Heat Pumps and Thermal Storage at MIT

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1 Introduction

Building decarbonization requires thermal electrification (i.e, the electrification of heating, cooling, and hot water). To reduce (and ultimately stop) the direct burning of natural gas for thermal needs, MIT should switch to heat pump based electric heating systems. Heat pumps supplemented with energy efficiency and thermal storage is a major step MIT can take to getting to a net-zero campus. The technology exists, and MIT can demonstrate its leadership by showing how an advanced thermal system can be implemented.

Heat pumps use electricity to move heat by cooling one air or fluid flow and heating a separate air or fluid flow, with the efficiency of the heat pump system being dependent on the temperature difference between the cooling and heating exchangers. Because they are moving heat, rather than generating heat, heat pumps are very efficient. There are two major heat pump technologies, fixed speed and variable refrigerant flow (VRF), and two applications, air source heat pumps (ASHP) and ground source heat pumps (GSHP). The most efficient heat pump application is GSHP, with VRF-GSHP being the most efficient. For a GSHP, a heat pump is coupled to a group loop buried underground that transfers heat between the ground and the building. There are two types of GSHP systems, open loop and closed loop. Open loop systems use surface or an underground water source (lake, river, or well) as both the heat source and sink. Closed loop systems use the earth as the heat source and sink with anti-freeze additive to the loop water. GSHPs take advantage of the moderate stable temperature of the ground (around 55 degrees Fahrenheit in Boston) about 10 to 1000 feet below the surface (when undisturbed) to use as an energy exchange medium (U.S. Department of Energy, 2011). This enables GSHPs to be very efficient, with coefficients of performance (COP) generally between 3.5 to 6.5, which is the ratio of heat produced to electrical input. In contrast, an oil or gas furnace has a COP less than 1.

Although GSHPs are a proven technology and the most efficient system for heating and cooling, adoption has been slow due to high capital and installation costs and land-use requirements and lack of public awareness. However, entities are starting to see GSHPs as the path forward. Some natural gas utilities are looking to pivot to managing community-scale GSHP systems (Gilman, 2021). For example, the nonprofit Home Energy Efficiency Team (HEET) is working in partnership with Eversource in the greater Boston area to launch three GeoMicroDistrict pilots, networks of communities using GSHPs. Larger community-scale (or campus scale) installations with diverse heating and cooling needs allows for thermal balancing and addresses many of the barriers to individual GSHP installations. This type of system would be a two-pipe design, providing milder loop temperatures and higher efficiencies than compared to a four-pipe system (Mitsubishi Electric, 2014). For example, in 2011 Miami University of Ohio renovated its two oldest buildings to switch from coal-fired steam to using ground-source heat pumps with VRF zoning for its heating and cooling, resulting in a 61% decrease in energy consumption (Mitsubishi Electric, 2014).

In order to implement heat pumps at MIT, an initial study needs to be conducted to understand the process load dynamics. This requires knowing peak-hour loads, which are necessary for sizing heating and cooling equipment in systems, as well as time-dependent loads throughout the year in order to predict thermal storage effects (Chiasson, 2016). MIT also needs to test the geology below the campus, drill test bores, and perform thermal response tests to determine thermal conductivity. The design and analysis requires engineers and designers with Certified GeoExchange Designer (CGD) certification. If the system is designed by those without the proper certification, it can lead to poorly designed and improper systems. A properly designed system will be both reliable and economical.

In this paper, heat load analysis has been started on three of MIT's buildings, specifically, Building 76, Building 9, and Building E60. These three buildings were chosen with the help of MIT facilities to represent a good mix of the types of buildings on campus. This paper focuses on thermal analysis; thus electricity usage is not included. Current electric loads within the buildings are not temperature dependent. These electrical loads represent loads such as fans, lighting, plug loads, elevators, and other miscellaneous equipment.

2 Total Thermal Electrification

A total thermal electrification will have several implications. It will reduce carbon emissions. However it will also increase electricity consumption on campus. This section first explores the carbon reduction potential of switching to ground source heat pumps. It then considers options that can be used to reduce the resulting increased electricity demand.

2.1 Emissions Reduction Potential

In 2019, of MIT emitted 200,679 MTCO2e of Scope 1 and 2 emissions. Around 70% of these emissions were for the thermal needs of MIT's buildings. In 2019, MIT's CUP produced 1,105,767 MMBTU of steam and 659,849 MMBTU of chillwater. In total, it used 1,765,616 MMBTU for thermal needs. At the same time, MIT purchased 97,707 MMBTU of electricity and its CUP produced 589,009 MMBTU of electricity, or a total electricity consumption of 686,717 MMBTU (201,256,689 kWh). This means, currently if all of MIT's thermal needs were met with ground-source heat pumps with an average COP of 4, MIT will use an additional 129,362,805 kWh of electricity. Assuming MIT's current (2019) MTCO2e of electricity of 235.8 gCO2e/kWh, GHG emissions from thermal needs using ground-source heat pumps would be 30,505 MTCO2e, for a total of 77,964 MTCO2e GHG emissions for total electricity. This is a 61% reduction from MIT's current GHG emissions. As the emissions factor of electricity reduces going forward, total emissions would also reduce. These estimates are conservative; in the HEET analysis, they assumed an average COP for heating of 5 and an average COP for cooling (also known as the energy efficiency ratio (EER)) of 6 (Home Energy Efficiency Team, 2019).

2.2 Thermal Storage

Converting the heating system to electricity will increase the campus demand for electricity, including aggregate demand and peak (instantaneous) demand. This can be mitigated by implementing a fully distributed, fully adaptive thermal system, which includes thermal balancing and thermal storage. As mentioned, the diverse heating and cooling needs of MIT's mixed-use building allows for thermal balancing and diversity efficiency. Internal "waste" thermal energy can be recycled by time-shifting that energy via storage, increasing system efficiency (Net Zero Foundation, 2016). For example, a possible design to reduce system costs is to implement underground thermal storage tanks in series between the geothermal boreholes and the heat pumps (Bonamente et al., 2016). This would allow for a significant reduction in needed length and/or number of boreholes to be drilled. In such a design, the boreholes would exchange heat independently of the heat pump, at an average rate that is optimized to guarantee 24-hour stability. The geothermal boreholes are able to exchange heat with the water tank, even when the heating (or cooling) is off. Also, the heat pump can use the tank as an energy reservoir with a high enough heat-capacity to support the power demand.

Another concern is that using GSHP heat pumps will significantly alter the temperature of the ground (MacKay, 2009). Because a GSHP system will change the ground temperature as heat is extracted and rejected, long-term functionality of a system depends on the amount of heat input in the summer generally equaling the amount of heat extraction in the winter. The combination of GSHP with thermal energy storage (TES) is an effective measure to address the problems from imbalanced heating and cooling, for both daily and seasonal storage (Zhu et al., 2014). Types of TES technologies that can be integrated with GSHP include ice storage tanks, solar collectors, and phase change materials (PCM). Some demonstrations include Borehole Thermal Energy Storage (BTES) at the Marine Corps Logistic Base in Albany, Georgia and Aquifer Thermal Energy Storage (ATES) at Ft. Benning Georgia (Hammock & Hammock, 2017). Implications and additional cost savings from these different technologies are out of the scope of this paper, but should be investigated.

3 Buildings Overview

In this paper, three of MIT's buildings are studied, specifically, Building 76, Building 9, and Building E60. MIT classifies Building 76 as "Lab and Mixed Use" and Building 9 and Building E60 as "Office and Mixed Use." Table 1 summarizes some metrics from EnergizeMIT (MIT, 2021). As the table shows, Building 76 is the most energy intense, both in terms of total energy consumption, but also in regards to the energy per area. This makes sense because it is a laboratory heavy building, with strict ventilation needs. Fig. 1 shows the energy breakdown of each of these buildings, showing that thermal needs make up the bulk of the energy usage for all three buildings. Hourly building power consumption data which is used for the analysis in this paper was provided by Siobhan Carr and Carlo Fanone of MIT Facilities. Data for Building 76 and Building 9 are from 2019 and data for Building E60 is from 2018. This section gives a brief overview of these three buildings.

Table 1: Buildings Overview for 2019

	Building 76	**Building 9**	**Building E60**
Total GHG MTCO2E	7822	1061	268
Square Footage	367,689	77,414	30,130
GHG MTCO2E/SqFt	0.02127	0.01371	0.00889

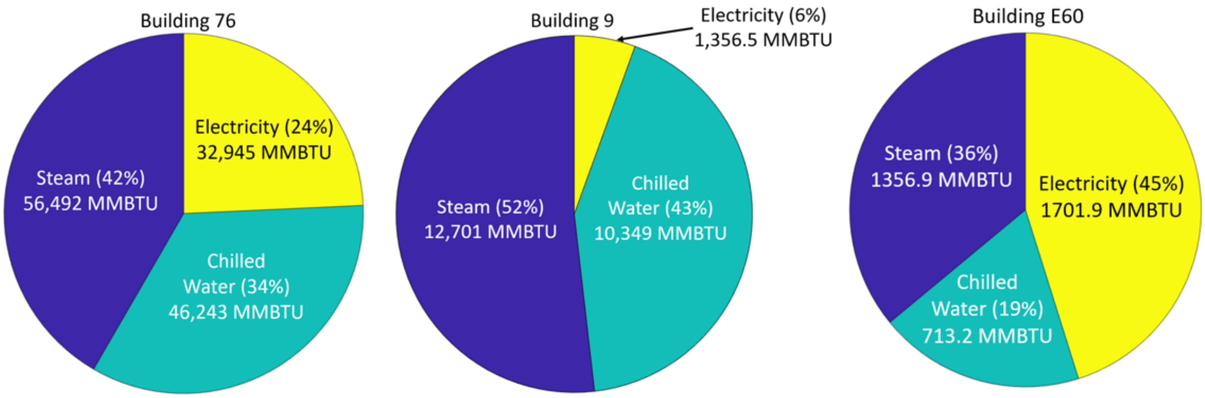


Figure 1: Energy consumption breakdown for each building.

3.1 Building 76

Construction of Building 76 was completed in 2010, encompassing over 40 laboratories (MIT, n.d.). The building houses the Institute for Integrative Cancer Research. The building is LEED Gold certified, using energy efficiency measures such as heat recovery methods incorporated in the HVAC systems, low-flow fume hoods to reduce ventilation requirements, and low-velocity duct work to reduce fan energy. Steam and chilled water consumption account for a majority of the energy use for Building 76. This is due to the fact that the laboratory spaces in Building 76 require 100% outside fresh air supply, resulting in large cooling, heating, and reheating loads.

3.2 Building 9

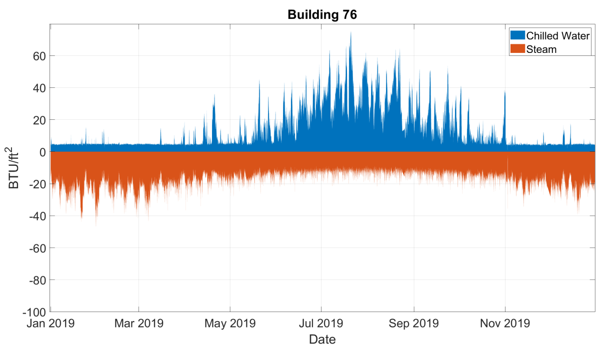
Building 9 in a six story building, originally built in 1968. It most recently underwent partial renovation in 2016, in which it received infrastructure upgrades, including new double-glazed energy efficient windows, new air handling equipment to feed floors two to six, and new exterior wall insulation (MIT, n.d.). Building 9 includes the Department of Urban Studies and Planning. Steam and chilled water consumption account for a majority of the energy use in Building 9.

3.3 Building E60

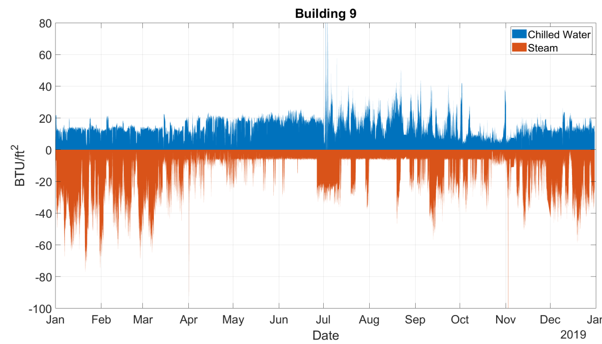
Building E60 was originally constructed in 1916 and is the headquarters for the dean of the MIT Sloan School of Management and other Sloan administrative groups (MIT, n.d.). It underwent a full renovation, which was completed in 2011. As a result of this renovation, Building E60 achieved LEED Gold certification. The added sustainable design practices include heat recovery methods incorporated into HVAC systems, chilled beams (an air-conditioning system that uses water instead of air to remove heat), low-energy lighting, and high-performance spray foam insulation. Steam and chilled water encompass a little more than half of the energy needs for this building.

4 Energy Analysis

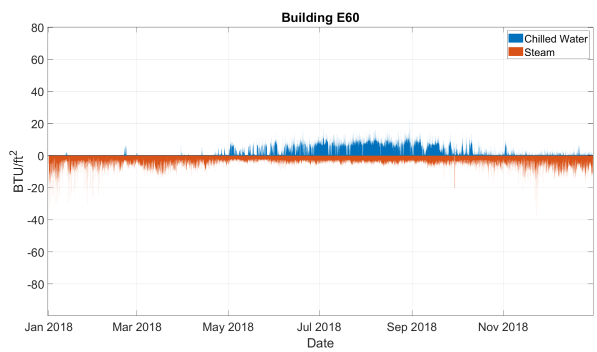
To begin the energy analysis, the energy consumption of each building was normalized to BTU per square foot, enabling easy comparison between the buildings. Fig. 2 shows the chilled water and steam analysis, where chilled water is plotted positive and steam is plotted negative. These plots give insight into the potential for a heat recovery system by showing heating and cooling overlap. For Building 9, in the original data, it looked like there was a sensor scaling issue in the chilled water data, after (or before) approximately July 5 as indicated by what looked like a step change in the data. Because of this, I multiplied the data starting from July 5th by 2.4094, which is the mean of the data before July 5th divided by the mean of the data after July 5th. This is the data that is plotted in Fig. 2, which looks reasonable enough to carry on with analysis.



(a) Building 76



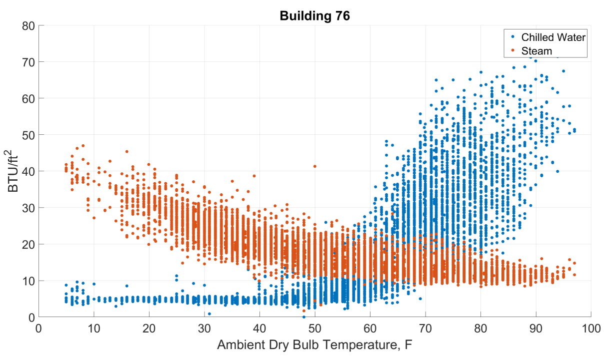
(b) Building 9



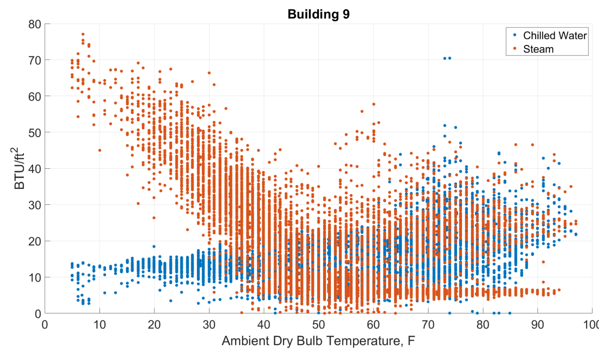
(c) Building E60

Figure 2: Steam and chilled water demand showing potential opportunities for waste heat recovery.

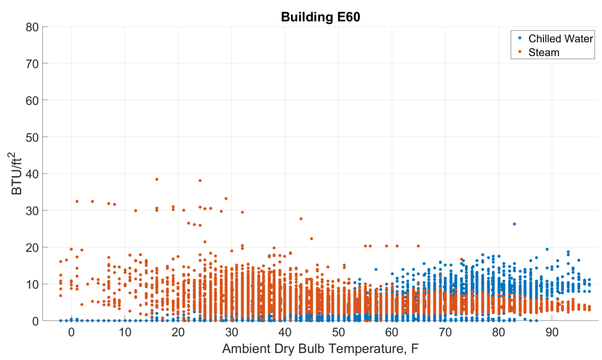
The conclusions drawn from MIT's heat load analysis for Building 76 (*Energy Study MIT Building 76*, n.d.) is helpful in providing insight into Fig. 2. For Building 76 there is a significant increase in consumption in chilled water in the summer months. This is expected because all space cooling requirements are served by the chilled water service. There is also a base chill water load during the whole year, most likely associated with cooling requirements for associated lab and vivarium spaces, as well as cooling requirements for spaces with additional process loads. This base consumption is about 110,000 ton-hrs/month (1,342,400 kBTU/month). The steam consumption for Building 76 increases in winter months. This is as expected, since most of the space heating is served by the steam service. There is a base-load steam consumption throughout the year associated with terminal reheat, humidification, domestic hot water production, laboratory hot water production, vivarium processes such as sterilization, cage/rack washing and tunnel washers, and laboratory process sterilization and washing equipment. These base load heat and load cooling could potentially be supplied by a waste energy recovery system. Although we couldn't get a heat load analysis for Building 9 or Building E60, some conclusions can be drawn. Building 9 also has a base cooling load and a base heating load. Building E60 exhibits an increase in heating in winter months and cooling in the summer months, although at a much smaller magnitude than Building 76. Building E60 is a great example of a high efficiency building with extremely low outdoor air temperature impact. It has a small base heating load for the entire year, some of which could be "controls" related.



(a) Building 76



(b) Building 9



(c) Building E60

Figure 3: Building load versus outside temperature.

A main factor in the net heat gain or loss in a building is the outdoor ambient temperature. The two dominant reasons a building loses heat is conduction (heat flowing directly through walls, windows, and doors) and ventilation (air flowing through gaps or deliberate ventilation ducts) (MacKay, 2009). Both of these heat losses are proportional to the temperature difference between the outdoor and indoor air. Thus, it is important to compare the thermal load versus the outdoor air dry-bulb temperature. Fig. 3 shows the BTU/ft^2 for the range of ambient dry bulb temperatures in Boston. Hourly weather data was from the weather station at Boston Logan Airport (National Oceanic and Atmospheric Administration, n.d.). Some interesting observations can be drawn, such as the high cooling needs for Building 76 and high heating needs for Building 9. Building 9 has high heating needs, even at high temperatures. This can possibly be due to reheat. This should be further investigated. It is also important to determine the amount of energy being lost through ventilation and potential for further energy recovery. For example, Building 76 has 100% fresh air with about 50% energy recovery. However, there is potential to recover the rest of the "exhaust" air energy through exhaust air heat pump energy recovery (Fracastoro & Serraino, 2010). Upgrading the ventilation to active full energy recovery should happen in conjunction with, or more likely before a GSHP upgrade. This would prevent overbuilding of the GSHP system.

4.1 System Sizing and Cost

This section provides analysis of potential sizing and cost for a GSHP system for the three studied buildings. These are **very** rough estimates. The capacity of a GSHP advanced thermal system requires detailed engineering analysis, based on composition of soil and rocks, depth to bedrock, seasonal ground temperatures, and many other factors (Home Energy Efficiency Team, 2019). Much more detailed assessment needs to be performed at to fully understand the sizing and costs. According to MassCEC data, the average cost of installing a vertical GSHP system in Massachusetts for residential and small-scale projects is approximately $13,000 per ton of heating capacity (however the range of reported costs were from below $3,000 per ton to more than $40,000 per ton) (Home Energy Efficiency Team, 2019). HEET believes this data may be skewed towards more expensive projects and may not accurately reflect the cost of a larger-scale installation.

Table 2: Potential System Size and Costs

	Building 76	**Building 9**	**Building E60**
Peak MMBTU/day (Heating)	339.7	124.0	8.66
Peak MMBTU/day (Cooling)	591.3	69.3	7.64
Max Hourly Tons (Heating)	589.7	215.3	15.0
Max Hourly Tons (Cooling)	1026.5	120.4	13.3
System Cost	$6.75 million	$1.42 million	$98 thousand
Number of Boreholes	277	58	4
Land Requirements (Square Feet)	62,424	13,092	914

To give a back-of-the-envelope estimate of the potential cost and system size for a GSHP system for the three studied buildings, I will use the installation at Ball State University in Indiana as a guide. The GSHP system at Ball State University has approximately 3,400 boreholes which are each 400 to 500 feet (Environmental Resilience Institute, n.d.). The cost of the system was $6,579 per heating ton. With a system capacity of 12,600 tons, that results in approximately 3.7 tons per borehole. (The choice for a vertical closed-loop system for application to MIT here is arbitrary and I am not implying that this is the best solution for MIT). Next, I assume there is some form of thermal storage in place, so only 24-hour peaks need to be met. I calculated the maximum daily heating and cooling demand for each of the three buildings, and used the larger of the two to size the system. To calculate the land-use requirements of the system I used the spacing of the Ball Park University installation of 15 feet between boreholes, meaning each borehole requires 225 square feet of space. The results are shown in Table 2. The order of magnitude of these upfront costs are a reasonable expense for MIT. Furthermore, the payback period for GSHP systems are typically 5-15 years, so any upfront installation costs will be returned through the reduced energy footprint and reduced maintenance costs. Also, a majority of the installation cost is for infrastructure that will outlast multiple building equipment upgrades. The total land-use requirements for the 339 boreholes for three buildings is 76,430 square feet. Fig. 4 shows this approximate area outlined in black in the context of MIT's campus. This space is less than the size of Killian Court. The size of this system could be reduced if building energy efficiency measures were undertaken on the buildings prior to installation of a GSHP system, such as solving the ventilation energy losses in Building 76 through exhaust air heat pump energy recovery.

Figure 4: Estimated land-use requirement for a closed-loop vertical borehole field for Building 76, Building 9, and Building E60, outlined in black for current building energy usage.

5 Conclusions and Next Steps

One note I want to make is the importance of good data. As mentioned, I made a scale correction for half of the chilled water data from Building 9, but I do not actually know which half of the data was "good." Also in Building 9, there is really high heating demand between June 26 and July 13, as well as on some other summer days. The reason for this is currently unknown; it could be a sensor issue, or if the data is accurate, then the reason for such high heating demand should be investigated. As a lesson from the Ball State University installation, James Lowe, the associate vice president for their Facilities and Planning Management said, "If I had to do it all over again, we would have done a better job of collecting actual steam usage data by building in advance of starting the project" (Environmental Resilience Institute, n.d.). Incorrect data can lead to improper system specifications and sizing.

MIT should make it a priority to test the geology below the campus, drill test bores, and perform thermal response tests. This will help determine any issues, so that design and implementation can proceed. Further analysis should be done on the buildings, such as estimating the energy that is being lost through ventilation. Although MIT does employ some energy recovery, there is potential gain in installing active full energy recovery for further energy savings. An advanced thermal system, encompassing energy efficiency, recycling and recapturing of energy, thermal storage, and heat pumps will be a significant step MIT can take to reach net-zero emissions.

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