`University of Toronto
Faculty of Applied Science & Engineering
APS112 & APS113
Conceptual Design Specifications (CDS)

Team #	137	Date	Mar 26th

Tutorial Section	0126
Project Title	Reducing GHG Emissions from Homes and Buildings
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Please check off which components you are submitting for your assignment:
_✓_ CDS submitted as a PDF to Quercus with the following components:

- _✓ Cover Page
- _✓_ Executive Summary
- _✓_ Introduction
- _✓_ Problem Statement
- _✓_ Service Environment
- _✓_ Stakeholders
- _✓_ Detailed Requirements (FOCs)
- _✓_ Alternative Designs
- _✓_ Proposed Conceptual Design
- _✓_ Measures of Success
- _✓_ Conclusion
- _✓_ Reference list
- _✓_ Appendices

__ Attribution table with ALL team members’ signatures submitted as a PDF to Quercus. An incomplete or missing attribution table will result in zero on the assignment for the team.

Executive Summary

The client, Brototi Das, Senior Associate of Development and Planning at Emerson, has requested a solution to reduce the amount of greenhouse gas (GHG) emissions in an arbitrary City X released from homes or buildings. In City X, the lack of a cost-effective, zero-emission centralized heating, ventilation, and air-conditioning (HVAC) system is identified as the design gap. The team has chosen to scope the project to a central system for future high-rise (>5 floors) condominium buildings. The service environment for the design, which encapsulates the physical environment, living things, and virtual environment, uses data from Toronto because of the similarity of its HVAC emissions patterns with City X. In addition, the team has established stakeholders, primary and secondary functions, and determined objectives and constraints using standards such as the ASHRAE, provincial emissions targets, and benchmarks with current HVAC systems to guide the design. Ultimately, the final design should lower overall GHG emissions and maintain the performance and cost of operation for current designs.

After a consultation with the client to clarify the project requirements, the team went through the process of generating solutions to the problem. In order to accomplish this, the team used a variety of idea generation methods, such as free brainstorming, developing morph charts based on the primary and secondary functions, and SCAMPER. Afterwards, The team used methods such as multivoting and a graphical decision matrix to select three final suggested alternative designs:

Design 1: Ground Source Heat Pump (GSHP) + Thermostat

- A series of pipes regulates temperature of the unit so that it is similar to the ground temperature, eliminating the need for combusting natural gases
- The thermostat controls heat distribution in individual units, lowering overall consumption

Design 2: Steam Accumulator + RTD Circuit

- The steam accumulator can store thermal energy, recycled from waste byproducts generated from local industrial processes, therefore reducing net GHG emissions

Design 3: Air Source Heat Pump (ASHP) + Infrared Sensors

- Air is taken from external sources, which transfers heat to a refrigerant, which heats the unit without emitting GHGs. The circuit can be reversed to cool the unit.
- Infrared sensors can detect the temperature of the room and control the heating circuit

Using the Pugh Method, each design was compared to a conventional heating system that combusts natural gas. Based on this analysis, Design 1 was chosen as the best design to meet the client's needs. To evaluate the effectiveness of this design, a procedure for testing this design using ANSYS to assess the design's efficiency and air circulation rate will be executed in the following weeks.

1.0 Introduction

The client, Brototi Das, a senior Associate of Development and Planning at Emerson, which provides HVAC solutions for industrial and residential buildings, wants a solution to reduce greenhouse gas (GHG) emissions produced in a fictional metropolitan “City X”. In this report, the team has built on the project requirements by researching and analysing service environment, stakeholders and FOCs to guide the idea generation, selection and measures of success. The team was able to develop solutions to reduce GHG emissions compared to current HVAC systems.

2.0 Problem Statement

When GHGs, predominantly composed of CO_2 (Figure 1), are released to the atmosphere, it absorbs the sun’s heat, leading to an increase in global temperatures [1].

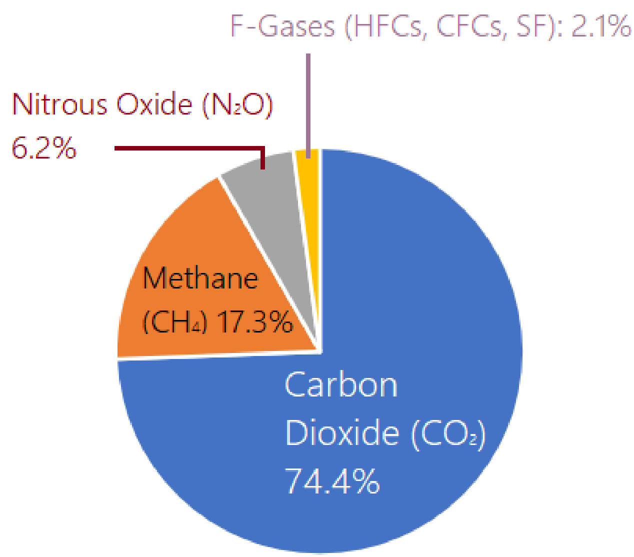


Figure 1. Distribution of GHG gases emitted globally (Source: [2])

In City X, a major emitter of GHGs are homes and buildings, responsible for 60% of emissions. Since GHG emissions in Toronto are comparable, at 54% from residential HVAC systems [3], the design scope chosen is future high-rise buildings with >5 floors in Toronto. The scope was chosen because it experienced the most growth from 2016 – 2021 of all residential building categories, representing 46.7% of private dwellings, compared to the second-highest category, single-detached houses with 23.3% growth [4].

In most residential heating systems, natural gas is combusted to warm cool air and a fan blows this air to the surroundings (Figure 2). One of the main byproducts of this process is CO_2 [5].

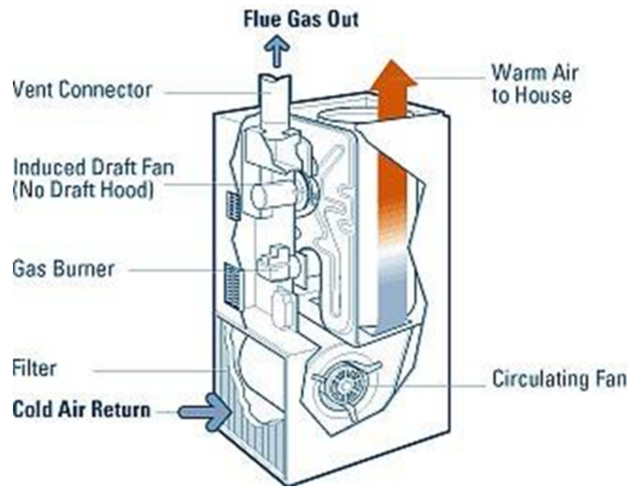


Figure 2. Diagram of a heat exchanger used in forced-air systems [6]

Alternatively, baseboard heaters, which use electric resistance heating, can be used (Figure 3), but this method tends to be costly and could not be scaled up for larger spaces [7].

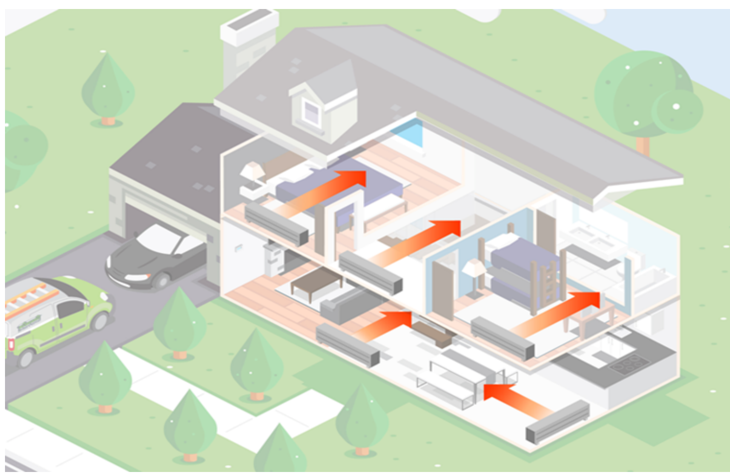


Figure 3. Layout of baseboard heaters in a house. One heater needed per room [8]

The identified gap is the lack of a cost-effective low-emission HVAC system for buildings. Therefore, the need is a centralized method to heat and circulate air without natural gas.

3.0 Service Environment

The physical and virtual environment for City X, is based on data from Toronto, ON. Living Things includes those in the building and those who may be affected externally.

3.1 Physical Environment

Temperature

The outside temperature will affect the usage of HVAC systems throughout the year. Generally, there will be a higher need for heating in November to March and cooling in June to August.

Figure 4 depicts the average temperatures recorded in toronto from January 2021 to December 2022.

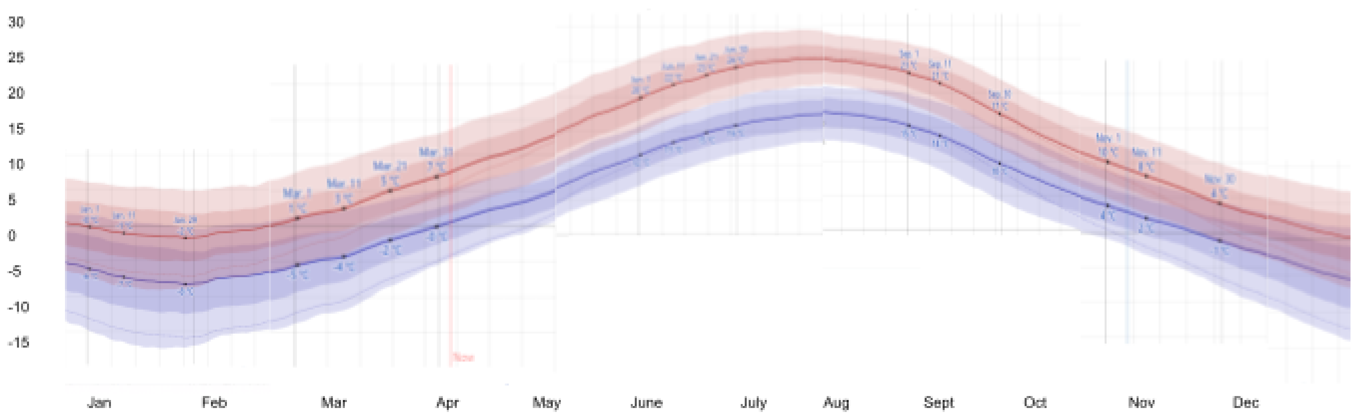


Figure 4: Average temperature in Toronto by month (Source: [68])

Table 1 shows recorded high and low temperatures recorded in Toronto for each month between 1840 to 2023 .

Tabe 1: Extreme temperatures in toronto from 1840 to 2023 [9]

Month	High	Low
Jan	16.1	-32.8
Feb	19.1	-31.7
Mar	26.7	-26.7
Apr	32.2	-15
May	34.4	-3.9
Jun	36.7	-2.2

Jul	40.6	3.9
Aug	38.9	4.4
Spet	37.8	-2.2
Oct	30.8	-8.9
Nov	23.9	-20.6
Dec	19.9	-30

Humidity will impact the usage of the HVAC systems in the building. Humidity can affect the health and overall comfort of living things inside the service environment, for example higher relative humidity will result in an increased need to cool the service environment to maintain a comfortable temperature for residents. High humidity can also shorten the life expectancy of HVAC systems. A graph of average monthly values for humidity is included in Figure 6.

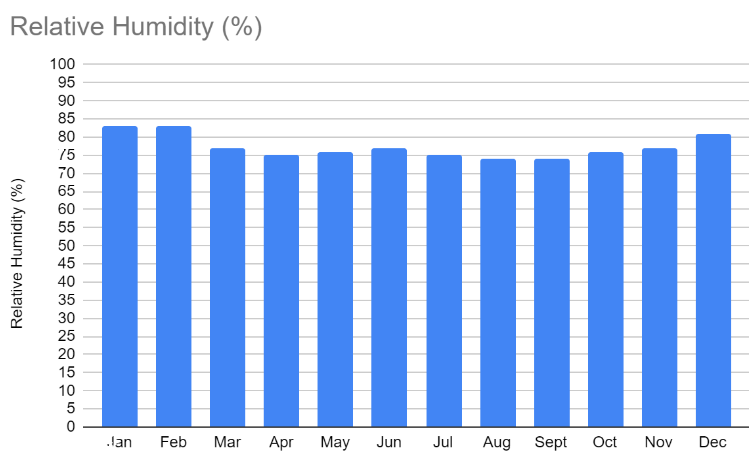


Figure 6: Average relative humidity percentage by month in Toronto (Source: [9])

<u>3.2 Living things</u>

Living things that could be affected by the HVAC system are listed in Table 1.

Table 2: Potential living things affected by the design

Living thing	Considerations
Indoor household plants	- Needs constant temperature and humidity for growth
Mold	- Malevolent beings grow and exist in temps 15-27 ∘C, RH above 60% for long periods.

	[11]
Humans inside and outside the building	- HVAC ducts can hold bacteria and dust, harming air quality. [12] - The system may affect air quality and the environment outside the building. - First responders may need to interact with the HVAC system in the event of an emergency
Animals	- Shedding and pet dander can get caught in the ventilation system, lowering the air quality in a space if not cleaned regularly. [69] - For animals such as dogs that have difficulties regulating body temperature, the HVACs systems ability to maintain constant temperature in a space is important for their health. [69]

3.3 Virtual Environment

Electricity in Toronto is largely generated in Ontario and supplied to buildings through the power grid (Figure 8). 92% of electricity in Ontario in 2019 was generated by renewable energy sources, 59% nuclear, 24% hydroelectric, 8% wind, 1% solar, and the remaining 8% was primarily from natural gas [14]. Furthermore, electricity generated from gas-fired sources is only used during periods of high demand.

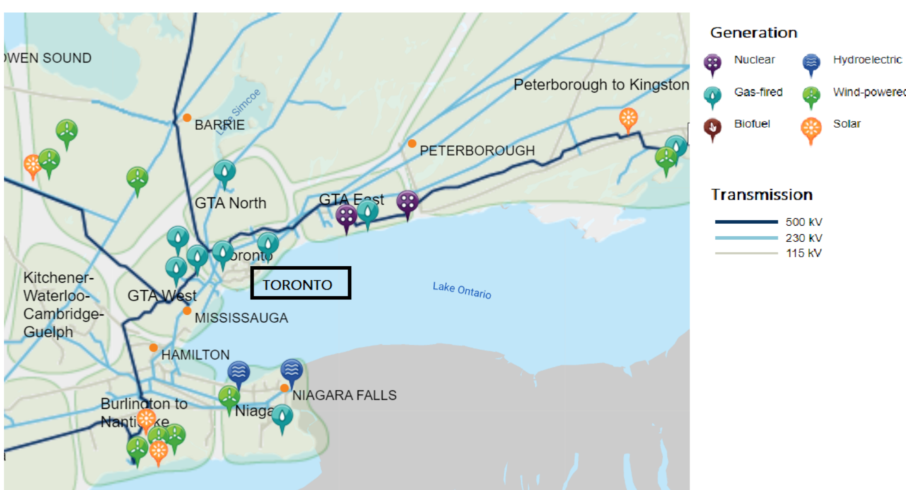


Figure 8. Ontario power grid with generation and transmission (Source: [15])

Table 2 lists several virtual environments inside a condominium building that a HVAC system may need to function in.

Table 3: Virtual environments within Condominium buildings.

Environment	How it affects HVAC system	Why it affects HVAC system
Alarm	Alarms are crucial to the safety of condo buildings in Toronto	HVAC systems detect abnormal temperatures and control flow of hazardous gases and minimize residential impact. [16]
Security Systems	Ensures safety of population inside the building	Security Systems detect and block hacking attacks[17]
Wifi	Allows maintenance to control and monitor building's HVAC systems	Wifi enhances efficiency, simplifies the operation and saves energy in an HVAC system. [18]

4.0 Stakeholders

Table 3 outlines stakeholders who have a vested interest in the reduction of GHG emissions of buildings.

Table 4: Identification of Stakeholders and Project Impact

Stakeholder	Impact
Toronto Hydro Corporation	Reducing emissions affects energy distribution within Toronto. [66]
Ontario Building Code Commission	Building alterations must follow bylaws and building codes set by the City. [66]
Environment and Climate Change Canada	GHG reduction must follow environmental regulations for safety outlined by Canada. [67]
Landlord Tenant Board Toronto	Building alterations affect building bylaws and therefore change real estate and rental regulations. [66]
Building Maintenance Personnel	Maintenance personnel must adapt to new systems to properly maintain them. [67]
HVAC Contractors and companies	HVAC companies must understand new HVAC systems

in Toronto	to effectively work with them. [67]
Architecture firms in Toronto	If new HVAC systems affect building layouts, architecture firms must accommodate them in new building designs. [67]
Condominium Authority of Ontario	New systems must follow bylaws and regulations set by the Authority. [66]

5.0 Detailed Requirements

5.1 Functions

The black-box method was used (refer to Appendix B) to develop functions as shown in Table 4.

Table 5: Functions of Design

Primary Function	Secondary Functions
Regulates thermal energy for buildings	Maintains current air temperature
	Senses air temperature
	Controls the flow of air in the building
	Dissipates/captures waste products from energy conversion processes

5.2 Objectives

Objectives were generated using a how-why tree is used (Appendix B), organized in order of importance in Table 5.

Table 6: Breakdown of objectives with goals and metrics

Primary objective	Secondary Objective	Metric	Goal
Sustainability	Maximizes usage of energy for heating and cooling	Coefficient of Performance	COP (cooling): 4.69 [19] COP (heating): 2.1 at -8.3°C and 3.4 at 8.3°C [19]
	Reduces amount of GHG emitted	Tonnes of GHG	Emissions <1.36 tonnes per residential unit [20],

			calculated in Appendix B
Performance	Maintains constant indoor temperature	Temperature in $_\circ$C	20 - 21 $_\circ$C [21]
	High life expectancy comparable to current systems	Time in years	Operation for >= 15 years [22]
	Maintains recommended air circulation levels	Flow in L/s	- 7.5L/s for living areas - 12 L/s for kitchens - 10 L/s for bathrooms [23]
	Adjusts temperature automatically	Temperature in $_\circ$C at activation	Heating system should activate at least 7$_\circ$C below setpoint [24] Cooling system should activate at least 4$_\circ$C above setpoint [24]
	Senses air temperature	Tolerance for error in %	Tolerance of +/- 0.30% (Appendix B)
Feasibility	Should not require frequent maintenance	Time in years	Professional servicing should be necessary yearly [26]
	Cost of operation should be similar to current systems	Cost in CAD for 1h	Costs $1.13/h of operation (Appendix B)

5.3 Constraints

Limits for the objective goals are listed in Table 6. Methodologies for determining each constraint is found in Appendix C.

Table 7. Design constraints with metrics and limits

Constraint	Metric with limit	Standard
Must meet efficiency standard	COP (cooling): at least 3.13	NECB standard for large air conditioners, Table 5.2.12.1-A [27]

	COP (heating): at least 3.20 at 8.3C, and 2.05 at -8.3C	NECB standard for large heat pumps, Table 5.2.12.1-A [27]
Cannot exceed current Toronto GHG emissions	3.12 tonnes of annual GHG emissions per residential unit	Statistics from Government of Canada (Appendix C)
Must maintain indoor room temperatures	Temperature of 18-22C	Ontario Building Code 6.2.1.2 [28]
Must maintain life expectancy of current systems	Life expectancy of 10 years	Standard from HVAC installation company [29]
Must meet air circulation standards	At least one room must have air circulation rate of at least 10 L/s, and 5L/s for all other rooms	Ontario Building Code 9.32.3.3 [28]
Must meet standards for temperature sensing	Heating system activates at least 5.6C below setpoint Cooling system activates at least 2.8C above setpoint Tolerance for error of 17.9%	ASHRAE 6.4.3.3.2 [30] ASHRAE 6.5.1.1.6 [30]
Cannot exceed operating cost of existing solutions	Cannot cost more than $1.74/h per residential unit	Upper bound based on electric baseboard heaters (Appendix C)

6.0 Generation, Selection and Description of Alternative Designs

6.1 Idea Generation Process

1. Brainstorming [Appendix D]:
   In this process, the team created a chart consisting of four columns: the primary function and three secondary functions. Each team member then generated ideas that met each individual function and put them in the corresponding columns. Over 50 ideas were generated.

2. SCAMPER Tool [Appendix D]:
   The team utilized this resource to create ideas that achieve all functions and the team feels meet the clients needs.

6.2 Alternative Design Selection Process

1. Feasibility check [Appendix D]:
   A Jamboard with all the ideas was generated in order to better visualize each idea based on the functions and eliminate unfeasible ones.

2. Multivoting [Appendix D]:
   Each team member voted for the three ideas they felt best met the clients needs among a total of 26 ideas.

3. Graphical Decision Matrix [Appendix D]:
   Ideas that received a vote were compared in a graphical decision chart with GHG emissions on the x-axis and maintaining temperature on the y-axis Ideas were placed on the graph based on how well they met objectives. The three ideas in the top right corner are the alternative designs.

6.3 Alternative Designs

6.3.1 Ground Source Heat Pump (GSHP) + Thermostat

A geothermal heat pump works by utilizing the stable temperature of the earth's crust to provide heating and cooling. The heat pump system consists of a series of pipes buried deep in the ground, which circulates a liquid mixture of water and antifreeze [31](Figure 9). The solution absorbs heat from the ground during the winter months, and the system transfers it to the building to provide heat. During the summer months, the system works in reverse, extracting heat from the building and depositing it into the earth. The temperature is then distributed through forced-air systems controlled by individual-unit thermostats, in which air heated by the pipes is then distributed via a series of fans to distribute heat as needed throughout the building. Thermostats are used in individual units so residents are able to control their own unit temperatures. They also have a centralized unit to control the pump itself to properly supply enough heat/cold to the building. The system is highly efficient, as it uses electricity to move heat from ground to building rather than generating it, making it a greener option compared to commonly used systems today.

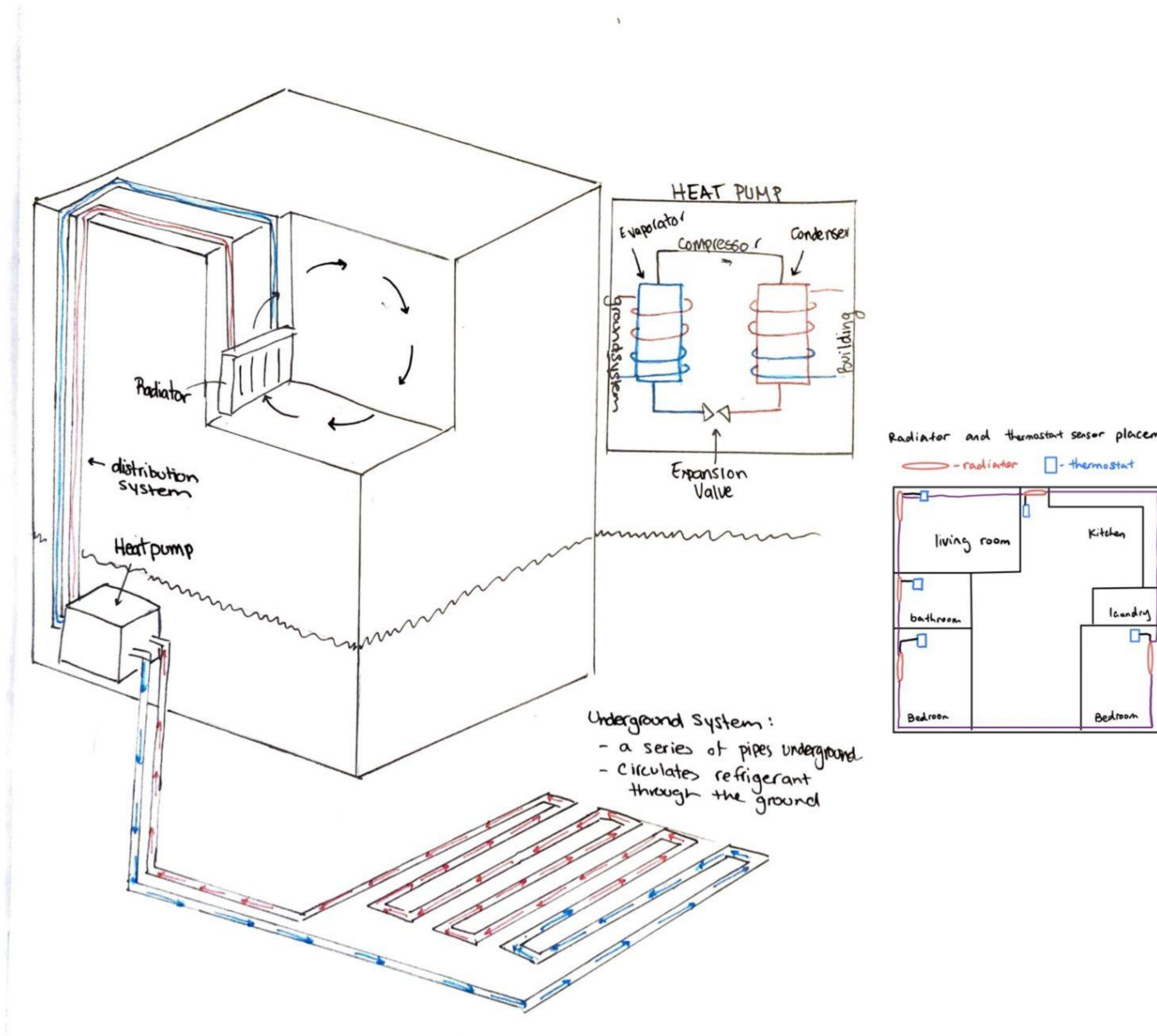


Figure (9). Design 1: GSHP + Thermostat

The ability for Design 1 to meet the design objectives is outlined in Table 7.

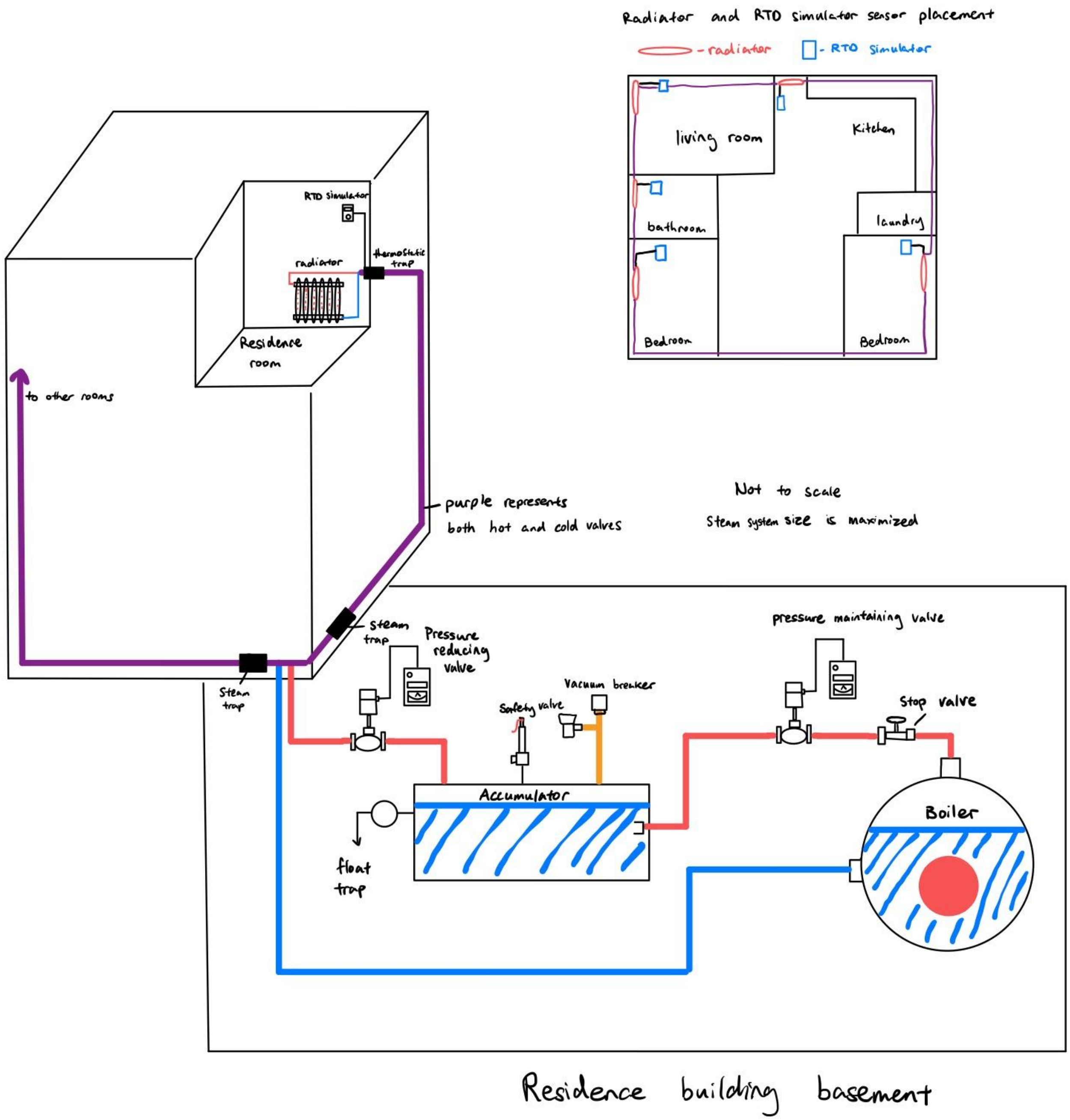
Table 8: Design 1 Objective Competence

Objective	Design Competence	
Sustainability	Efficiency	COP (Heating): 4.1 COP (Cooling): 3.6 [32]
	GHG Emissions	Estimated to be at most 0.75 tonnes/year [33]
Performance	Maintains indoor temperature	Can reach temperatures from -20 to 55 ∘C [34]
	Life Expectancy	20+ years for pump itself and 25-50 years

		for underground infrastructure [33]
	Maintains air circulation levels	18L/s with industrial radiators [35]
	Sensing range	Maintains temperature within +/- 5C of setpoint [36]
Feasibility	Maintenance	Recommended yearly maintenance on pump, but system runs autonomously [33]
	Cost	Estimated $0.75/hr (Appendix E) [37]

6.3.2 Steam Accumulator + RTD (Resistance Temperature Detector) Circuit

An RTD circuit-controlled steam accumulator uses a network of sensors and circuits to monitor and control steam pressure, temperature, and flow rates, (Figure 10). The RTD circuits are designed to provide precise measurements of the steam properties in real-time by increasing its resistance, allowing for optimal control of the system. It works by storing excess steam produced by the boiler during periods of low demand. Excess steam is stored in the accumulator vessel, which is designed to maintain pressure and temperature levels to prevent heat loss. During an increase in steam demand, the steam accumulator can quickly release steam through the thermostatic trap into the system to meet the increased demand. This reduces the need for the boiler to change its level of steam generation, thus saving energy [38].



Figure(10). Design 2: Steam Accumulator + RTD circuit

The ability for Design 2 to meet the design objectives is outlined in Table 8.

Table 9: Design 2 Objective Competence

Objective	Design Competence	
Sustainability	Efficiency	Energy recovery efficiency up to 80% [39]
	Reduce GHGs	0.24 tonnes per unit [40]
Performance	Maintains indoor temperature	20∘C [41]
	Life Expectancy	Lifespan of accumulator ~40 years and can increase lifespan of boiler by up to 15 years [39]
	Maintains air circulation levels	8L/s general circulation level [42]
	Sensing accuracy	Tolerance for error of 0.1% with range of -30C to 200C [43]
Feasibility	Maintenance	Bi-annual water and valve testing [39]
	Cost	$0.91/hr [40]

6.3.3 Air Source Heat Pump + Infrared Sensors

This design, shown in Figure 11, will use an air source heat pump (ASHP) that blows outdoor air to vapourize a low-pressure refrigerant, eliminating the need for combusting natural gases and therefore reducing GHG emissions. The vapour is transferred to a unit, condensed by the coils in the central fan, and distributed by the fan and underfloor system. When the infrared sensors that are placed around the unit detect a temperature above the setpoint, it controls the central fan to intake air from the unit and reverses the direction of the circuit through the reversing valve, therefore being able to maintain a constant temperature.

Alternative design 3

Air source heat pump + infrared sensors

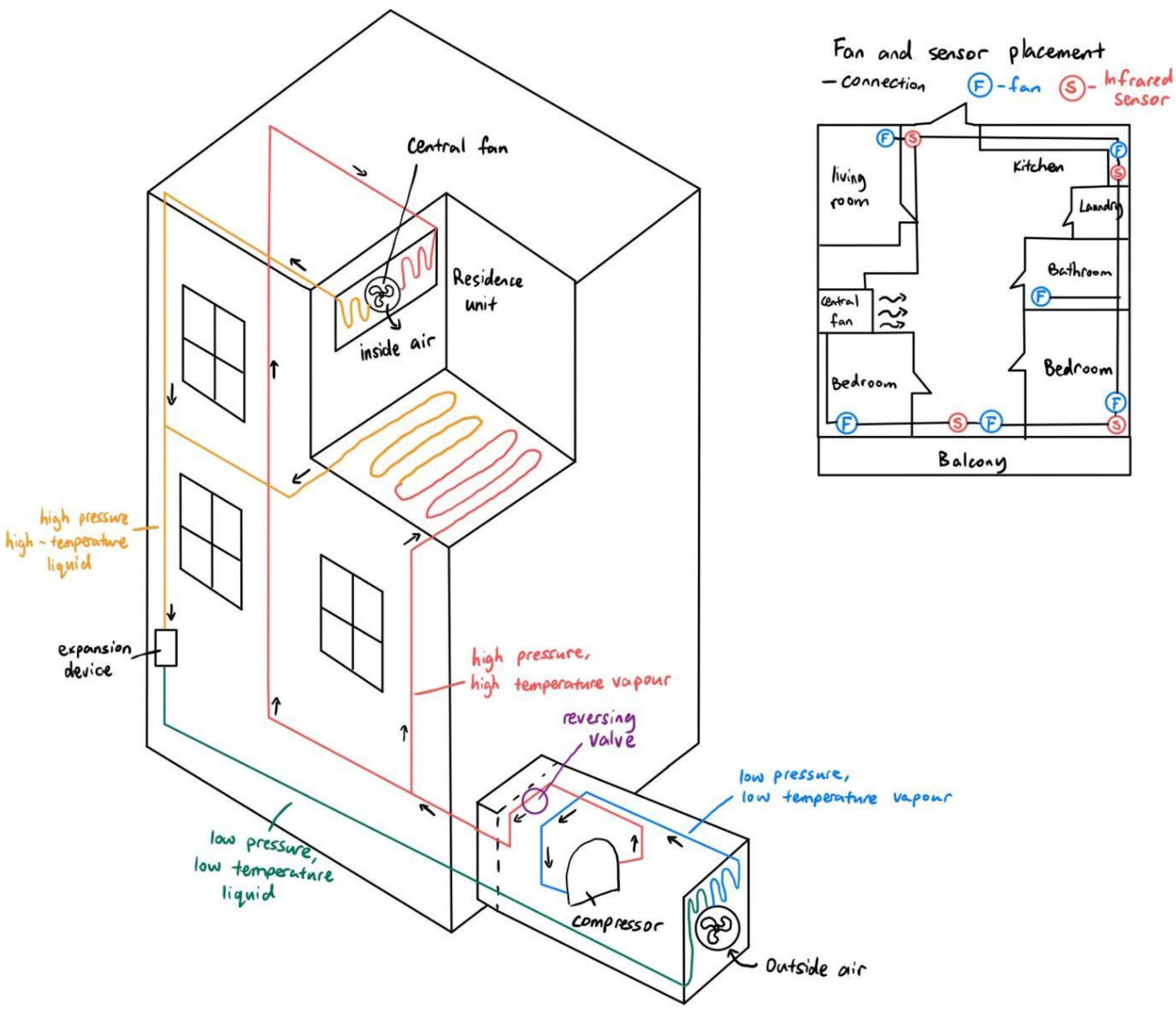


Figure 11. Design 3: ASHP + Infrared Sensors

The ability for Design 3 to meet the design objectives is outlined in Table 9.

Table 10: Design 3 Objective Competence

Objective	Design Competence	
Sustainability	Efficiency	COP (Heating): 2.78 - 3.81 COP (Cooling): 3.60 - 4.54 [44]
	GHG Emissions	Estimated 1.625 tonnes (Appendix E for estimation method)
Performance	Maintains indoor temperature	-40-80∘C effective temperature range [46]
	Life Expectancy	20 - 25 years [45]
	Air circulation	Additional fans in kitchen and bathrooms can increase ventilation rate to 10 L/s
	Sensing accuracy	Tolerance for error of +/-1.25% within -40 to 80C range [46]
Feasibility	Maintenance	Annual check for refrigerant leaks and wear [47]
	Cost	Estimated $0.89/hr (Appendix E) [48]

7.0 Proposed Conceptual Design Specification

The proposed design is a thermostat-controlled geothermal heat pump forced-air HVAC system. A geothermal heat pump is an energy-efficient heating and cooling system that uses thermal energy to regulate indoor temperatures. The heat from it is then transferred to air, which is then distributed by a thermostat-controlled ductwork system to send conditioned air throughout the building, providing heating and cooling as needed by residents. The system is controlled by individual-unit thermostats that monitor unit temperatures and adjust the system accordingly to maintain a comfortable temperature for residents. The thermostat system also controls the heat pump, ensuring it is generating enough energy for the building.

Out of the three designs, using the Pugh Chart (see Appendix D), this type of HVAC system fulfills the objectives set to meet the client's needs. In terms of sustainability, the system is highly energy-efficient, using the Earth's heat to regulate indoor temperatures. As supported by the US Department of Energy, this reduces the reliance on non-renewable energy sources, in-turn reducing GHG emissions [49]. For performance, the system relies on heat transfer through conduction instead of combusting fossil fuels, so energy usage is much less compared to traditional systems. Furthermore, it is highly effective due to its year-round nature both as a heating and cooling system. These factors allow the system to provide consistent and reliable temperature control throughout the year. In terms of feasibility, geothermal heat pump systems are becoming increasingly popular and accessible. The Canadian Federal government and local provincial companies offer incentives and tax credits for the installation of these systems, making them an attractive option for homeowners and businesses looking to reduce their environmental impact and save money on energy [50]. Furthermore, advances in technology have made these systems more efficient and affordable than ever before, making them a viable option for residential condominium use.

8.0 Measures of Success

To test the success of the design, two priority objectives will be measured:

1. The heat exchange temperature relative to the ground, according to the standard established by IEEE [51], simulated in ANSYS Fluent. Using these measurements, COP for the heating and cooling of the system can be calculated (Appendix F) to meet efficiency objective. The efficiency of the design can be used to determine its sustainability, which is considered by the client to be the most important primary objective.

2. The air circulation rate objective, simulated in ANSYS Fluent. This objective is necessary to test to determine the thermal comfort of users in the design, as required by ASHRAE Standard 55 [52].

Measures of success procedure is outlined in Table 10, assuming an action period from Mar 27 - Apr 14.

Table 11: Test Methodology for Measures of Success

Week	Personnel	Task	Deadline
Week 12 (Mar 27 – Apr 02): Obtain all materials	Michael, Bob	Design a floorplan for typical apartment unit in Toronto	Apr 02
	Eleni	Research seasonal soil conditions (Appendix F) in Toronto	
	Katelyn, Keli	Research temperature and heat capacity parameters (Appendix F) used for heat exchange calculation	
Week 12 (Apr 03 – Apr 09):	Keli, Eleni, Katelyn	Model borehole and inlets (Figure 12) in ANSYS	Apr 09

Prepare Simulations	Michael, Bob	Model apartment unit in ANSYS	

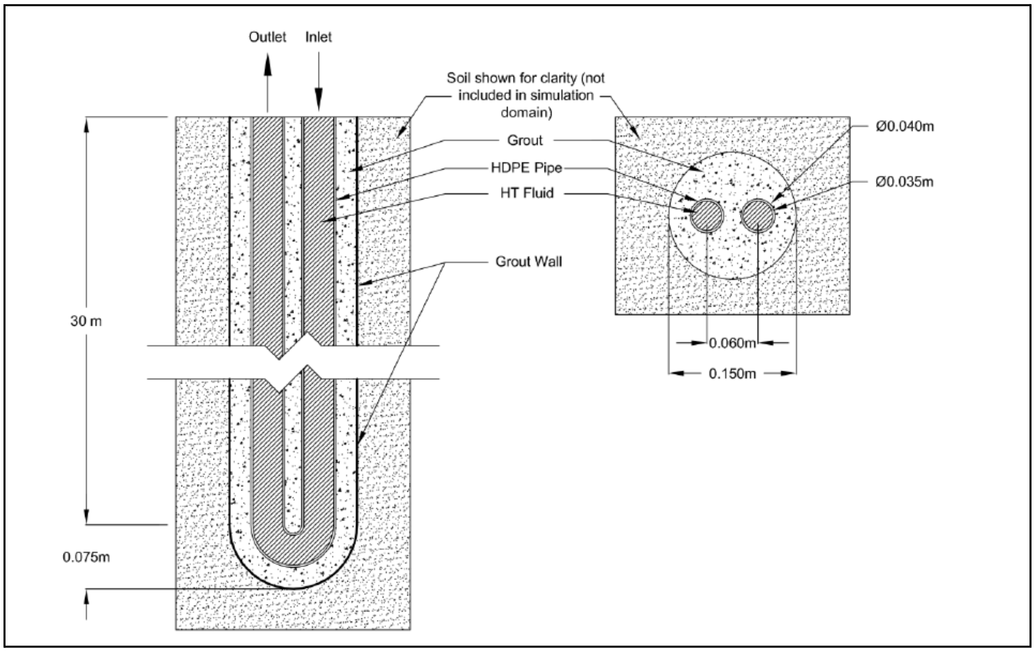


Figure 12. Geometry of borehole to be modelled in ANSYS [51]

Week 13 (Apr 10 – Apr 14): Run Simulations and gather data	Keli, Eleni	Record temperatures of heat transfer fluid in seasonal temperatures for depths of 2m, 3m, and 4m.	Apr 12
	Katelyn	Calculate COP using data from borehole simulation (Appendix F)	Apr 14
	Bob, Michael	Generate air circulation velocity and temperature plots of the room	Apr 14

9.0 Conclusion

By modifying current space heating systems that emit GHGs as a byproduct, it is possible to significantly reduce overall emissions. Through researching and examining stakeholders, service environment, and developing FOCs, the team has created a set of requirements to generate design ideas. After using a variety of selection methods, three alternative designs were chosen, and it was decided that the best design was the GSHP + Thermostat because it works best in the service environment and is the most efficient. In the upcoming weeks, the team will simulate the system using ANSYS Fluent and gather data to gain a better understanding of each design's overall effectiveness and environmental impact.

10.0 References

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Appendix

Appendix A - Methodology for generation of functions

The black box method was employed to generate primary and secondary functions (Figure C).

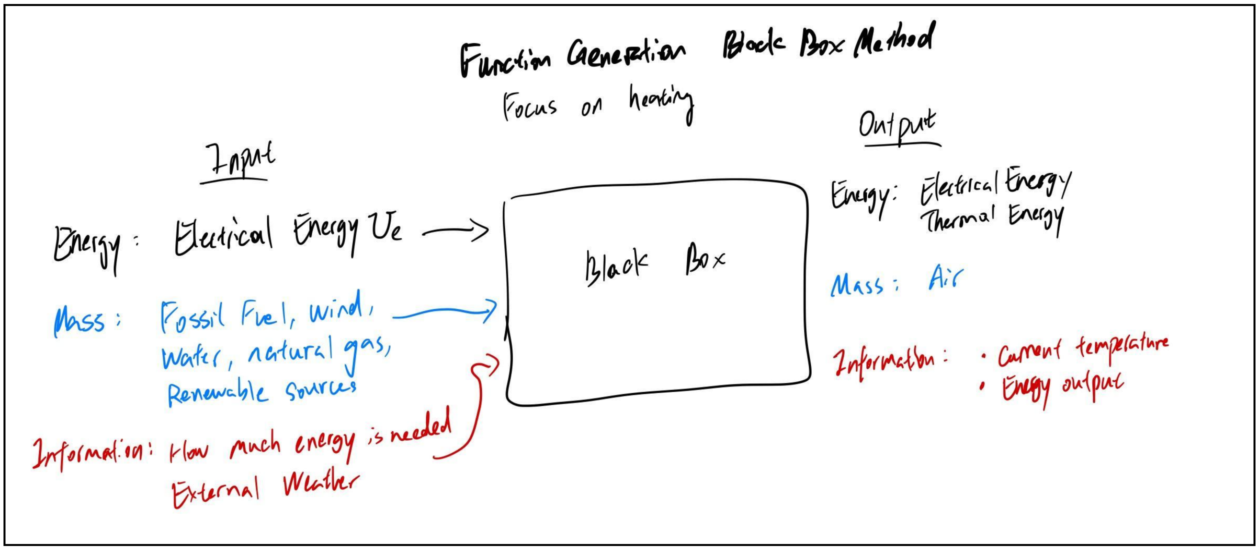

Figure A1 - Black Box Method

Generally, the primary function was to take in either electrical energy or thermal energy from the combustion of natural gases, and convert this to a thermal energy output. To enable this primary function, secondary functions such as sensing temperature, circulating air, and maintaining a constant temperature were needed.

Appendix B - Determination of Objectives

The objectives were determined based on three main observations the client meeting:

- The client and her company was concerned about sustainability;
- The client did not have many constraints but wanted the design to be feasible;
- The design should still work similarly to current residential heating and cooling systems.

The team then generated an objective tree (Figure B) to determine the primary and secondary objectives for the design.

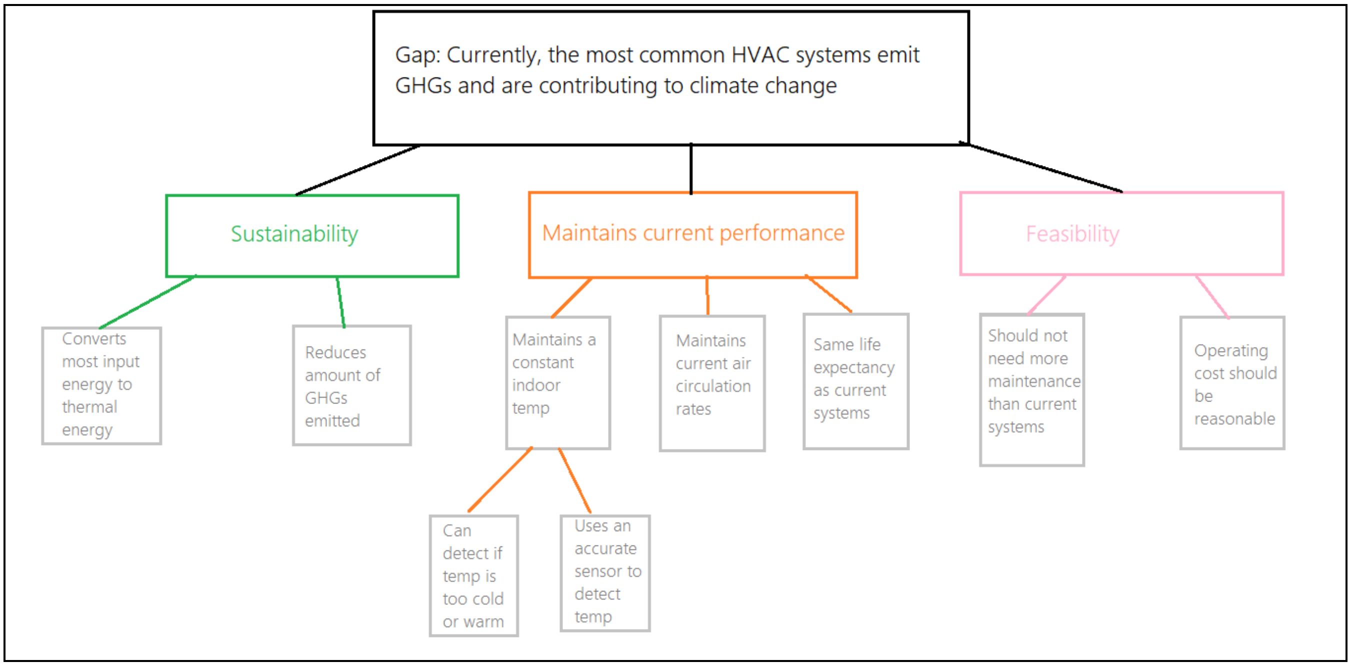

Figure A2. How-why tree to determine objectives

The efficiency ratings are based on the EnergyStar guide, which is a standard rating for appliances. The categories commercial unitary air conditioner (CUAC) and commercial unitary heat pump (CUHP) from the 135000 - 240000 Btu/h ranges are used [19]. Originally, the IEER value of 16.8Btu/h is used, but is converted to COP where COP = (IEER*1055)/3600 [53]

The amount of GHG emissions is taken using the largest residential unit as stated by a Canadian Real Estate article [50], of 1465 sq. ft for three or more bedroom condos. This value is converted to sq.m and multiplied to the Tier 3 recommended emission value for high-rise buildings. Tier 3 is chosen because according to Toronto's Transform TO report, the city aims to have all newly constructed buildings to reach Tier 3 by 2022 [55].

The sensing accuracy is expressed as a percentage of the range, which is +/- 3 kJ/kg for a 0-995 kJ/kg range [25]. The constraint is calculated in the same way.

The cost of operation is determined using the energy consumption or a 1000 sq.ft space, which was determined to be 45000 - 55000 BTU [56]. Since the values are given for the United States, which is warmer than Canada, a 60000 BTU HVAC system is used as an upper bound and is predicted to have an electricity consumption of 7.5 kWh [57]. The value is then multiplied to the peak cost of electricity from Toronto Hydro at 15.1 cents [58], and the cost per hour is $1.13.

Appendix C - Determination of constraints

The relevant standards and regulations for heating systems are taken from the following sources:

- National Energy Code of Canada for Buildings (2020) Performance Requirements for Air-Cooled Unitary Air Conditioners and Heat Pumps - Electrically Operated (Table 5.2.12.1-A) [27].
    - Since the design is focusing on multi-residential buildings, the constraint is based on a cooling or heating capacity of ≥ 223kW.
    - The original constraint used IEER for heating, but this is converted to COP using the method in Appendix B.

- The Ontario Building Code O. Reg. 33/12 (last updated Nov. 1, 2022) Part 6 (Heating, Ventilating, and Air-Conditioning), and Part 9.32 (Ventilation) [28]

- The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 90.1, Energy Standard for Buildings Except Low-Rise Residential Buildings (2013) [29]. This standard is included because it was referenced by the Ontario Building Code.

The emissions constraint is calculated based on the 2018 average emissions from an Ontario household, which was 4 tonnes in a year, taken from Statistics Canada [59]. In 2022, the Government of Canada has stated that 78% of emissions can be attributed to space heating [60]. Assuming the design emits the same amount of GHG, the expected amount would be 0.78 x 4.0 = 3.12 tonnes.

The temperature sensing accuracy uses the same method in Appendix B for objectives. According to the ASHRAE standard, the tolerance for error should be +/- 5kJ/kg within a 35-63 kJ/kg range [30].

To calculate the cost constraint, an upper bound for electric heating is used since natural gas is generally less expensive. According to the CBC, electric baseboard heating is the most common but expensive form of alternative heating [6]. Using the five largest rooms in the table published by the Gunnison County Electric Association [61] to represent an apartment, the total electricity consumption is calculated to be 11.5 kWh. The cost is then calculated by multiplying the consumption to the peak electricity rate from Toronto Hydro at 15.1 cents/h [58].

Appendix D - Generation of ideas

The free brainstorming chart classified by functions is included in Table A1.

Table A1. Free Brainstorming Chart based on functions

Outputs thermal	**Senses air**	**Controls the flow of**	**Dissipates or**

energy for buildings	**temperature**	**air in the building**	**captures waste products from energy conversion processes**
Furnaces	Thermocouple Sensor	Adjustable turbine	Turbo
Central gas furnace	AI algorithm	Computer-controlled air circulation system	Thermal Energy storage tank
Electric furnace	Infrared thermometers	Central electric heating coil + fan	Gas capture equipment
Condensing gas furnace	Individual smart-thermostats	Large heat sink in kitchen + fan	Porous filter built into walls
Oil furnace	Raspberry-Pi controlled thermistor circuit circuit	Wind-powered boiler + circulator	Climbing plants
Outside heat extractor	Remote temperature sensors	Temperature-controlle d water coils embedded in walls	Condenser (converts gas CO_2 -> liquid)
Electric motor	Flow sensor (liquid will have different viscosities at different temperatures)	Refrigerant coils in ceiling, heating coils in floor + fan	Fluidized bed reactor
Solar-powered furnace	Electromagnetic induction device	Fan + reflective solar disk	Chemical looping combustion
Boilers	mercury sensor thermostat	Mechanical rotors that create friction on rough plates underneath flooring	Biosafe naturalization gas
Hot water boiler			
Steam boiler			
Natural gas boiler			
Biomass compressors			
Hydrogen compressors			

Heat pumps			
Air-source individual heat pumps			
Air-source central heat pump			
Ground-source central heat pump			
Water-based geothermal heat pumps			
Storage systems + fan			
Fertilizer-based energy storage system			
Metal hydride heating/cooling			
Salt hydrate HVAC system			
Sulfur thermal energy storage system			
Dual-tank storage system			
Molten salt tank			
Passive concrete			
Thermocline			
Steam accumulation			
DeVap			
Electric Baseboard Heaters			

Feasibility Check

Any ideas that were deemed infeasible were taken out of the chart. The remaining ideas were placed in the Jamboard (see Figure A3), with more important ideas clustered towards the center of the function in green.

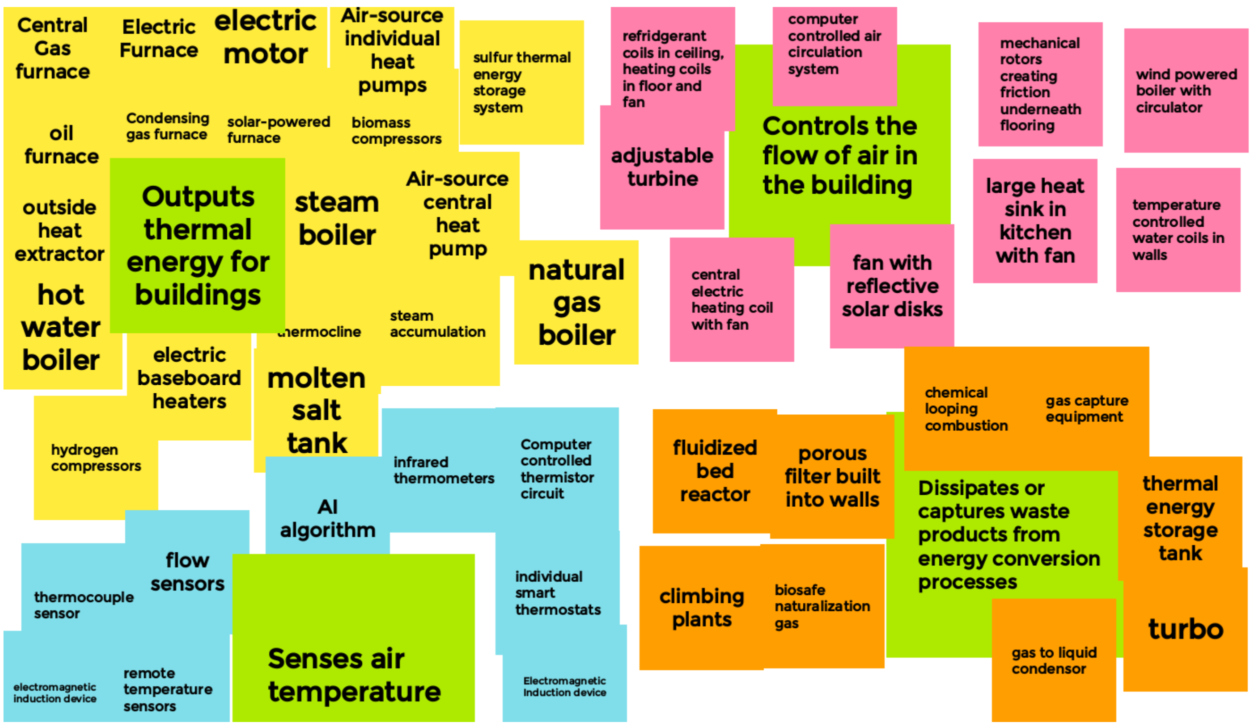

Figure A3. Jamboard of ideas after feasible ideas

The remaining ideas were then modified to create solutions with SCAMPER:

1. Ground-source heat pump system that uses radiator coils on the floor, and a temperature-controlled pressure valve

2. A reflective solar disk that captures sunlight and stores heat. When heating is needed, a fan blows across it to circulate the hot air, but when cooling is needed it sucks in air and runs through a plate with cool refrigerant. A raspberry-pi thermistor circuit is used to control this

3. Maintain the current HVAC system using a more sensitive thermostat, and modify the compressor so it decomposes CO_2

4. Use a solar-powered boiler that can also store excess electricity that powers a circulating fan. The temperature of the space is controlled with a thermostat

5. Incorporate heating coils underneath the floorboard and cooling coils in the ceiling, use fans and ventilation ducts, controlled by an NTD circuit and thermostat

6. Coils filled with water run through the walls. This is temperature controlled externally from outside the unit using a central thermostat

7. Electric heating is used, controlled by an infrared sensor circuit. Passive concrete is used as a building material to cool the space if needed

8. Similar HVAC circuit using heat exchangers but relying on the combustion of hydrogen. The water is stored and used to cool the space when needed. A generic thermostat is used to control the temperature

9. Steam accumulation – steam is used from factories around Toronto and used to power a compressor, turbine, and condenser HVAC system, with each unit equipped with a smart thermostat

10. A metal hydride thermochemical energy system operates pumps that controls the temperature of the space and regulated by an PTD circuit.

11. Use mechanical rotors on a high-friction surface, which generates thermal energy stored in a thermal energy storage tank. An AI algorithm is used to control the temperature

12. An air-source central heat pump is used and circulated with an adjustable turbine. A flow-sensor that measures the density of the air relative to the temperature is used to monitor the temperature

13. A normal HVAC system is used but replacing the current thermostat with an AI system along with a fluidized bed reactor for carbon capture and storage

14. Use a water-based geothermal pump, using Lake Ontario as a thermocline. Temperature is regulated through using an IC-chip with a thermistor circuit

15. A wind-powered electric furnace with a set of turbines that circulates air throughout the space. A mercury thermometer is used to monitor temperature and controlled with an Arduino.

16. Using Electric motor to generate thermal energy and use pipe system and turbine to deliver heat, use infrared sensor to sense temperature

17. Passive solar heating, use windows to capture and store in an internal storage system that will convert optic radiation to heat energy. Will use Al algorithm to sense temperature

18. Water vapor is extracted from the air and put through a desiccant filter (DEVAP). A fan circulates the air throughout the space and infrared sensors are used to monitor the temperature

19. Programmable materials that can absorb external heat energy and store them in a tank for future use. Use a thermostat to control temperature

20. A gigantic hydrogen reactor that produces heat due to reaction of hydrogen and oxygen, and byproduct water can regulate temperature. An infrared sensor will sense the temperature

21. A device to get waste heat from industrial manufacturing, to be delivered through pipes and use AI software based thermostat for temperature control

22. A Thermophotovoltaic system, which generates heat energy from thermal radiation. Thermostat will be used for control temperature

23. A huge magnetic induction device that generates heat through induced electric currents. An electromagnetic sensor for temperature sensing

24. Vortex tubes separate hot and cold air streams from a compressed air source, and can be used for heating or cooling. A thermostat goes with this

25. Use of highly efficient insulation that prevents heat losses, PTD circuit will be used for controlling temperature

26. Use biomass to create heat energy and deliver it using a turbine, regulating temperature using a thermistor

The Multivoting System

Screenshots of the multivoting system, using Microsoft Excel, is shown below in Figure A4.

Vote three Solutions by fill the color in the same row under your name column, vote three!

No.	Solution	Bob	Katelyn	Michael	Eleni	Ke li
1	Ground-source heat pump system that uses radiator coils on the floor, and a temperature-controlled pressure valve					
2	A reflective solar disk that captures sunlight and stores heat. When heating is needed, a fan blows across it to circulate the hot air, but when cooling is needed it sucks in air and runs through a plate with cool refrigerant. A raspberry-pi thermistor circuit is used to control this					
3	Maintain the current HVAC system using a more sensitive thermostat, and modify the compressor so it decomposes CO_2					
4	Use a solar-powered boiler that can also store excess electricity that powers a circulating fan. The temperature of the space is controlled with a thermostat					
5	Incorporate heating coils underneath the floorboard and cooling coils in the ceiling with air pump heat source, use fans and ventilation ducts, controlled by an NTD circuit and thermostat					
6	Coils filled with water run through the walls. This is temperature controlled externally from outside the unit using a central thermostat					
7	Electric heating is used, controlled by an infrared sensor circuit. Passive concrete is used as a building material to cool the space if needed					
8	Similar HVAC circuit using heat exchangers but relying on the combustion of hydrogen. The water is stored and used to cool the space when needed. A generic thermostat is used to control the temperature					

9	Steam accumulation – steam is used from factories around Toronto and used to power a compressor, turbine, and condenser HVAC system, with each unit equipped with a smart thermostat
10	A metal hydride thermochemical energy system operates pumps that controls the temperature of the space and regulated by an PTD circuit.
11	Use mechanical rotors on a high-friction surface, which generates thermal energy stored in a thermal energy storage tank. An AI algorithm is used to control the temperature
12	An air-source central heat pump is used and circulated with an adjustable turbine. A flow-sensor that measures the density of the air relative to the temperature is used to monitor the temperature
13	A normal HVAC system is used but replacing the current thermostat with an AI system along with a fluidized bed reactor for carbon capture and storage
14	Use a water-based geothermal pump, using Lake Ontario as a thermocline. Temperature is regulated through using an IC-chip with a thermistor circuit
15	A wind-powered electric furnace with a set of turbines that circulates air throughout the space. A mercury thermometer is used to monitor temperature and controlled with an Arduino.
16	Using Electric motor to generate thermal energy and use pipe system and turbine to deliver heat, use inflared sensor to ense tempearture

17	Passive solar heating, use windows to capture and store in internal storage system that will convert optic radiation to heat energy. Will use AI algorithm to sense
18	Water vapour is extracted from the air and put through a dessicant filter (DEVAP). A fan circulates the air throughout the space and infrared sensors are used to monitor the temperature
19	Programmable materials that can absorb external heat energy and store them in a tank for future use. Use a thermostat to control temperature
20	A gigantic hydrogen reactor that produce heat due to reaction of hydrogen and oxygen, and byproduct water can regulate temperature. An inflared sensor will sense the temperature
21	A device to get waste heat from industrial manufacturing, to be delivered through pipes and use AI software based thermostat for tempeature control
22	A Thermophotovoltaic system, which generates heat energy from thermal radiation. Thermostat will be used for control temperature
23	A huge magnetic induction device that generate heat through induced electric currents. An electromagnetic sensor for temperature sensing.
24	Vortex tubes separate hot and cold air streams from a compressed air source, and can be used for heating or cooling. A thermostat goes with this
25	Use of highly efficient insulation that prevents heat losses, PTD circuit will be used for controlling temperature
26	Use biomass to create heat energy and deliver it using a turbine, regulating temperature using a thermistor

Figure A4. Multivoting spreadsheet, made with Microsoft Excel

Graphical Decision Chart

The numbers are aligned with those on the multivoting system chart (see Figure A5).

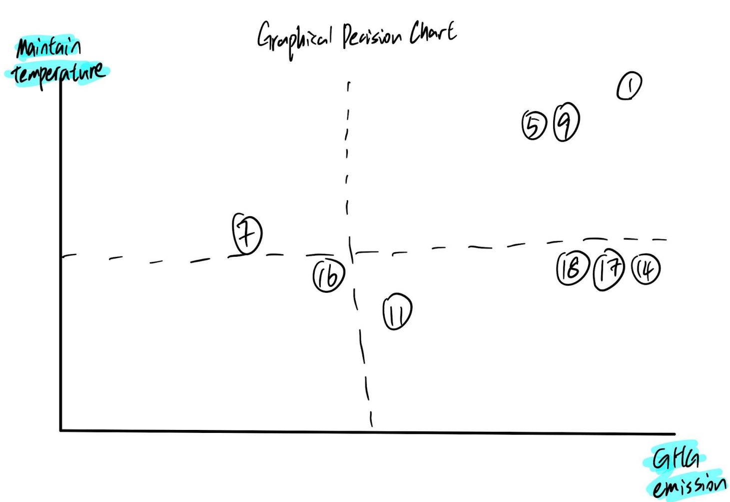

Figure A5. Graphical Decision Chart for selection of alternative designs

Pugh Chart

The datum used for the Pugh chart is the current HVAC system outlined in the problem statement, using conventional heat exchangers. Tables A2 - A4 compares the three alternative designs to this datum.

Table A2. Pugh Chart for Geothermal heat pump + Thermostat

	Datum	Score	Justification
Sustainability	S	+2	-Doesn't utilize the burning of fossil fuels to produce heat -Geothermal energy is a renewable energy source -Estimated GHG emissions were found to be at most 0.75 tonnes/year [33]
Performance	S	+2	Geothermal heat pump systems are expected to last upwards of 20 years. Furthermore, the underground system lasts between 20 - 50 years. Compared to HVAC systems whose lifespan is between 10-20 years. [33]
Feasibility	S	+2	-Geothermal energy systems require less regular maintenance compared to current HVAC solutions -High upfront cost -Longterm energy savings (5-10yrs) [33] -Many new condo buildings are currently using this technology to heat and cool the building

Table A3. Pugh Chart for Steam accumulator + RTD circuit

	Datum	Score	Justification
Sustainability	S	+1	-Energy recovery efficiency up to 80% [39]
Performance	S	+0	-The boiler is continuously being run at high demand levels could result in a reduction in lifespan and efficiency, as well as increase levels of maintenance [39]

			-These effects can be mitigated by having multiple boiler systems [39]
Feasibility	S	+1	-Lower overall utility bill -Lifespan of accumulator is approximately 40 years, compared to current HVAC systems whose lifespan is between 10-20 years[37]

Table A4. Pugh Chart for ASHP + Infrared Sensors

	Datum	Score	Justification
Sustainability	S	+1	-Estimated 1.625 tonnes of GHG released per year
Performance	S	+2	-In homes, a Air Source Heat Pump Can produce three times more heat than energy it consumes to operate [63] -Transfers heat, as opposed to converting it through combustion of fossil fuels [63]
Feasibility	S	+1	-Not usually used in regions with long periods of sub zero temperatures, however technology has been advancing and similar systems have been adapted for colder climate [64] -Residential homes can see annual saving of approximately 3000kWh [63]

Appendix E - Justification for Alternative Designs

Alternative Design 1: GSHP + Thermostat

A heat exchanger transfers heat between the refrigerant in the heat pump and the antifreeze solution in the closed loop. [31]

The emissions for the GSHP is 75% - 80% reduction from the baseline [33]. Assuming the baseline is the constraint of 3.12 tonnes annually, emissions is estimated to be 0.75*3.12 = 0.78 tonnes/yr.

Alternative Design 2: Steam Accumulator + RTD Circuit

The average off-load steam demand must be lower than the boiler capacity (the maximum continuous rating or MCR), such that sufficient surplus boiler capacity is available to recharge the water stored in the accumulator during off-peak times. [38]

Although exact figures for reduction of emissions cannot be found, the team has argued that the steam accumulator is a suitable solution for the following reasons:

1) The steam accumulator stores heat through water. Thus, when steam is released, there will be no GHG emissions because CO_2 is not a product from the vaporization of water.
2) The only GHG emissions will result from the generation of steam. However, steam generated from industrial processes can be repurposed for heating applications at lower pressures. [62]

Alternative Design 3: ASHP + Infrared Sensors

According to the study by Berardi and Jones, Toronto has a baseline emissions of 4.8 $kg \cdot CO_2/m^2$ [44], which is assumed to be equivalent 3.12 tonnes per year (as set by the constraint, which is based on residential emissions of CO_2). The upper bound for CO_2 emissions by ASHP is 2.5 $kg \cdot CO_2/m^2$ [44]. If we maintain this proportionality (since heating/cooling usage should be the same), this amounts to 1.625 tonnes of emissions annually.
Using the same 60000 BTU system from the objectives, the sensing circuit energy consumption is assumed to be negligible compared to the ASHP. The ASHP with the lowest SEER rating at 14 consumes 4286 W of power in warm weather and 7500 W of power in cold weather per hour [45]. Taking the average, this ASHP consumes approximately 5.893 kWh. With the cost of electricity in Toronto during peak hours 15.1 cents/hr [28], this is calculated to cost \$0.89/hr of operation.

Temperature is proportional to energy by the formula q = mcT where q is equivalent to heat energy. When measuring sensing accuracy, the tolerance can be expressed as a percentage of the range.

Appendix F - Methodology for Measures of Success

Test 1: Efficiency Test
The coefficient of performance (COP) of the ground source heat pump system can be measured by determining how effectively heat transfers from the ground to the fluid contained in the pump and vice versa. The COP calculation using the method described by Abdelrahman S. Ramadan, from the University of Western Ontario as shown in Table A5.

Table A5. Equations for determining COP [65]

Equation	Explanation

$COP_{heating} = \frac{Q_C + W}{W}$ $COP_{cooling} = \frac{Q_C}{W}$	Q_C - amount of heat transferred W - amount of energy needed to power the system
$Q_C = Q_{fluid/g} + Q_{g/fluid}$ $Q_{fluid/g} = \frac{T_g - T_{f2}}{R_g + R_{p2} + R_{f2}}$ $Q_{g/fluid} = \frac{T_g - T_{f1}}{R_g + R_{p1} + R_{f1}}$	$Q_{fluid/g}$- amount of heat transferred from heat transfer fluid to ground (hole 2) $Q_{g/fluid}$ - amount of heat transferred from ground to heat transfer fluid (hole 1) T_g - temperature of grout wall T_{f1}, T_{f2} - temperature of heat transfer fluid in pipe 1 and 2 R_{p1}, R_{p2} - conductive thermal resistance of pipe material R_g - conductive thermal resistance of grout R_{f1}, R_{f2} - convective thermal resistance between fluid and pipe

A diagram of each variable is shown in Figure A6.

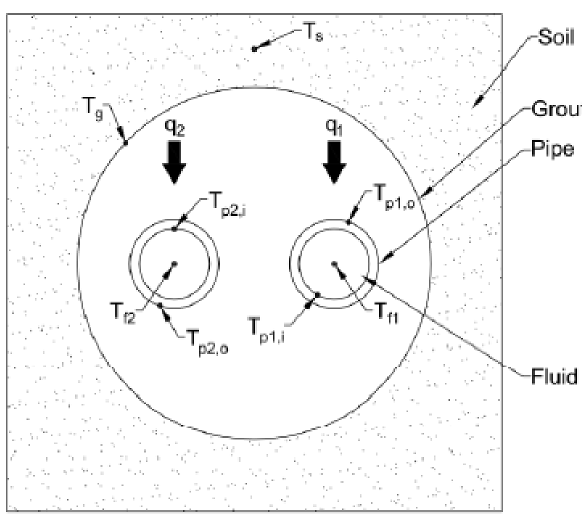

Figure A6. Cross-section of borehole with variables [65]

$R_f = \frac{1}{2\pi hr[in]}$	h - heat transfer coefficient of fluid

$R_P = \frac{ln(\frac{r[out]}{r[in]})}{2\pi k}$	r[in] - inner radius of pipe r[out] - outer radius of pipe k - thermal conductivity of pipe

During Week 12, the thermal resistance of the heat transfer fluid, grout material, and piping material will be determined. In addition, the following boundary conditions set in the simulation according to IEEE [48] will be researched:

- Soil temperature (for winter and summer)
- Soil conductivity
- Dimensions of borehole for load size (i.e. high-rise apartment building)
- Energy consumption of system

Test 2: Air Circulation Test

The air circulation test relies on creating an accurate model of an apartment unit, and using the ANSYS Fluent simulation to determine air circulation rate and temperature. During Week 12 and 13, the geometry of the unit including ducts and vents will be created and tested in Week 14. Using the data from the simulation, the team will make changes or draw conclusions for how to improve air circulation.