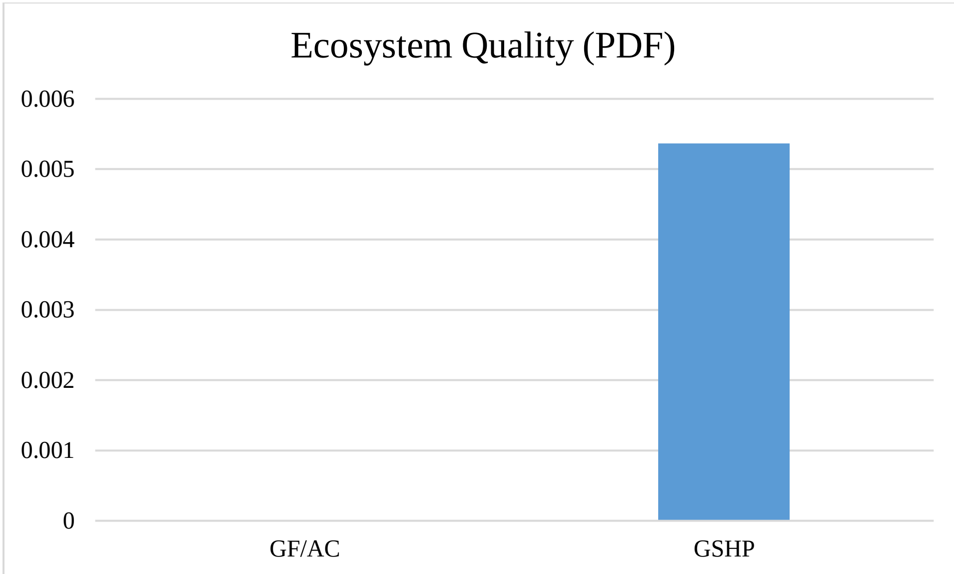

Figure 36: Overall Impact on Ecosystem Quality - GF/AC vs GSHP System

As shown in Figure 37, the GF/AC system has a slightly greater impact on resource depletion. The GSHP system impact is only greater than the GF/AC system impact by a factor of 1.04.

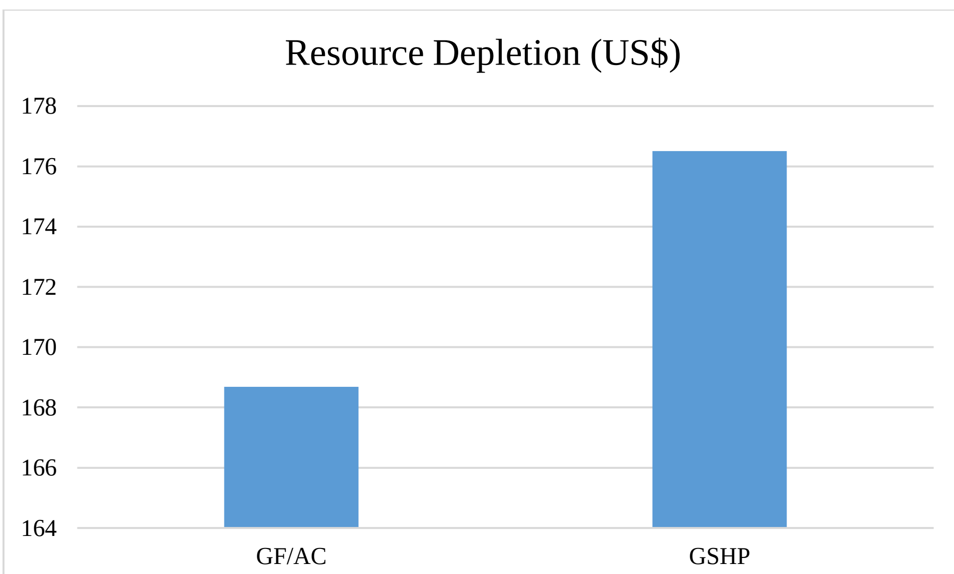

Figure 37: Overall Impact on Resource Depletion- GF/AC vs GSHP System

These results can be compared with those of Greening and Azalpagic [20], which concluded that the GSHP system reduced operational CO_2 by 36% in comparison to a NG boiler; however, the overall environmental impact of the GSHP increased by 73%. Rodriguez *et al.* [44] studied the GSHP system versus an oil boiler and determined that the GHSP system had double the impact on ecosystem quality. By contrast, the results of Rodriguez *et al.* [44] also concluded that the GSHP had half of the impact on the human health and resource depletion categories in comparison to the oil boiler.

These results have made a contribution towards filling the knowledge gap regarding the specific environmental impacts of the entire life cycle of the HVAC systems as opposed to just their operational stages. As was presented, the GSHP system generated less of an overall impact on the environment compared to the GF/AC system during the operational stage. With the final results depicting a significantly larger overall environmental impact for the GSHP system, it is evident that cradle-to-grave assessments are imperative in order to make fully informed decisions on the basis of sustainability.

5.0 CONCLUSIONS AND FUTURE WORK

Ground source heat pump systems are an extremely efficient HVAC system that can significantly reduce energy consumption and CO_2 emissions throughout its operational life cycle stage when compared to the natural gas and air conditioner system. While GSHP systems remain a benefit to Ontario buildings due to the decreased energy consumption as well as decreased overall operational level environmental impacts; however, they have the potential to cause a greater overall negative environmental impact globally. The Ontario Climate Action Plan seeks to reduce fossil fuel use in buildings, which makes the GSHP is an excellent alternative. However, if the overall environmental impact of the system's life cycles is taken into consideration, the GSHP has a greater impact primarily due to the manufacturing of its components. A large portion of the environmental impacts may not be experienced directly in Ontario, as the manufacturing of most of the components take place in other countries. While these impacts may not represent a threat to Ontario directly, it is valuable to consider the potential of inflicting a greater environmental impact on a global scale.

The GSHP had a greater overall environmental impact in the manufacturing, transportation, and installation stage of the life cycle. The results determined that the heat pump and the ground loop had the greatest contribution to the manufacturing stage of the GSHP. The GSHP system had a larger impact than the GF/AC system during the transportation stage due to the fact that the GSHP required more components to be transported. While the GSHP system required an installation stage, the borehole drilling was found to have the smallest contribution to the overall environmental impact. The overall operational environmental impact of the GSHP system was lower than the GF/AC system. Consistent with the literature, the GSHP system reduced CO_2 emissions by 70% in the operational stage in comparison to the GF/AC system. Overall, the endpoint category results indicated that the GSHP system produced a greater impact on human health and ecosystem quality compared to the GF/AC system, while their impacts on resource depletion were comparable.

In order to reduce the total life cycle environmental impact of the GSHP system, a greater focus on research in the manufacturing of the GSHP system components is needed. Future research would benefit from conducting a sensitivity analysis to determine whether local manufacturing of system components would result in a decrease in the manufacturing environmental impact. Research would also benefit from studying the effect on the overall manufacturing impact if greater recycled resources were incorporated in the manufacturing stage. It would also be interesting to conduct a similar study on different building types, such as a commercial building, to see if the results would vary due to the difference in operational needs.

APPENDICES

Appendix A: Impact Category Data Results from GaBi

GROUND LOOP (GSHP SYSTEM)							
Impact Category	**TOTAL**	**China Electricity**	**HDPE Pellets**	**Heavy Fuel Oil**	**Lubricating Oil**	**Ocean Freight**	**Truck**
Agricultural land occupation [m^2]	12.3838582	12.15293		0.000648	0.179		
Climate change [kg CO_2 eq]	688.2756099	609.0649	0.0101	0.12	35	0.938	0.125
Fossil depletion [kg oil eq]	221.7729278	145.8861		0.327	32.1		
Freshwater ecotoxicity [kg 1,4-DB eq]	0.075362981	0.038645	1.88E-05	0.000214	0.0204		3.35E-12
Freshwater eutrophication [kg P eq]	0.000273683	0.00014	9.57E-07	1.07E-07	8.22E-05		
Human toxicity [kg 1,4-DB eq]	114.6810866	108.5547	8.96E-05	0.0336	4.46		8.99E-08
Ionising radiation [kg U235 eq]	4.098190384	3.585559		0.000225	0.0552		
Marine ecotoxicity [kg 1,4-DB eq]	0.814143883	0.74283	1.50E-05	0.000307	0.0416		8.78E-11
Marine eutrophication [kg N-Equiv.]	0.067064581	0.056499	3.28E-05	1.80E-05	0.00436	0.000963	3.81E-05
Metal depletion [kg Fe eq]	2.93243985	2.786524		0.000578	0.0838		
Ozone depletion [kg CFC-11 eq]	6.42E-10	2.10E-10		7.07E-14	8.95E-12		
Particulate matter formation [kg PM_{10} eq]	2.230523367	2.109699	0.00164	0.000262	0.0725	0.0092	3.64E-05
Photochemical oxidant formation [kg NMVOC]	1.76373598	1.492816	0.0135	0.000562	0.108	0.0268	0.000155
Terrestrial acidification [kg SO_2 eq]	2.6730287	2.319929	0.000472	0.000687	0.205	0.0297	8.28E-05
Terrestrial ecotoxicity [kg 1,4-DB eq]	0.051724983	0.050395	5.00E-12	2.66E-06	0.00109		9.83E-12
Water depletion [m^3]	786.4645478	765.987		0.0393	11.1		

GLYCOL (GSHP SYSTEM)								
Impact Category	**Total**	**US Electricity**	**Diesel**	**Methanol**	**Natural Gas**	**Propylene Oxide**	**Sodium Hydroxide**	**Truck**
Agricultural land occupation [m^2]	0.362	0.327	0.00514			0.0285	0.000781	
Climate change [kg CO_2 eq]	95.3	89.1	0.0227		0.0412	5.91	0.0278	0.131
Fossil depletion [kg oil eq]	27.8	23.5	0.0508			4.31	0.00746	
Freshwater ecotoxicity [kg 1,4-DB eq]	0.017515	0.015597	3.52E-05		9.66E-09	0.00187	1.18E-05	3.57E-11
Freshwater eutrophication [kg P eq]	5.36E-05	3.85E-05	1.09E-06			1.39E-05	1.43E-07	
Human toxicity [kg 1,4-DB eq]	1.816514	1.583859	0.00364		0.00026	0.228	0.00119	9.59E-07
Ionising radiation [kg U235 eq]	10.73228	10.6256	0.000306			0.104	0.00245	
Marine ecotoxicity [kg 1,4-DB eq]	0.011812	0.009106	4.93E-05		2.54E-07	0.00265	3.90E-06	9.36E-10
Marine eutrophication [kg N-Equiv.]	0.006274	0.005722	2.06E-05			0.000446	4.84E-06	7.99E-05
Metal depletion [kg Fe eq]	0.267018	0.255037	0.000299			0.0115	0.000135	
Ozone depletion [kg CFC-11 eq]	3.76E-08	3.76E-08	9.82E-13			6.50E-11	1.36E-12	
Particulate matter formation [kg PM_{10} eq]	0.074793	0.067247	3.39E-05		0.00427	0.00316	1.71E-05	6.86E-05
Photochemical oxidant formation [kg NMVOC]	0.157975	0.116944	9.60E-05	0.0154	0.00186	0.0235	5.42E-05	0.000177
Terrestrial acidification [kg SO_2 eq]	0.292085	0.259464	0.000111		0.0214	0.011	4.91E-05	5.80E-05
Terrestrial ecotoxicity [kg 1,4-DB eq]	0.000989	0.000941	1.51E-07		2.84E-08	4.73E-05	5.00E-07	1.05E-10
Water depletion [m^3]	57.41678	52.61823	0.0101			4.66	0.11	

GROUT (GSHP SYSTEM)					
Impact Category	**Total**	**Cement**	**Diesel**	**Grout**	**Truck**
Agricultural land occupation [m^2]	0.16		0.16		
Climate change [kg CO_2 eq]	8.57E+02	852	0.708		4.06
Fossil depletion [kg oil eq]	79.95719	78.4	1.58		
Freshwater ecotoxicity [kg 1,4-DB eq]	0.020602	0.0195	0.0011		6.38E-10
Freshwater eutrophication [kg P eq]	1.73E-04	1.39E-04	3.40E-05		
Human toxicity [kg 1,4-DB eq]	11.97372	11.9	0.114		1.71E-05
Ionising radiation [kg U235 eq]	2.161039	2.15	0.00952		
Marine ecotoxicity [kg 1,4-DB eq]	0.059654	0.0581	0.00154		1.68E-08
Marine eutrophication [kg N-Equiv.]	0.073932	0.0713	0.000642		0.00195
Metal depletion [kg Fe eq]	6.865216	6.86	0.00933		
Ozone depletion [kg CFC-11 eq]	4.17E-05	4.17E-05	3.06E-11		
Particulate matter formation [kg PM_{10} eq]	0.645165	0.643	0.00106		0.00119
Photochemical oxidant formation [kg NMVOC]	2.10137	2.09	0.00299		0.00388
Terrestrial acidification [kg SO_2 eq]	2.038416	2.03	0.00345		0.0014
Terrestrial ecotoxicity [kg 1,4-DB eq]	0.016363	0.0164	4.7E-06		1.87E-09
Water depletion [m^3]	1.585127	0.37	0.315	0.9	

HEAT PUMP (GSHP SYSTEM)									
Midpoints	**TOTAL**	**US Electricity Mix**	**Ontario Electricity Mix**	**Copper**	**Diesel**	**Lubricating Oil**	**Polyvinyl chloride**	**Steel**	**Truck**
Agricultural land occupation [m^2]	1.749371497	0.0483	0.0052	1.66	0.0283	0.007571	0	0	0
Climate change [kg CO_2 eq	390.3050441	8.55	3.67	81	0.125	1.816191	0	294.42525	0.718598
Fossil depletion [kg oil eq]	109.1778916	2.45	1.37	24.6	0.28	2.074233	0	78.403659	0
Freshwater ecotoxicity [kg 1,4-DB eq]	0.809931681	0.00113	0.0167	0.142	0.000194	7.39E-04	1.78971E-06	0.6491672	5.46E-11
Freshwater eutrophication [kg P eq]	0.001712127	5.52E-06	2.07E-06	0.000211	6.01E-06	4.56E-06	0	0.0014829	0
Human toxicity [kg 1,4-DB eq]	71.73934147	0.137	0.272	47.7	0.0201	1.06E-01	0.00424	23.5	1.47E-06
Ionising radiation [kg U235 eq]	21.93208	0.535	17.8	3.57	0.00168	0.0254			
Marine ecotoxicity [kg 1,4-DB eq]	1.959866701	0.00093	0.00387	1.93	0.000271	1.46E-03	0.0000357	0.0233	1.43E-09
Marine eutrophication [kg N-Equiv.]	0.01229908	0.00063	0.000477	0.0108	0.000114	0.000154	1.08E-05	0.000123	0.000219
Metal depletion [kg Fe eq]	1392.59081	0.0483	0.237	1300	0.00165	0.00386		92.3	
Ozone depletion [kg CFC-11 eq]	6.3759E-07	1.89E-09	2.22E-10	9.46E-09	5.41E-12	1.3E-11		6.26E-07	
Particulate matter formation [kg PM_{10} eq]	0.5111251	0.00414	0.0013	0.246	0.000187	0.00134	2.61E-05	0.258	0.000132
Photochemical oxidant formation [kg NMVOC]	0.952846	0.0119	0.00522	0.222	0.000529	0.00369	0.000039	0.709	0.000468
Terrestrial acidification [kg SO_2 eq]	1.407248	0.0128	0.00367	0.408	0.00061	0.00498		0.977	0.000188
Terrestrial ecotoxicity [kg 1,4-DB eq]	0.120807231	0.0000758	0.000309	0.108	8.31E-07	1.72E-05	4.4E-06	0.0124	1.6E-10
Water depletion [m^3]	1273.0957	38.8	924	309	0.0557	1.24			

GAS FURNACE (GF/AC SYSTEM)									
Midpoint	**Total**	**US Electricity**	**Copper**	**Steel Sheet**	**Galv. Steel**	**Diesel**	**Natural Gas**	**Aluminium**	**Truck**
Agricultural land occupation [m^2]	1.49268	0.019630	0.679058	0.193443	0.55074682	0.013507	0.0363		
Climate change [kg CO_2 eq	203	5.34525622	33.14882	39.64153	104.945152	0.059709	10.5	9.58	0.343
Fossil depletion [kg oil eq]	72.92518	1.406459	10.05764	10.753756	28.3228020	0.133537	19.8	2.44	
Freshwater ecotoxicity [kg 1,4-DB eq]	0.120875	0.00093524	0.057903	0.00822739	0.04709548	9.24E-05	0.00502	0.0016	5.38E-11
Freshwater eutrophication [kg P eq]	0.00034	2.31E-06	8.62E-05	6.26E-05	0.00016974	2.87E-06	5.55E-06	1.09E-05	
Human toxicity [kg 1,4-DB eq]	94.8602	0.09497419	19.49687	20.6436777	53.9340918	0.009575	0.252	0.429	1.45E-06
Ionising radiation [kg U235 eq]	4.312223	0.63715105	1.461296	0.30814768	1.68088740	0.000803	0.0124	0.212	
Marine ecotoxicity [kg 1,4-DB eq]	0.952953	0.000546	0.790768	0.04117779	0.11266381	0.000129	0.00513	0.00253	1.41E-09
Marine eutrophication [kg N-eq.]	0.022837	0.000343	0.004407	0.00447668	0.01192599	5.41E-05	0.000851	0.000614	0.000164
Metal depletion [kg Fe eq]	683.7312	0.015292	533.467545	39.9783422	109.364121	0.000787	0.326	0.579	
Ozone depletion [kg CFC-11 eq]	1.08E-06	2.25E-09	3.87E-09	3.17E-10	2.01E-09	2.58E-12	2.45E-11	1.07E-06	
Particulate matter formation [kg PM_{10} eq]	0.326867	0.004032	0.100688	0.05604306	0.148923605	8.91E-05	0.00547	0.0115	0.0001
Photochemical oxidant formation [kg NMVOC]	0.533585	0.007012	0.090958	0.10781642	0.28366214	0.000252	0.0258	0.0177	0.000327
Terrestrial acidification [kg SO_2 eq]	0.682681	0.015558	0.166755	0.12043984	0.32719973	0.000291	0.0144	0.0379	0.000118
Terrestrial ecotoxicity [kg 1,4-DB eq]	0.052032	5.64E-05	0.044160	0.00161958	0.00470986	3.96E-07	2.54E-05	0.00146	1.58E-10
Water depletion [m^3]	250.938	3.155188	126.5327	21.5641058	99.1223501	0.026559	0.518	0.0195	

AIR CONDITIONER (GF/AC SYSTEM)									
Midpoint	**Total**	**Ontario Electricity**	**US Electricity**	**Aluminium**	**Copper**	**Diesel**	**Galv. Steel**	**Steel Sheet**	**Truck**
Agricultural land occupation [m^2]	2.59542	0.002431403	0.031409	0	1.282666	0.0216	0.419	0.838	
Climate change [kg CO_2 eq]	379.4333	1.717485186	8.55241	54.27563	62.61445	0.0955	79.8	172	0.548
Fossil depletion [kg oil eq]	104.0522	0.639992792	2.25E+00	13.8009	18.99777	0.214	21.5	46.6	
Freshwater ecotoxicity [kg 1,4-DB eq]	0.199386	0.007831516	0.001496	0.009051	0.109374	0.000148	0.0358	0.0357	8.61E-11
Freshwater eutrophication [kg P eq]	0.000634	9.66E-07	3.69E-06	6.17E-05	0.000163	4.58E-06	0.000129	0.000271	
Human toxicity [kg 1,4-DB eq]	170.0454	0.127105742	0.151959	2.430856	36.82744	0.0153	41	89.5	2.31E-06
Ionising radiation [kg U235 eq]	15.94372	8.349666454	1.02E+00	1.198854	2.760226	0.00128	1.28	1.34	
Marine ecotoxicity [kg 1,4-DB eq]	1.775082	0.001809467	0.000874	0.014359	1.493674	0.000207	0.0857	0.178	2.26E-09
Marine eutrophication [kg N-Equiv.]	0.041399	0.00022317	0.000549	0.00348	0.008324	8.66E-05	0.00907	0.0194	0.000263
Metal depletion [kg Fe eq]	1.27E+03	1.11E-01	0.024469	3.280704	1007.661	0.00126	83.2	173	
Ozone depletion [kg CFC-11 eq]	6.07E-06	1.04E-10	3.60E-09	6.06E-06	7.31E-09	4.13E-12	1.53E-09	1.37E-09	
Particulate matter formation [kg PM_{10} eq]	0.618995	0.000609886	0.006452	0.065277	0.190189	0.000143	0.113	0.243	0.00016
Photochemical oxidant formation [kg NMVOC]	0.969942	0.002443796	0.01122	0.100507	0.17181	0.000403	0.216	0.467	0.000523
Terrestrial acidification [kg SO_2 eq]	1.327849	0.001718622	2.49E-02	0.214737	0.314983	0.000466	0.249	0.522	0.000189
Terrestrial ecotoxicity [kg 1,4-DB eq]	0.102523	0.000144564	9.03E-05	0.008272	0.083414	6.34E-07	0.00358	0.00702	2.53E-10
Water depletion [m^3]	845.5825	432.5113954	5.048302	0.11033	239.0064	0.0425	75.4	93.4	

Appendix B: Endpoint Category Data Results from GaBi

GROUND LOOP (GSHP SYSTEM)									
Endpoint	**Total**	**China Electricity**	**Diesel**	**Ethylene**	**HDPE Pellets**	**Heavy Fuel Oil**	**Lubricati ng Oil**	**Ocean Freight**	**Truck**
Agricultural land occupation [species/yr]	2.44E-07	2.39E-07	9.69E-11	9.22E-10		1.27E-11	3.51E-09		
Climate change Ecosystems [species/yr]	5.46E-06	4.83E-06	1.73E-10	3.41E-07	8.04E-11	9.54E-10	2.78E-07	7.44E-09	9.90E-10
Climate change Human Health [DALY]	0.000964	8.53E-04	3.05E-08	6.02E-05	1.42E-08	1.68E-07	4.90E-05	1.31E-06	1.75E-07
Fossil depletion [$]	36.6	24.1	0.00803	7.17		0.054	5.29		
Freshwater ecotoxicity [species/yr]	6.43E-11	3.32E-11	2.86E-14	1.37E-11	1.62E-14	1.81E-13	1.73E-11		2.93E-21
Freshwater eutrophication [species/yr]	1.22E-11	6.22E-12	4.64E-14	2.19E-12	4.25E-14	4.74E-15	3.65E-12		
Human toxicity [DALY]	7.98E-05	7.57E-05	2.36E-09	1.11E-06	6.27E-11	2.28E-08	3.05E-06		6.27E-14
Ionising radiation [DALY]	6.72E-08	5.88E-08	4.80E-12	7.49E-09		3.69E-12	9.05E-10		
Marine ecotoxicity [species/yr]	1.43E-10	1.31E-10	8.36E-15	5.19E-12	2.64E-15	5.43E-14	7.33E-12		1.57E-20
Metal depletion [$]	0.21	0.199	2.05E-05	4.38E-03		4.13E-05	0.00599		
Ozone depletion [DALY]	1.31E-12	5.44E-13	1.66E-15	7.50E-13		1.34E-16	1.83E-14		
Particulate matter formation [DALY]	0.00058	5.49E-04	8.44E-09	9.66E-06	4.25E-07	6.82E-08	1.89E-05	2.39E-06	9.48E-09
Photochemical oxidant formation [DALY]	6.88E-08	5.82E-08	3.59E-12	4.76E-09	5.28E-10	2.19E-11	4.20E-09	1.05E-09	6.04E-12
Terrestrial acidification [species/yr]	1.55E-08	1.35E-08	6.15E-13	6.77E-10	2.74E-12	3.98E-12	1.19E-09	1.72E-10	4.81E-13
Terrestrial ecotoxicity [species/yr]	7.81E-09	7.61E-09	2.18E-14	3.60E-11	7.35E-19	4.02E-13	1.65E-10		1.46E-18

GLYCOL (GSHP SYSTEM)								
Endpoints	**TOTAL**	**US Electricity**	**Diesel**	**Methanol**	**Natural Gas**	**Propylene Oxide**	**Sodium Hydroxide**	**Truck**
Agricultural land occupation [species/yr]	7.12E-09	6.44E-09	1.01E-10			5.61E-10	1.54E-11	
Climate change Ecosystems [species/yr]	7.55E-07	7.07E-07	1.80E-10		3.27E-10	4.69E-08	2.20E-10	1.04E-09
Climate change Human Health [DALY]	0.000133	0.000125	3.18E-08		5.77E-08	8.27E-06	3.89E-08	1.83E-07
Fossil depletion [$]	4.59	3.87	0.00839			0.711	0.00123	
Freshwater ecotoxicity [species/yr]	1.48E-11	1.32E-11	2.98E-14		8.45E-18	1.59E-12	1.01E-14	3.12E-20
Freshwater eutrophication [species/yr]	2.38E-12	1.71E-12	4.84E-14			6.17E-13	6.33E-15	
Human toxicity [DALY]	1.26E-06	1.10E-06	2.47E-09		1.81E-10	1.55E-07	8.23E-10	6.69E-13
Ionising radiation [DALY]	1.76E-07	1.74E-07	5.01E-12			1.70E-09	4.02E-11	
Marine ecotoxicity [species/yr]	2.08E-12	1.61E-12	8.73E-15		4.53E-17	4.68E-13	6.90E-16	1.67E-19
Metal depletion [$]	0.0191	0.0182	2.14E-05			0.000825	9.66E-06	
Ozone depletion [DALY]	6.64E-11	6.62E-11	1.73E-15			1.16E-13	2.44E-15	
Particulate matter formation [DALY]	1.94E-05	1.75E-05	8.81E-09		1.11E-06	8.20E-07	4.45E-09	1.78E-08
Photochemical oxidant formation [DALY]	6.16E-09	4.56E-09	3.74E-12	6.00E-10	7.25E-11	9.15E-10	2.11E-12	6.91E-12
Terrestrial acidification [species/yr]	1.69E-09	1.50E-09	6.43E-13		1.24E-10	6.41E-11	2.85E-13	3.37E-13
Terrestrial ecotoxicity [species/yr]	1.49E-10	1.41E-10	2.28E-14		4.23E-15	7.16E-12	7.55E-14	1.56E-17

GROUT (GSHP SYSTEM)				
Endpoints	**Total**	**Cement**	**Diesel**	**Truck**
Agricultural land occupation [species/yr]	3.15E-09		3.15E-09	
Climate change Ecosystems [species/yr]	6.80E-06	6.76E-06	5.62E-09	3.22E-08
Climate change Human Health [DALY]	0.0012	1.19E-03	9.92E-07	5.69E-06
Fossil depletion [$]	13.2	12.9	0.261	
Freshwater ecotoxicity [species/yr]	1.75E-11	1.65E-11	9.29E-13	5.58E-19
Freshwater eutrophication [species/yr]	7.67E-12	6.16E-12	1.51E-12	
Human toxicity [DALY]	8.27E-06	8.20E-06	7.69E-08	1.20E-11
Ionising radiation [DALY]	3.55E-08	3.53E-08	1.56E-10	
Marine ecotoxicity [species/yr]	1.04E-11	1.02E-11	2.72E-13	2.99E-18
Metal depletion [$]	0.491	0.491	0.000667	
Ozone depletion [DALY]	1.01E-07	1.01E-07	5.4E-14	
Particulate matter formation [DALY]	0.000168	1.67E-04	2.75E-07	3.09E-07
Photochemical oxidant formation [DALY]	8.20E-08	8.17E-08	1.17E-10	1.51E-10
Terrestrial acidification [species/yr]	1.18E-08	1.18E-08	2.00E-11	8.11E-12
Terrestrial ecotoxicity [species/yr]	2.51E-09	2.51E-09	7.09E-13	2.79E-16

HEAT PUMP (GSHP SYSTEM)								
Endpoints	**TOTAL**	**US Electricity**	**Copper**	**Diesel**	**Lubricating Oil**	**Polyvinylc hloride**	**Steel**	**Truck**
Agricultural land occupation [species/yr]	3.45E-08	9.50E-10	3.27E-08	5.57E-10	1.49E-10	0	0	0
Climate change Ecosystems [species/yr]	3.10E-06	6.78E-08	6.43E-07	9.93E-10	1.44E-08	0	2.33E-06	5.70E-09
Climate change Human Health [DALY]	5.46E-04	1.20E-05	0.000113	1.75E-07	2.54E-06	0	0.00041219	1.01E-06
Fossil depletion [$]	1.80E+01	4.04E-01	4.06	0.0462	0.342248	0	12.9366037	0
Freshwater ecotoxicity [species/yr]	6.99E-10	9.56E-13	1.20E-10	1.64E-13	6.25E-13	1.53E-15	5.64E-10	4.77E-20
Freshwater eutrophication [species/yr]	7.60E-11	2.45E-13	9.36E-12	2.67E-13	2.02E-13	0	6.59E-11	0
Human toxicity [DALY]	4.94E-05	9.50E-08	3.28E-05	1.36E-08	7.19E-08	2.92E-09	1.62E-05	1.02E-12
Ionising radiation [DALY]	3.61E-07	8.78E-09	5.86E-08	2.76E-11	4.17E-10	0	0	0
Marine ecotoxicity [species/yr]	3.45E-10	1.64E-13	3.40E-10	4.81E-14	2.58E-13	6.32E-15	4.28E-12	2.56E-19
Metal depletion [$]	9.97E+01	0.00345	93.1	0.000118	0.000276	0	6.60631932	0
Ozone depletion [DALY]	2.09E-09	3.33E-12	1.67E-11	9.55E-15	2.34E-14	0	2.07E-09	0
Particulate matter formation [DALY]	1.33E-04	1.08E-06	6.40E-05	4.86E-08	3.47E-07	6.79E-09	6.70E-05	3.44E-08
Photochemical oxidant formation [DALY]	3.72E-08	4.62E-10	8.67E-09	2.06E-11	1.44E-10	1.52E-12	2.76E-08	1.83E-11
Terrestrial acidification [species/yr]	8.16E-09	7.40E-11	2.36E-09	3.54E-12	2.89E-11	0	5.67E-09	1.09E-12
Terrestrial ecotoxicity [species/yr]	1.83E-08	1.14E-11	1.64E-08	1.25E-13	2.61E-12	6.70E-13	1.82E-09	2.39E-17

NATURAL GAS FURNACE (GF/AC SYSTEM)									
Endpoint	**Total**	**US Electricity**	**Copper**	**Steel Sheet**	**Galv. Steel**	**Diesel**	**Natural Gas**	**Aluminium**	**Truck**
Agricultural land occupation [species/yr]	2.94E-08	3.86E-10	1.34E-08	3.81E-09	1.08E-08	2.66E-10	7.14E-10		
Climate change Ecosystems [species/yr]	1.61E-06	4.24E-08	2.63E-07	3.14E-07	8.32E-07	4.73E-10	8.31E-08	7.59E-08	2.72E-09
Climate change Human Health [DALY]	0.000285	7.48E-06	4.64E-05	5.55E-05	0.000147	8.36E-08	1.47E-05	1.34E-05	4.80E-07
Fossil depletion [$]	12.03265	0.232	1.66	1.77	4.67	0.022	3.27	0.402	
Freshwater ecotoxicity [species/yr]	1.03E-10	7.91E-13	4.90E-11	7.06E-12	4.00E-11	7.83E-14	4.26E-12	1.35E-12	4.71E-20
Freshwater eutrophication [species/yr]	1.51E-11	1.02E-13	3.83E-12	2.78E-12	7.54E-12	1.27E-13	2.46E-13	4.84E-13	
Human toxicity [DALY]	6.54E-05	6.59E-08	1.34E-05	1.42E-05	3.72E-05	6.48E-09	1.74E-07	2.97E-07	1.01E-12
Ionising radiation [DALY]	7.07E-08	1.04E-08	2.40E-08	5.05E-09	2.76E-08	1.32E-11	2.03E-10	3.47E-09	
Marine ecotoxicity [species/yr]	1.68E-10	9.63E-14	1.39E-10	7.28E-12	1.99E-11	2.29E-14	9.12E-13	4.42E-13	2.52E-19
Metal depletion [$]	48.85042	0.0010941	38.10551	2.858896	7.820090	5.63E-05	0.0233	0.0414	
Ozone depletion [DALY]	1.91E-09	3.97E-12	6.83E-12	5.64E-13	3.58E-12	4.55E-15	4.33E-14	1.89E-09	
Particulate matter formation [DALY]	8.50E-05	1.05E-06	2.62E-05	1.46E-05	3.87E-05	2.32E-08	1.42E-06	3.00E-06	2.60E-08
Photochemical oxidant formation [DALY]	2.08E-08	2.73E-10	3.55E-09	4.20E-09	1.11E-08	9.83E-12	1.01E-09	6.92E-10	1.28E-11
Terrestrial acidification [species/yr]	3.96E-09	9.02E-11	9.67E-10	6.99E-10	1.90E-09	1.69E-12	8.37E-11	2.20E-10	6.84E-13
Terrestrial ecotoxicity [species/yr]	7.92E-09	8.47E-12	6.73E-09	2.47E-10	7.15E-10	5.98E-14	3.88E-12	2.24E-10	2.35E-17

AIR CONDITIONER (GF/AC SYSTEM)									
Endpoint	**Total**	**Ontario Electricity**	**US Electricity**	**Aluminium**	**Copper**	**Diesel**	**Galv. Steel**	**Steel Sheet**	**Truck**
Agricultural land occupation [species/yr]	5.11E-08	4.79E-11	6.18E-10		2.52E-08	4.25E-10	8.25E-09	1.65E-08	
Climate change Ecosystems [species/yr]	3.01E-06	1.36E-08	6.78E-08	4.30E-07	4.97E-07	7.57E-10	6.33E-07	1.36E-06	4.35E-09
Climate change Human Health [DALY]	0.000531	2.40E-06	1.20E-05	7.60E-05	8.77E-05	1.34E-07	0.000112	0.00024	7.68E-07
Fossil depletion [$]	17.2	0.106	0.371	2.28	3.13	0.0353	3.56	7.69	
Freshwater ecotoxicity [species/yr]	1.69E-10	6.60E-12	1.27E-12	7.66E-12	9.25E-11	1.25E-13	3.05E-11	3.06E-11	7.53E-20
Freshwater eutrophication [species/yr]	2.82E-11	4.29E-14	1.64E-13	2.74E-12	7.24E-12	2.04E-13	5.74E-12	1.20E-11	
Human toxicity [DALY]	0.000117	8.88E-08	1.05E-07	1.68E-06	2.54E-05	1.04E-08	2.83E-05	6.17E-05	1.61E-12
Ionising radiation [DALY]	2.61E-07	1.37E-07	1.67E-08	1.97E-08	4.53E-08	2.11E-11	2.10E-08	2.19E-08	
Marine ecotoxicity [species.yr]	3.12E-10	3.18E-13	1.54E-13	2.51E-12	2.63E-10	3.67E-14	1.51E-11	3.15E-11	4.03E-19
Metal depletion [$]	90.6	0.00793	0.00175	0.235	72	9.00E-05	5.95	12.4	
Ozone depletion [DALY]	1.08E-08	3.58E-13	6.36E-12	1.07E-08	1.29E-11	7.29E-15	2.73E-12	2.44E-12	
Particulate matter formation [DALY]	0.000161	1.59E-07	1.68E-06	1.70E-05	4.94E-05	3.71E-08	2.95E-05	6.31E-05	4.16E-08
Photochemical oxidant formation [DALY]	3.78E-08	9.53E-11	4.38E-10	3.92E-09	6.70E-09	1.57E-11	8.42E-09	1.82E-08	2.04E-11
Terrestrial acidification [species/yr]	7.70E-09	9.97E-12	1.44E-10	1.25E-09	1.83E-09	2.70E-12	1.44E-09	3.03E-09	1.09E-12
Terrestrial ecotoxicity [species/yr]	1.56E-08	2.15E-11	1.36E-11	1.27E-09	1.27E-08	9.57E-14	5.44E-10	1.07E-09	3.77E-17

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