Ground Source Heat Pumps: Considerations for Large Facilities in Massachusetts
September 2020

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ABSTRACT

Ground-source heat pump (GSHP) systems have been implemented at large scales on several university campuses to provide heating and cooling. In this study, we test the idea that a GSHP system, as a replacement for an existing Combined Heat and Power (CHP) heating system coupled with conventional cooling systems, could reduce CO_2 emissions, and provide a cost benefit to a university campus. We use the existing recorded annual heating and cooling loads supplied by the current system and an established technique of modeling the heat pumps and borehole heat exchangers (BHEs) using a TRNSYS model. The GSHP system is modeled to follow the parameters of industry standards and sized to provide an optimal balance of capital and operating costs. Results show that despite a decrease in heating and cooling energy usage and CO_2 emissions are achieved, a significant increase in electric demand and purchased electricity result in an overall cost increase. These results highlight the need for thermal energy storage, onsite distributed energy resources and/or demand response in cases where electric heat pumps are used to help mitigate electric demand during peak periods.

Keywords: Heat Pumps, TRNSYS, Energy System Modelling, Heat Electrification, Decarbonization

Highlights

- An established TRNSYS model for borehole heat exchangers is applied.
- A case study using real-world data from a university building complex is presented.
- Economic viability of a heat pump system is compared to the current system.
- CO_2 emissions are reduced when using regional grid electricity.

Nomenclature

Acronyms

ASHP	Air-source heat pump
BAS	Building Automation System
BHE	Borehole heat exchanger
CHP	Combined heat and power
COP	Coefficient of Performance
CTG	Combustion Gas Turbine
GSHP	Ground-source heat pump
HRSG	Heat Recovery Steam Generator
HVAC	Heating, Ventilation, and Air-conditioning
ISO-NE	Independent Service Operator – New England
TRNSYS	Transient System Simulation Tool
UMass	University of Massachusetts – Amherst

1. INTRODUCTION

Borehole and well drilling have a long history reaching back millennia as a method of extracting water as well as other resources such as oil and natural gas. Geothermal boreholes, those drilled for the specific purpose of harnessing geothermal energy, can directly extract heat from the ground; however, this requires specific geology with active geologic activity to produce high enough temperatures to be useful. Since the 1980's, research has focused on a second approach to harnessing the power of geothermal energy [1,2]. This second method relies on borehole heat exchangers (BHE) connected to ground source heat pumps (GSHPs). In this type of installation, the ground itself is used as a heat source or sink for the GSHPs. With the world-wide push toward CO_2 emissions reduction targets, there has been a significant increase in the interest and implementations of heat pump systems for HVAC purposes in general and of ground source heat pumps (GSHPs) in particular.

A heat pump is essentially a heat engine operated in reverse, such that mechanical work is done to move heat from a cold reservoir to a hot reservoir. This allows for the heat pump to heat a building using heat from a lower temperature heat source, such as outdoor air, even when the outdoor air temperature is lower than the desired building temperature. A heat pump's efficiency increases as the temperature difference decreases between the heat source and sink. Use of the ground as a heat source in the heating season and a heat sink in the cooling season allows for higher efficiencies compared to an air source heat pump (ASHP) system [3,4]. Several types of geothermal systems exist. Of these, a closed loop vertical borehole type system is commonly used for large-scale, commercial geothermal systems. This type of system consists of a large area, into which a field of boreholes is drilled, typically several hundred feet. Cross-linked polyethylene (PEX) tubing forming the closed loop is used, running down and up each borehole in a "U-bend" shape. The boreholes are finished by adding a thermally conductive grout and backfilling to maintain the structural integrity of the boreholes.

This study aims to test the idea that a GSHP or ASHP system, as a replacement for an existing combined heat and power (CHP) plant and conventional cooling systems, could reduce CO_2 emissions and also provide a cost benefit to a large energy consumer, in this case the university campus. The resulting energy usage, costs and CO_2 emissions will be analyzed for the GSHP and ASHP cases and will be compared to the current systems.

2. CASE STUDY METHODOLOGY

2.1 University Building Complex

Simulation of GSHPs using the TRNSYS duct ground heat storage model Type 557 and related methods is an established technique [5–8]. We will apply this type of simulation to a building complex on the campus using the existing heating and cooling loads. The Commonwealth Honors College Residential Complex (CHCRC) on the campus was chosen as the study location. This building complex, completed in 2013, is a LEED Silver certified green building with 47,600 m^2 of building area containing 1,500 student beds, 9 classrooms and a 24/7 café and is occupied during all months of the year. Unlike many buildings on the campus that use steam for heating directly, these buildings use a dual water system to deliver hot water for heating and cold water for cooling. Lower temperature heating distribution systems are more conducive to heat pump replacement than higher temperature heating distribution systems, thus this building complex is an example of buildings that could utilize heat pumps with their current heat distribution system.

2.2 Utility Electric and Heating Costs

For small energy consumers, such as a typical residential home, utility costs are charged based mainly on usage of electricity or fuel. For example, a consumer may pay a certain rate in $ per kilowatt-hour for electricity and a rate in $ per liter or m^3 for heating fuel. In such a situation, comparison of a conventional heating and cooling system to an electrified heat pump system for heating and cooling is relatively straight forward, as the average seasonal efficiency of the heat pump can be used to compare usage of electricity for the heat pump to usage of fuel and/or electricity in a conventional system. The resulting costs will then depend on local electric and fuel rates.

While this holds true for a small energy consumer, larger energy consumers such as large commercial or industrial customers may have a more complex energy rate structure. For most large energy consumers, particularly those in deregulated markets, it is common for electricity to be charged based mainly on three components: total electricity usage in kWh, monthly demand in kW, and an annual capacity charge in kW used at a yearly peak time for the regional grid. Rates may also vary between on and off peak hours and between summer and winter months. A demand ratchet may also be included to specify the minimum demand charge as a percentage of the yearly maximum demand. This makes analysis of the effect of installing electric heat pumps more complex, as the increase in electric demand must be calculated on a sub-hourly basis to determine the resulting cost increase due to increased demand.

Further, the case of a facility using a combined heat and power (CHP) plant to satisfy both heating and electricity needs introduces yet another complexity. In analyzing a replacement of the entire heating load by electric heat pumps, the loss in electrical generation must also be considered. As many CHP plants are operated to primarily satisfy the required heating, this could mean loss of all generated electricity.

This research focuses on the effect of transitioning the known, measured heating and cooling loads of a building complex on the university campus to electric heat pumps. As noted, the utility costs and presence of a CHP plant make this a unique challenge. The energy usage and demand will be analyzed, and system costs will be calculated using the university's rate structure.

2.3 Previous Studies and Installations

At the University of Massachusetts, there have been two previous studies considering geothermal boreholes for seasonal heat storage [9,10]. This research builds upon the collected data from these previous studies on the ground thermal conductivity and geological feasibility of a ground source heat exchanger system in particular and the simulation methods for such a system. As well, these studies have demonstrated a desire to implement a geothermal system in the future.

Geothermal heat pump systems for large scale heating and cooling have been implemented in several areas. In the United States, one noteworthy project was implemented at Ball State University in Muncie, Indiana [11]. Ball State installed a campus wide geothermal heat pump system in two phases with three borehole fields totaling 3,400 boreholes in total, which heats and cools 47 buildings. This project was completed between 2009 and 2014 and has since generated significant interest in GSHPs at other campuses.

At the University of Massachusetts, the campus police station building uses a system where fluid is circulated by a set of primary pumps from the BHEs to a set of secondary pumps, which are then used to circulate fluid through the building to multiple terminal heat pump units [12].

2.4 Grid Scale Demand Issues and Solutions

Electrified heating by heat pumps has been previously shown to potentially increase variability and peak demand when simulated at a grid scale [13–19]. Demand issues are particularly a concern for large electricity consumers that need to consider the effect of such technologies on the resiliency of their microgrid as well as the financial impact of increased electric demand. Previous studies modeled the UK grid to examine the impact of electrified heating [14]. The model simulates the electricity supply side with both dispatchable and non-dispatchable generation. The electricity demand side is also simulated with the demand from sources including heat pumps considered. Two heating demand profiles for the heat pumps were considered: one "flat" profile where heating was provided at a constant rate throughout a 24 hour period, and an unrestricted profile where the heat pump demand was allowed to vary to meet the hourly heating load. Heat pump demand increased by ~50% when using the unrestricted profile compared to the flat profile and heat pump demand constituted the majority of increased grid demand. The heat pumps in this study will follow an unrestricted profile to meet the current 15 minute heating load. Waite and Modi assessed the impacts of building space heating electrification and found that 53% of spacing heating in the U.S. could be electrified without increases in peak load and at 100% electrification, the U.S. electric system peak capacity would need to increase by 70%. In the 100% electrified case, it was shown that utilizing heat pumps and retaining existing fossil fuel infrastructure to provide 1-3% of heating demands could allow for 97% electrification without needing to increase electric system capacity [15]. Previous studies have found that heat pumps utilizing thermal energy storage for peak load shifting and/or demand response for load management can greatly reduce peak load increases due to electrification [13,16–19].

Control strategies such as a restricted "flat" heating profile or other methods of demand management, such as thermal or electrical storage, could be used, but were not considered in this study.

3. HEAT PUMP MODEL CALCULATIONS

3.1 Data Acquisition

Heating and cooling load data for the building complex was obtained from data collected by a building automation system (BAS). The campus uses Johnson Controls' Metasys BAS for control and data acquisition of HVAC systems. This system measures the heating and cooling water system's total fluid flow rate, as well as the water temperature at the source and return. The fluid flow rate is measured using Venturi flow meters and the temperatures using temperature sensors. The data is measured and recorded at 15-minute intervals. This data can be used to estimate the total heating and cooling load required by the building by the following equation:

$$\dot{Q} = \rho \times \dot{V} \times c_p \times \Delta T$$

Where, ρ is the density of water, $\dot{V}$ is the flowrate of the heating or cooling water, c_p is the specific heat of water, and ΔT is the temperature change in the water from the source to return.

While both heating and cooling load can be measured in this manner, the cooling load can be measured more directly in this case by measuring the total electrical load of the chillers. This electrical power measurement was obtained from the same BAS and used to calculate the total cooling load, based on manufacturer provided part-load performance data for this model chiller, York YK 400 ton. The total heating load over the course of the year is determined to be 5,712,089 kWh (19,490 MMBtu) and the total cooling load over the course of the year is 4,818,344 kWh (16,440 MMBtu).

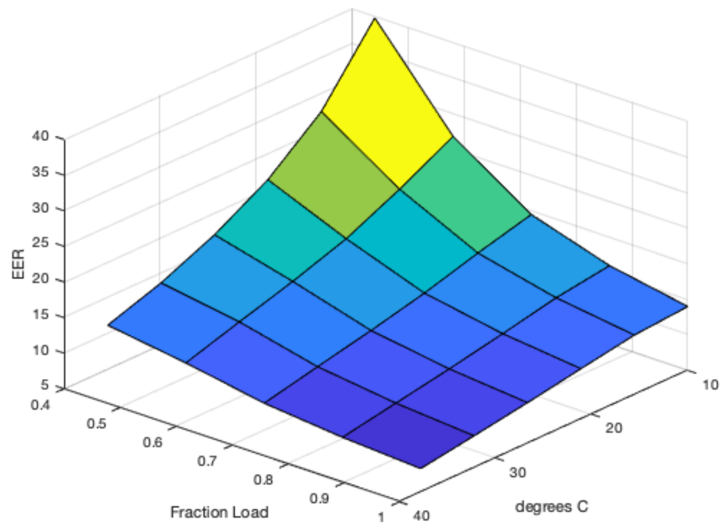
In addition to the electric load from conventional cooling, the building complex has an additional electric load due to ventilation, lighting, and plug load. This will be referred to in this research as the “building load” and is assumed to remain the same whether heating or cooling is done with heat pumps or conventional means. The total annual building load is 3,586,209 kWh.

3.2 Heat Pump Performance Characteristics

The simulation of GSHPs requires simulation of the heat pumps themselves as well as the GHEs. Simulation of the heating, cooling and electricity required by the heat pumps can be done simply by following data provided by the manufacturer for the capacity and power requirements of the particular heat pump model used at the specific operating conditions such as entering water temperature, flowrate, and fraction load. The performance data provided and used were for the Waterfurnace Versatec 180 water-to-water heat pump (Figure 1), Carrier 25VNA060 air source heat pump (Figure 2), and the conventional York YK centrifugal chillers (Figure 3). The heat pump performance is a function of load fraction and borehole fluid temperature in the case of the water-to-water heat pump. In the case of the air source heat pump the performance is a function of load fraction and outside air temperature. The recommended heat pumps run at a variable speed and variable capacity. The efficiency of the heat pumps increases uniformly up to a maximum efficiency at the minimum part load. The optimal percentage load of the heat pumps is the minimum percentage load that satisfies the current heating and cooling load. Thus, the load fraction is calculated as:

$$\text{(Load Fraction)} = \frac{\text{(Heating Load + Cooling Load)}}{\text{(Installed Heat Pump Capacity)}}$$

The efficiency of the particular GSHP model chosen is lower at the same condenser temperature compared to the current chillers. However, the actual condenser temperature when operating in the GSHP case is expected be lower than that of the conventional chillers or ASHPs, resulting in an overall higher COP.



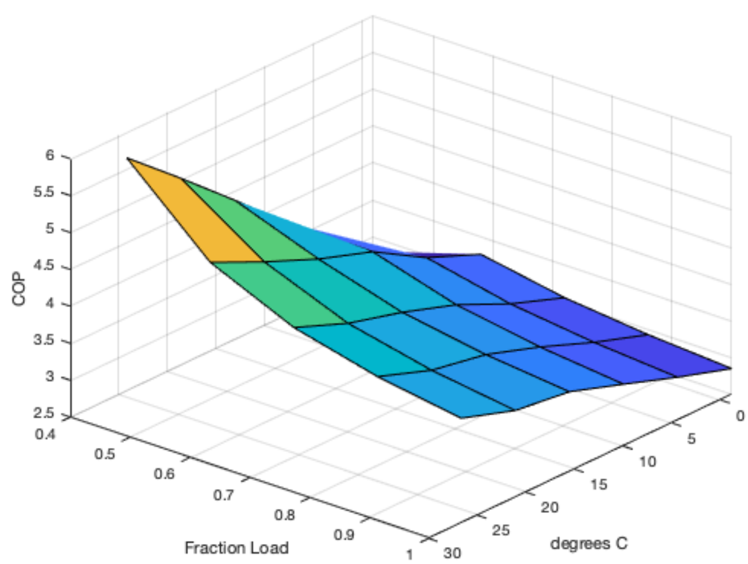


Figure 1: Water-source heat pump cooling (top) and heating (bottom) performance

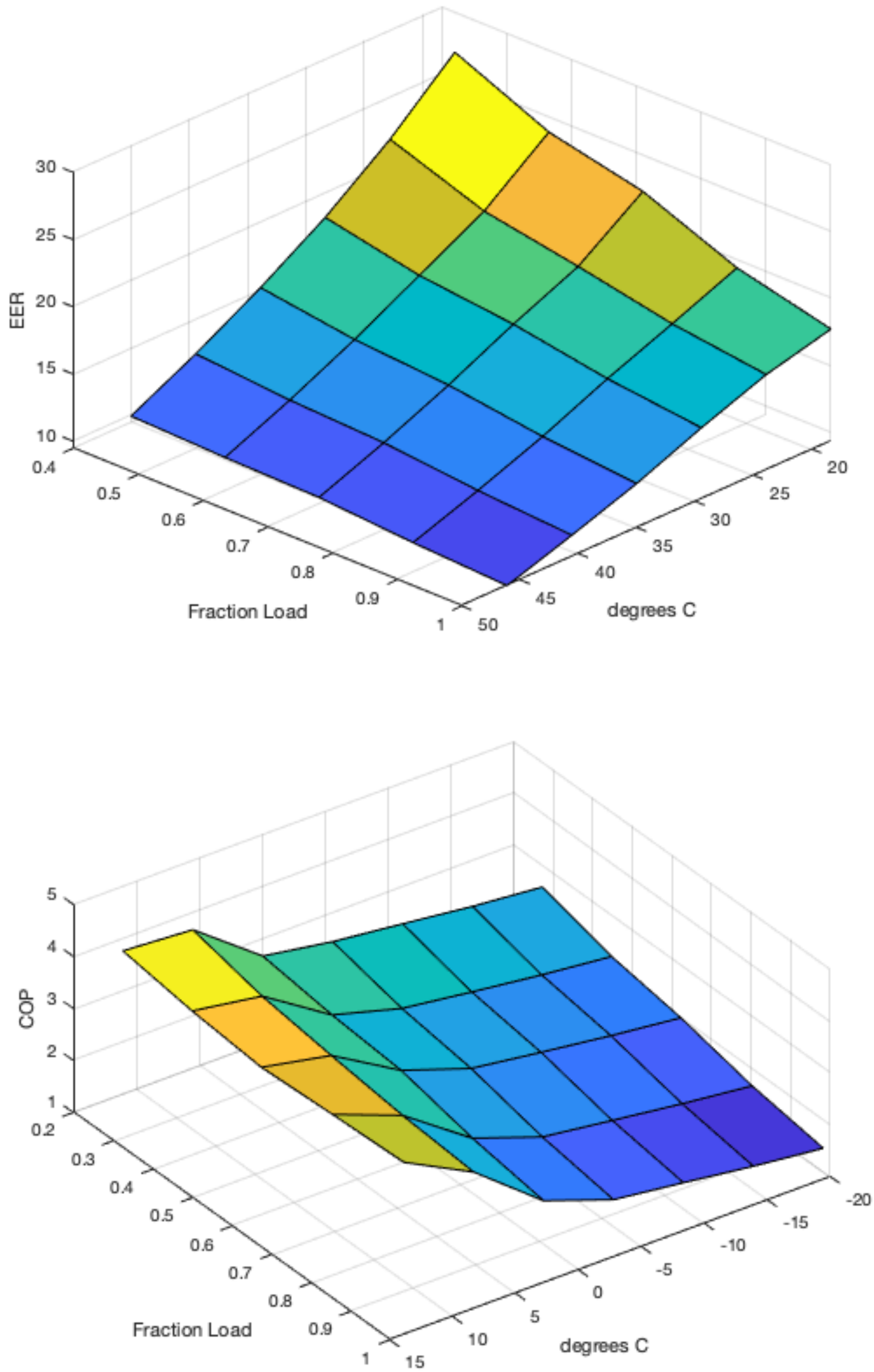


Figure 2: Air-source heat pump cooling (top) and heating (bottom) performance

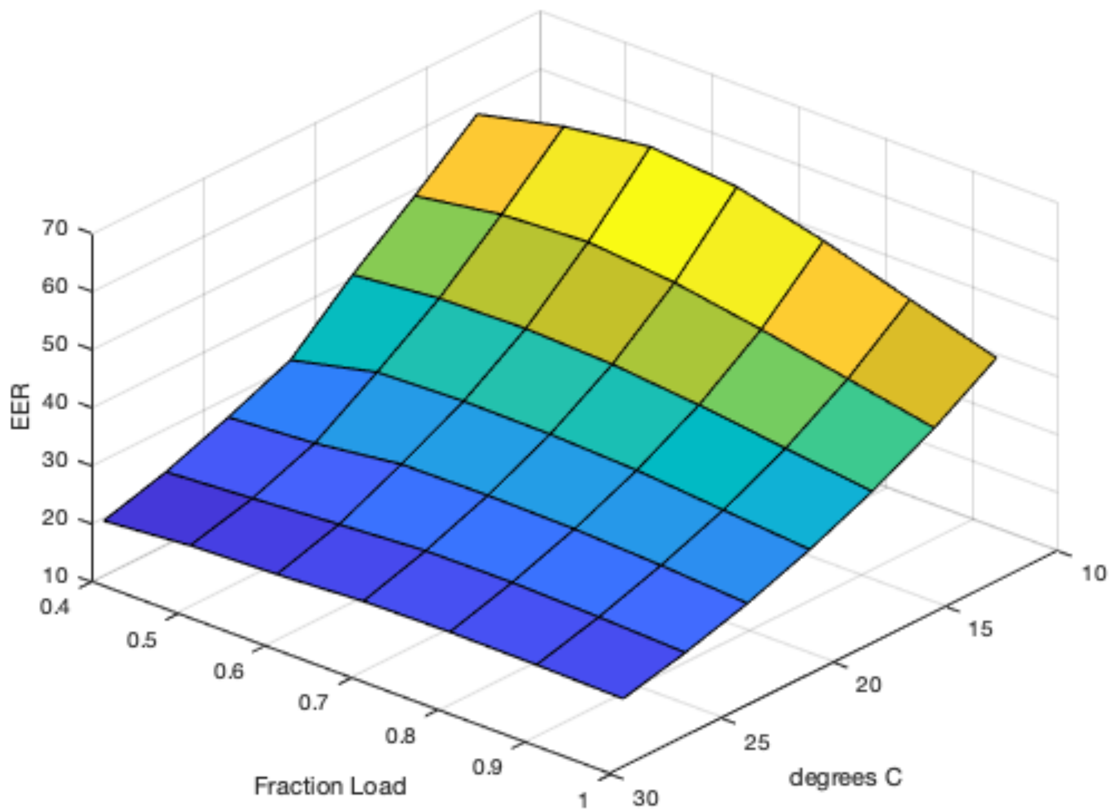


Figure 3: Current chiller cooling performance

3.3 Borehole Parameters

The parameters of the GHEs were set to be within the International Ground Source Heat Pump Association (IGSHPA) *Closed-Loop/Geothermal Heat Pump Systems, Design and Installation Standards* [20].

A thermal grout with thermal conductivity of $6.2303 \frac{\text{kJ}}{\text{hr m K}}$ was used. This is representative of a medium grade thermally enhanced bentonite grout used for modern borehole systems. The ground thermal conductivity and volumetric heat capacity of the soil in the area has been studied as part of the previous thermal energy storage studies [9,10]. Thus, the previously found ground thermal conductivity of $4.4 \frac{\text{kJ}}{\text{hr m K}}$ and volumetric heat capacity of $3{,}960 \frac{\text{kJ}}{\text{m}^3 \text{ K}}$ are used.

The fluid used for the geothermal loop of vertical boreholes was a 10% by weight ethylene glycol to water mixture. The addition of an antifreeze such as ethylene glycol is necessary in cold climates to prevent freezing of the liquid during the heating season.

3.4 TRNSYS Simulation

In the case of the ground source heat pumps, a TRNSYS project with unit Type557 using the above parameters was used to calculate the ground temperature and the resulting water temperature to and from the ground heat exchangers. This simulates the GHEs through a duct ground heat storage model as described previously. This water was then provided to the water-to-water heat pumps. The performance data for a variable speed water source heat pump was provided from manufacturer operating specifications. In sum, this results in a MATLAB and TRNSYS program that was able to simulate the operation of water-to-water heat pumps with vertical boreholes used to provide ground temperature water.

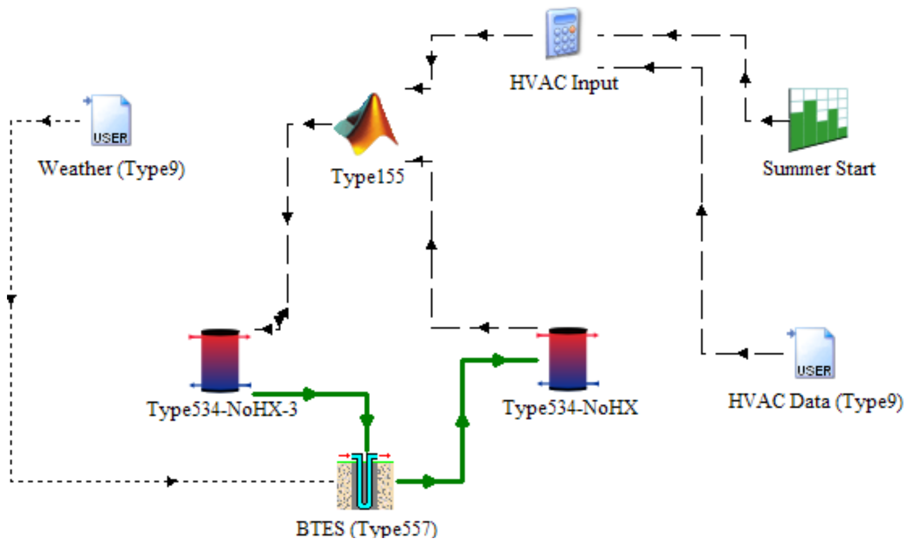


Figure 4: TRNSYS Project Used to Model GSHPs

In the case where air source heat pumps are considered, the outside air temperature data for Amherst, MA was used to simulate the outside air temperature provided to the heat pumps. A MATLAB program was used to calculate the performance of the heat pumps at the required load and outside air conditions. The heating and cooling capacities and power consumption of the heat pumps was provided from the manufacturer as a table of capacity and power consumption values at specific outdoor coil entering air temperature and percent load. These values were then linearly interpolated as specified by the manufacturer's data sheets to obtain values at the exact load and temperatures required by the simulation.

3.5 Ground Source Heat Exchanger System Potential Degradation

In a ground source heat pump system, the temperature of the ground can change over the course of several years if there is a significantly greater amount of heating required over the course of one year compared to the amount of cooling or vice versa. If this ground temperature change occurs, it will affect the water temperature being delivered to the heat pumps, and in turn this will affect the heating and cooling performance. In the building case studied, the heating load was slightly larger than the cooling load, thus the average ground temperature slightly decreased from one point in one year to the same time in the next year as shown in Figure 5 below.

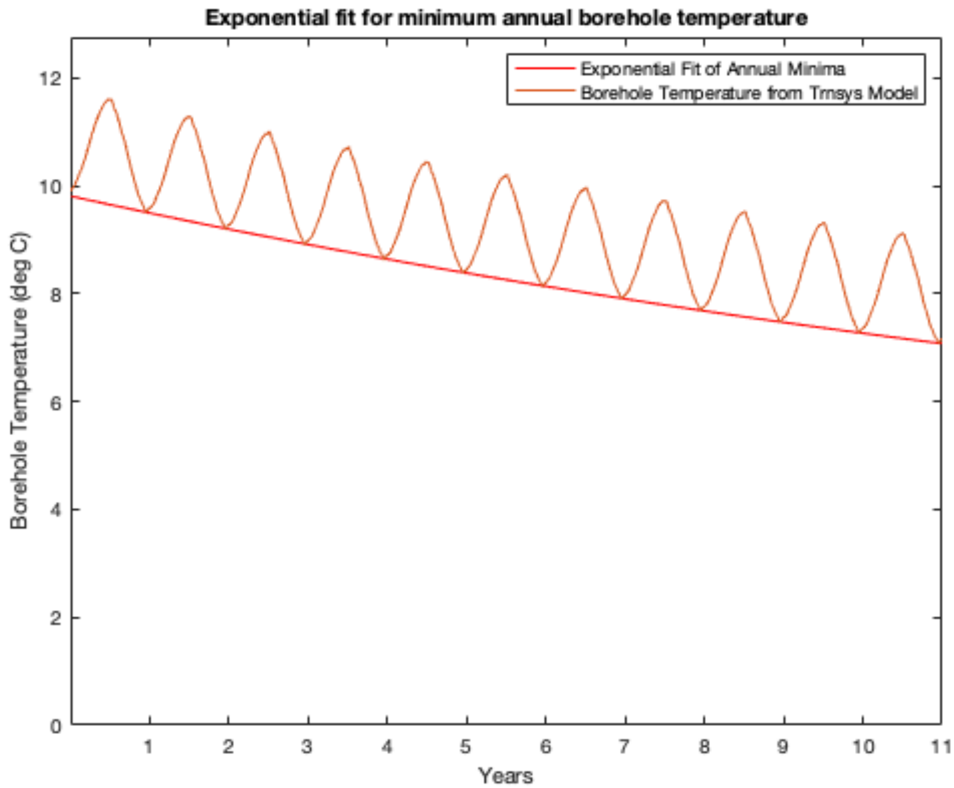


Figure 5: The average ground temperature in the ground storage over time

Note year to year temperature can be fit to an exponential function. Given an exponential function of the form:

$$y = 6.53e^{-0.049x} + 3.28$$

This equation gives an approximation of the annual minimum temperature at steady-state of 3.28°C. After 24 years, the borehole temperature changes by less than 0.1°C per year.

In the event that a building load is heating dominated, the ground temperature would be lower in the following year as the heat pump extracts more heat from the ground to the building in the heating season than is rejected from the building to the ground in the cooling season. Without mitigation, this would result in lower water temperatures from the ground source heat pumps and thus decreased heating performance from the heat pumps. One technique for mitigating this ground temperature decrease is to install solar thermal collectors to deliver additional heat to the ground storage [21–24].

In the case that the building load is cooling dominated, the ground temperature would increase in the following year as the heat pump would reject more heat to the ground in the cooling season than is extracted during the heating season, decreasing cooling performance. One mitigation for this would be a hybrid ground-source and air source system where the condenser water for the heat pumps can be delivered by either the geothermal heat exchangers or an air cooled cooling tower system. This would allow for a balance between the heating and cooling energy extracted and rejected from the ground, allowing for a stable temperature without degraded performance. A second possible mitigation for a cooling dominated system would be to use a desuperheater on the heat pump to recover excess heat during the cooling season. Such a desuperheating system is common on some heat pumps as it allows excess heat to be used to provide hot water heating production [25,26].

Following the heating and cooling loads provided, the studied building complex has a slightly greater heating load than cooling load, making it slightly "heating dominated". However, due to external factors such as building occupancy, climate change, and individual behavior the load in the future could vary from the previous year's load. As a result, previous research [27] has suggested that a full-size GSHP system with auxiliary backup such as cooling towers for potential additional cooling and solar collectors for potential additional heating has potential for the greatest economic benefit.

4. RESULTS AND DISCUSSION

4.1 Current HVAC System

The base case of the current HVAC system is used to compare to the heat pumps performance. This current system provides cooling by two (2) York YK centrifugal variable speed 400 ton chillers cooled using two (2) cooling towers. Heating is provided by steam distribution from a CHP plant burning natural gas, as well as liquefied natural gas and ultra-low sulfur diesel occasionally during winter curtailments. The CHP plant provides heating and electricity using a combustion gas turbine (CTG), heat recovery steam generator (HRSG), high pressure steam turbine, high pressure boiler, low pressure steam turbine, and 2 low pressure boilers. Generated electricity from the CHP plant constitutes 66% of the annual total electricity. As a result of the electrical generation from the CTG component of the CHP plant, heat is produced as a byproduct. Some of this heat is recovered by the HRSG. The heat recovered as a byproduct of the electrical generation for the building complex provides a portion of the heating load, however, additional heating is needed, particularly in the winter months. Additional heating beyond the heat recovered from the CTG is provided by additional firing of duct burners on the HRSG as well as production of steam by the high and low pressure boilers. Fuel is required as an input to the CTG to produce electricity and as an input to the HRSG and boilers to provide additional heating. The efficiencies of these components are defined as follows. [28]

$$\eta_{CTG} = \frac{E_{electricity,CTG}}{Q_{fuel,CTG}}$$

$$\eta_{heat} = \frac{Q_{steam}}{Q_{fuel,heat} + Q_{exhaust}}$$

Where, η_{CTG} is the electrical generation efficiency of the CTG, $E_{electricity,CTG}$ is the electrical energy produced and $Q_{fuel,CTG}$ is the energy content of fuel consumed by the CTG. η_{heat} is the efficiency of the heating components, Q_{steam} is the useful heating energy of the steam, $Q_{fuel,heat}$ is the energy content of the fuel consumed by the heating components, and $Q_{exhaust}$ is the heat energy of the exhaust from the CTG into the HRSG.

Using 15-minute interval production data for the CHP plant from 2019, these efficiencies were calculated. The annual average efficiency of the CTG is 29.1%, the average efficiency of the heating components is 77.6% and the overall CHP system annual efficiency of 74.6%. Using these efficiencies, along with the quantities of electricity generated for the building complex, heat recovered as a byproduct of that generation, and total heating load of the building complex, the fuel required by the CHP components to provide electrical generation and heat to the building complex are obtained and are given in Table 1.

4.2 Comparison of GSHP, ASHP and Current System Cases

From the simulation of the heat pumps, the electrical energy required to meet the current heating and cooling load is obtained. This is a 15-minute data series following the data for the heating and cooling loads. From this, the total annual electricity consumption can be calculated for a variety of GSHP systems as well as an air source heat pump (ASHP) system and compared to the current system's energy usage.

In the first case, a heat pump system with ground source heat pumps and electricity purchased from the grid at typical prices will be considered. In the second case, a heat pump system with air source heat pumps and electricity purchased from the grid at typical prices will be considered. These two cases will be compared to the current system with heating and generated electricity provided by a CHP plant and cooling provided by variable speed chillers cooled by cooling towers. In comparing the different systems, typically one of the most important criteria is the total energy usage and resulting cost of operation. Also, of importance for a new system is the cost of installation. Finally, the total CO_2 emissions are an important factor for considering the environmental impacts.

Figures 3 and 4 show the energy usage of the GSHPs as well as the current system for heating and cooling. The annual totals for monthly energy usage in each case are given in Table 1.

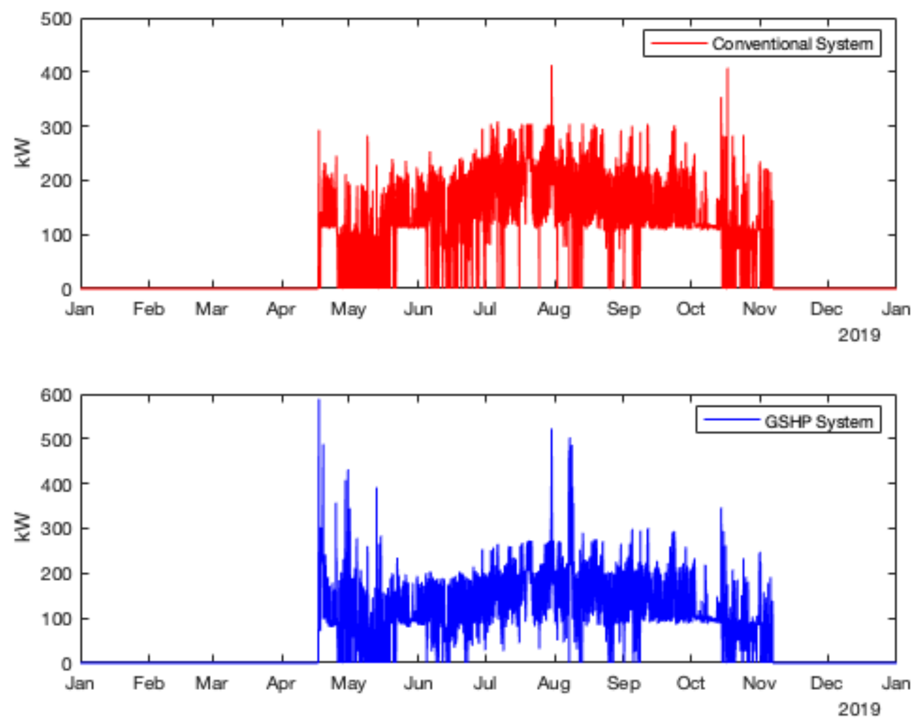


Figure 6: Electrical usage of current cooling system compared to GSHPs for cooling

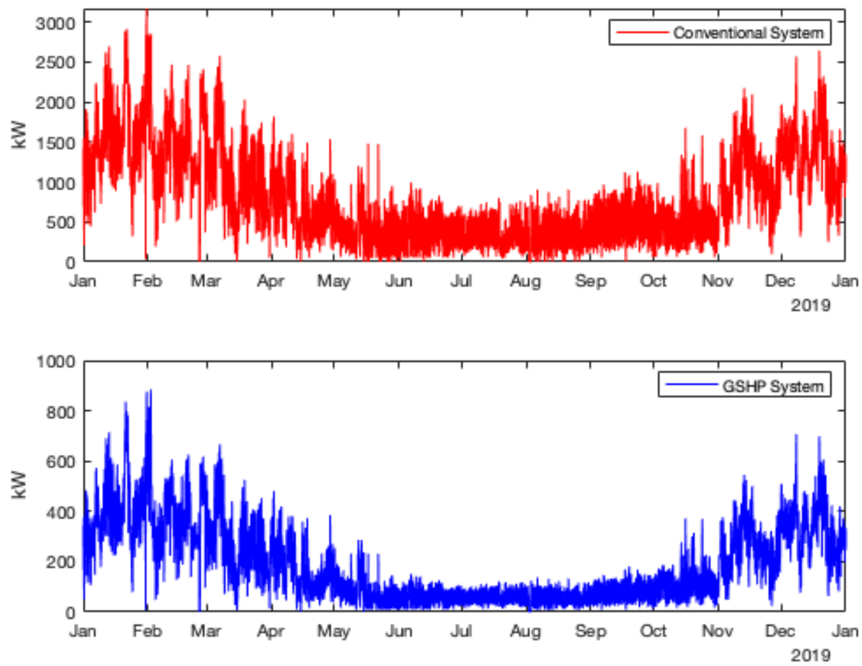


Figure 7: Heating energy input to the current CHP system compared to electrical consumption of GSHPs for heating

Month	Heating Load (kWh) (MMBtu)	Heating Energy Input (kWh)					Cooling Load (kWh) (MMBtu)	Cooling Electricity (kWh)		
		GSHP	ASHP	Current CHP				GSHP	ASHP	Current
				Heating Fuel	Heat Recovery	Extra Heat				
Jan	988,118 (3,371)	295,352	355,901	786,332	312,429	-504	0 (0)	0	0	0
Feb	913,819 (3,118)	275,904	319,932	606,015	399,021	-6,602	0 (0)	0	0	0
Mar	681,943 (2,327)	201,735	224,503	370,824	371,793	-11,301	0 (0)	0	0	0
Apr	425,615 (1,452)	119,619	124,476	200,335	292,731	-43,312	-301,083 (-1,027)	51,666	70,111	39,478
May	198,222 (676)	53,596	51,282	24,384	300,492	-123,178	-565,880 (-1,931)	73,586	127,695	78,910
Jun	154,953 (529)	41,544	43,967	574	329,053	-174,444	-718,917 (-2,453)	89,230	151,710	109,073
Jul	158,967 (542)	42,172	46,942	1,063	358,357	-200,346	-960,542 (-3,277)	133,114	195,719	155,486
Aug	140,470 (479)	37,140	41,466	115	357,769	-217,369	-855,115 (-2,918)	121,779	181,759	127,622
Sep	220,374 (752)	56,863	60,327	470	414,402	-194,316	-771,752 (-2,633)	104,677	166,700	113,217
Oct	307,094 (1,048)	79,142	82,965	40,847	410,232	-137,399	-565,660 (-1,930)	70,964	132,686	82,339
Nov	686,615 (2,343)	187,544	190,076	308,538	431,127	-16,973	-79,395 (-271)	9,239	19,164	11,733
Dec	835,901 (2,852)	242,992	274,314	485,652	416,508	-2,821	0 (0)	0	0	0
Total:	**5,712,089 (19,490)**	**1,633,603**	**1,816,153**	**2,825,148**	**4,393,913**	**-1,128,563**	**-4,818,344 (-16,440)**	**654,256**	**1,045,544**	**717,858**

Table 1: Monthly energy consumption of the heating and cooling components in the GSHP, ASHP and current system cases

Month	Building Fixed Electric Load (kWh)	CHP Generated Electricity (kWh)	CHP Fuel Used for Electric Generation (kWh)	Total Purchased Electricity (kWh)			Total Current System Fuel Usage (kWh)
				GSHP	ASHP	Current System	
Jan	288,010	181,434	672,519	583,362	643,911	106,576	1,458,172
Feb	367,041	236,396	863,591	642,945	686,973	130,645	1,462,077
Mar	335,600	217,082	801,478	537,335	560,103	118,518	1,159,685
Apr	342,679	187,733	647,858	513,964	537,267	194,424	795,827
May	237,707	193,161	665,483	364,889	416,683	123,456	507,484
Jun	217,283	231,263	748,479	348,056	412,960	95,093	458,312
Jul	247,210	257,839	821,117	422,496	489,870	144,856	518,833
Aug	241,810	256,283	818,637	400,729	465,035	113,148	462,513
Sep	332,450	295,134	946,505	493,990	559,478	150,534	626,463
Oct	333,722	254,132	898,948	483,828	549,373	161,929	785,722
Nov	328,042	260,822	938,481	524,825	537,281	78,953	1,228,472
Dec	314,656	257,204	911,884	557,648	588,970	57,452	1,394,296
Total:	**3,586,209**	**2,828,483**	**9,734,979**	**5,874,068**	**6,447,906**	**1,475,585**	**10,857,855**

Table 2: Monthly electricity and fuel consumption in the GSHP, ASHP and current system cases

4.3 GSHP System Installation Cost Optimization

The financial cost and benefit depend heavily on the price of the components and cost of energy. As a result, these costs were tailored to those typical of Massachusetts and the university in particular. For this analysis, month-by-month electricity and fuel cost forecasts for the university were used. The 2020 average volumetric cost of electricity is $0.0766/kWh. Monthly demand was $11.53/kW and yearly capacity charges were $95.40/kW per year based on the year's designated Independent System Operator of New England (ISO-NE) peak hour. The costs of fuel for the CHP plant resulted in a weighted average of $0.0272/kWh for 2020. These costs can then be used to calculate the annual cost of operation for the GSHP system given several borehole system parameters.

In analyzing the viability of such a system, the cost of installing the system is a significant barrier. The installed cost of the GSHP system is estimated using the regional residential system installation costs reported by MassCEC [29] and previous studies investigating large installations at other institutions [30]. These costs are averaged to provide up-to-date, regional cost data. This results in total installation costs of $48.16/m for the vertical geothermal loop and $1,000/kW for the water-to-water heat pumps. Using these costs, the installation and electricity costs of the proposed 3,517 nominal kW GSHP system with 550 to 800 boreholes each to a depth of 100 meters with a spacing of 5.886 m was calculated. The most financially beneficial system can be assessed assuming a lifespan of 40 years for the GSHP system with a replacement of the heat pumps midway through the system's lifetime. From 2020 to 2050, electricity costs from the university's 30-year energy price forecast were used. Beyond 2050, a 2.2% increase in energy costs per year, as projected by the U.S. Energy Information Administration's Annual Energy Outlook, was used. This results in a total lifetime cost as follows:

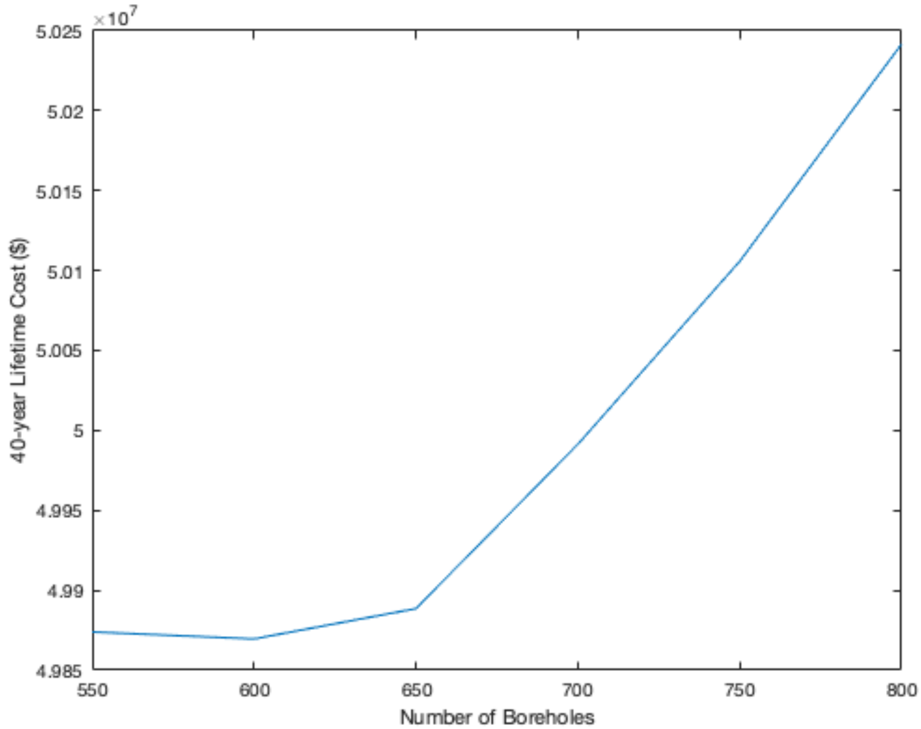


Figure 8: Lifetime cost of GSHP system over 40 year period

Systems with fewer than 550 boreholes were found to have loop temperatures below the freezing point of the 10% ethylene glycol to water fluid mixture used. Thus, smaller systems are not possible with the proposed system configuration. This makes the 600 borehole system the most optimal system from this financial perspective. This system has a total installed cost of $6,407,409 and an annual electricity cost of $664,744 to power the system at 2020 electricity prices. Comparison of GSHP annual costs to the ASHP and current systems follows in Table 4.

4.4 Building Demand

As previously stated, for this research it is assumed the GSHP system uses electricity for heating and cooling and eliminates the electricity generated by the CHP. As a result, all the electricity for the building complex is shifted to the grid. In addition, the electric requirements of the heat pumps also increase the electrical load. The change in electrical power purchased from the grid can be seen in Figure 9 below:

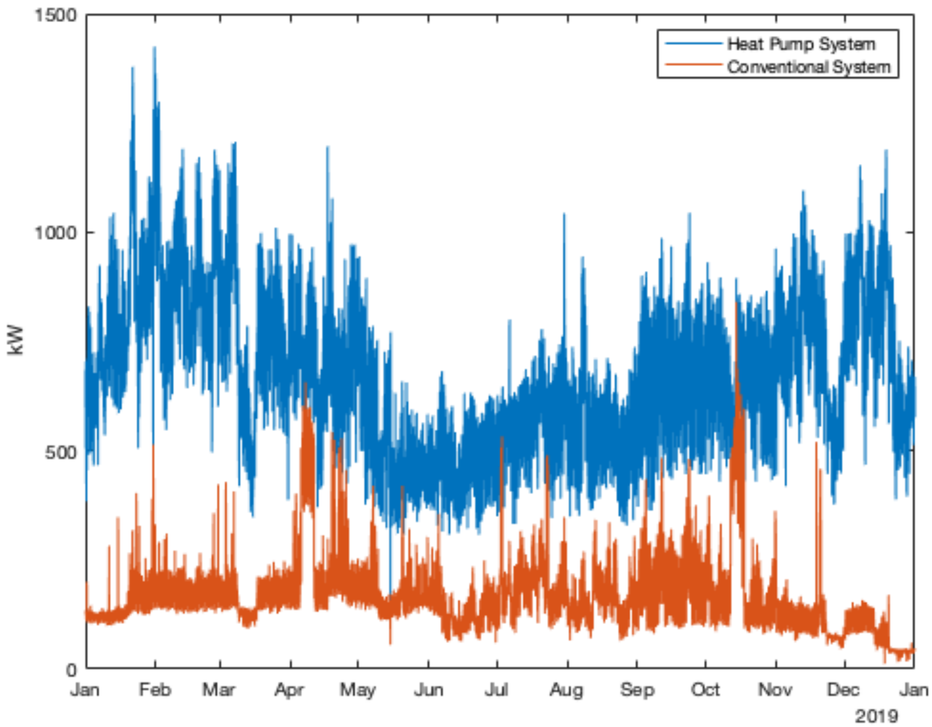


Figure 9: Electrical power purchased from the grid by the building complex

In the case of UMass, monthly demand charges are based on the electricity usage during a peak hour each month, defined by the utility. For 2019, these peak hours are:

Month:	1	2	3	4	5	6	7	8	9	10	11	12
Day:	21	1	6	1	20	28	21	19	11	2	13	19
Hour:	18	19	19	20	18	18	18	16	18	15	18	19

Table 3: Monthly demand peak hours for 2019

Thus, the monthly demand at the grid peak hours is shown in Figure 10.

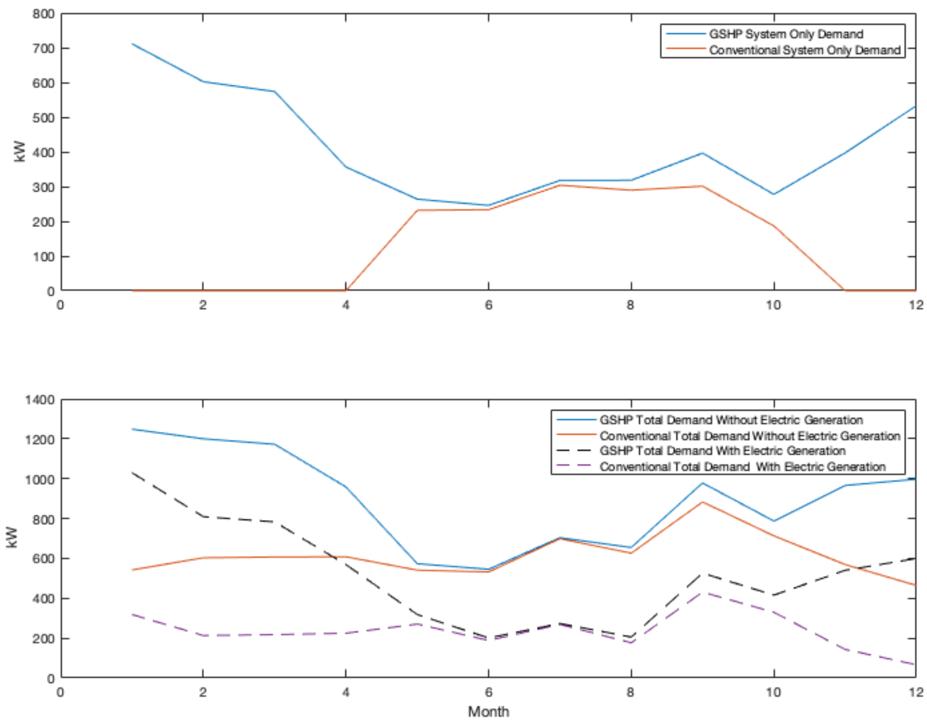


Figure 10: Monthly demand of the building complex

Figure 10 shows the inclusion of electric generation results in lower demand throughout the year. It can be seen in all cases that the GSHP system significantly increases demand during the winter months due to usage of the electric heat pumps for heating. Overall, the GSHP case results in a greater reliance on the grid in general, as well as a significantly higher peak load during the winter. The overall maximum peak shifts from 431 kW in September in the current system case to 1,248 kW in January in the GSHP case.

Additionally, a yearly capacity charge is assessed based on the electricity usage during the annual peak hour of the regional grid. In 2019, this peak hour was July 30th, 5:00PM to 6:00PM. Thus, the capacity charge in the GSHP system case is 846 kW and in the current system case is 213 kW.

At a monthly demand cost of $11.53/kW and a capacity charge of $95.40/kW/year, this overall increase in demand adds an additional total of $151,904 to the annual cost of the GSHP system over the current system.

4.5 Overall Cost and Emissions Comparison

Utility costs in the heat pump cases result from: electricity usage of the heat pump system, additional electricity usage of the building complex, and additional demand costs from the grid purchased electricity. This compares to the current system case, where utility costs result from: the fuel usage cost for the CHP plant, electricity usage cost of the cooling system, the additional usage cost of the building electric load, and additional demand costs. Building electricity and demand costs are greater in the heat pump cases compared to the current CHP case due to generation of electricity by the CHP plant. The utility costs for each case are given in Table 4.

Year	System Cost ($)			Additional Demand Cost ($)			Additional Building Electricity Cost ($)			Total Cost ($)		
	GSHP	ASHP	Current	GSHP	ASHP	Current	GSHP	ASHP	Current	GSHP	ASHP	Current
2020	182,199	225,100	323,221	205,094	232,238	53,190	277,451	277,451	62,761	664,744	734,789	439,171
2021	194,158	239,123	328,271	196,061	221,915	51,098	294,804	294,804	64,974	685,023	755,842	444,343
2022	205,803	251,283	306,067	187,686	210,735	48,793	309,428	309,428	68,157	702,916	771,446	423,017
2023	213,999	259,565	314,108	166,263	185,169	43,396	319,657	319,657	70,293	699,919	764,391	427,797
2024	217,286	261,803	323,808	201,767	226,600	52,416	321,958	321,958	71,100	741,011	810,361	447,324
2025	220,712	264,679	336,850	219,949	247,309	56,983	324,634	324,634	72,408	765,294	836,621	466,242
2026	221,592	265,598	340,296	237,009	267,172	61,349	325,839	325,839	72,642	784,440	858,609	474,288
2027	218,944	262,431	340,211	267,761	303,208	69,200	321,971	321,971	71,763	808,675	887,610	481,174
2028	221,383	265,408	343,704	273,276	309,399	70,630	325,733	325,733	72,545	820,393	900,539	486,879
2029	216,230	259,179	344,426	279,027	315,848	72,121	317,977	317,977	70,884	813,234	893,004	487,431

Table 4: Summary of Annual Utility Costs

The cost comparison of the current system to the heat pump systems depends on the relative cost of natural gas compared to electricity. An increase in electrical or demand costs relative to the cost of natural gas would make the current CHP system more financially viable, whereas an increase in natural gas costs relative to electricity costs would further increase the cost savings of the heat pump systems.

The resulting costs, given in Table 4, show the clear system energy usage cost benefit to a GSHP system or an ASHP system over the current system. However, due to the additional cost of demand and the cost to replace the electricity generated by the CHP plant, this combines to a total cost deficit of $225,572. An ASHP system was also found to not result in savings over the current system, as net annual costs increased by $295,617.

The pollutant emissions from an electrified heat pump system depend on the primary energy source used to generate the electricity used to run them. As a result, for a heat pump using electricity from the grid, the emissions can change as the electricity sources for the grid change. For this analysis, the following average emissions factors for Massachusetts provided by ISO-NE were used to calculate the emissions from the electrical energy used from the grid [31].

	CO_2 (kg/MWh)	NO_x (kg/MWh)	SO_2 (kg/MWh)
ISO-NE Electricity	370.59	0.21772	0.05443

Table 5: Average emissions factors for grid purchased electricity in Massachusetts

To compare to the current CHP system, emissions factors for the CHP plant for the 2019 Massachusetts Greenhouse Gas reporting were used. The CHP plant operates a selective catalytic reduction system to reduce NO_x emissions.

	CO_2 (kg/MWh)	NO_x (kg/MWh)	SO_2 (kg/MWh)
CTG Fuel Input	172.53	0.01459	0.00334
Boiler Fuel Input	186.39	0.01054	0.00105

Table 6: Emissions factors of the CHP per MMBtu of fuel consumed

The total emissions from the heat pump system are simply the emissions resulting from the total purchased electricity. The total emissions from the current CHP system are the sum of the emissions from the fuel combustion in the conventional boilers for heating, the emissions from the fuel consumption of the CTG for electrical generation and heat, as well as the emission from the purchased electricity. Comparisons of the emissions of the GSHP, ASHP and current systems are given in Table 7.

System Case	Heating System CO2 (tons)	Cooling System CO2 (tons)	Additional Building Electric Usage CO2 (tons)	Total System + Building CO2 (tons)	Total System + Building NOx (kg)	Total System + Building SO2 (kg)
GSHP	605	242	1,329	2,177	1,279	320
ASHP	673	387	1,329	2,389	1,404	351
Current	1,475	266	769	2,510	475	114

Table 7: Summary of GSHP, ASHP and current system case emissions

The CO_2 emissions of the GSHP system are found to be 333 metric tons (13.3%) lower than that of the current system. NO_x and SO_2 emissions increase by 169% and 180% respectively in the heat pump cases due to use of more sulfur containing fossil fuels such as coal and oil in power generation by the electrical grid and use of a selective catalytic reduction system in the CHP plant. As the GSHP system uses grid electricity, there is potential for greater emissions savings as more renewable energy generation is added to the grid.

5. CONCLUSIONS

In summary, it is found that either an ASHP system or a GSHP system would result in a net utility cost increase when compared to the current system without changes to the current energy costs. This highlights a need for energy storage, on-site generation and/or demand response to mitigate these issues. However, there are significant reductions in CO_2 emissions from a heat pump system utilizing electricity purchased from the grid over the current CHP system. As a result, it could be beneficial to install a GSHP system if a large financial cost to ongoing CO_2 emissions, such as a carbon tax, were introduced.

A market-based carbon pricing mechanism, such as a cap and trade system or carbon fee, has been implemented in 11 US states [32]. Additionally, bills have been introduced in state and federal legislatures to add additional carbon pricing mechanisms. Bills introduced in the 116th US Congress have included carbon fees ranging from $15/ton (HR.4051) to $52/ton (S.1128). In such scenarios, the potential savings of the GSHP system over the current system could increase by $4,995 to $17,316 annually through the avoidance of additional carbon fees.

In this simulation, the heat pumps were operated to satisfy the current heating and cooling loads. It should be noted that the CHP plant follows the thermal load and thus the heating load profile has not been optimized to reduce peak demand. As a result, peaks in the heating and cooling load profiles result in significantly increased demand if an electrified heating system such as heat pumps are installed. A mechanism for shifting these thermal load peaks would be needed to minimize electrical demand of the heat pumps. An established method for peak shifting is a thermal energy storage system allowing the heating or cooling load profile to be "smoothed out" to reduce excess demand. Operation and control of such a system has not been modeled and would require further work to optimize the heating and cooling load profiles for greatest financial benefit.

This study compares an existing CHP system to a GSHP system modeled to replace it. The GSHP system purchases electricity from the grid to replace the lost generation capacity.

This is only one of multiple strategies for integration of heat pumps into an existing HVAC system. Other implementations of a GSHP system could use on-site electrical generation to reduce the cost of electricity and potentially increase the financial viability of such a system. Electrical generation done through renewable technologies such as photovoltaics (PV) or wind would also have the benefit of reducing the overall CO_2 emissions. Another method of heat pump integration could be a hybrid approach where both the current CHP system and a GSHP system are utilized to provide heating and cooling. A method of marginally adding heat pumps to the existing system could be one of significant interest, as a smaller, marginal system would have a smaller installation cost and therefore may be easier to afford and implement. Such a system would allow use of heat pumps for heating during high heating and low electric demand periods, such as on cold winter nights, and use of the heat pumps for cooling as well to improve cooling efficiency during the summer. This could allow the current CHP plant to maximize the amount of useful work extracted from its fuel. Analysis of both the current CHP system, as well as a GSHP system, at a component level would allow for optimization of such a system.

Acknowledgements
This research was funded in part by the U.S. Department of Energy under Grant number DE-EE0007708.

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