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Applications of Thermal Energy Storage with Electrified Heating and Cooling

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APPLICATIONS OF THERMAL ENERGY STORAGE WITH ELECTRIFIED HEATING AND COOLING

A Thesis Presented

by

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ABSTRACT

APPLICATIONS OF TES WITH ELECTRIFIED HEATING AND COOLING

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With a clear correlation between climate change and rising CO_2 emissions, decarbonization has garnered serious interest in many sectors to limit the adverse effects of global warming. Heating and cooling systems have been a focus of decarbonization efforts, with heat pumps becoming more popular in the United States and abroad. In fact, heating, ventilation, and air conditioning accounts for nearly 27% of total energy use in the United States [1]. Ground source heat pumps (GSHP) utilizing borehole heat exchangers (BHE) have been shown to be an effective method of electrifying heating and cooling systems, maintaining some of the best performance for any electrified heating and cooling system currently available. Electrification, however, does come with some significant challenges. One of particular importance is the significant increase in peak demand during the heating season, which can result in a serious cost increase for the operator of the electric heating system, as well as adding operational complexities to grid operations by shifting from a summer peak to a winter peak as more heating loads are electrified.

Thermal energy storage (TES) has been shown to be effective in mitigating the increase in peak demand that is seen with electrified heating and cooling systems. By storing thermal energy during off-peak hours, demand can be effectively shifted away from the peak hours. In this study, we investigate the potential of a ground source heat pump coupled with a TES system, in the form of water storage tanks, for the University of Massachusetts, as a way of decarbonizing the institution’s HVAC system while minimizing operating and installed costs.

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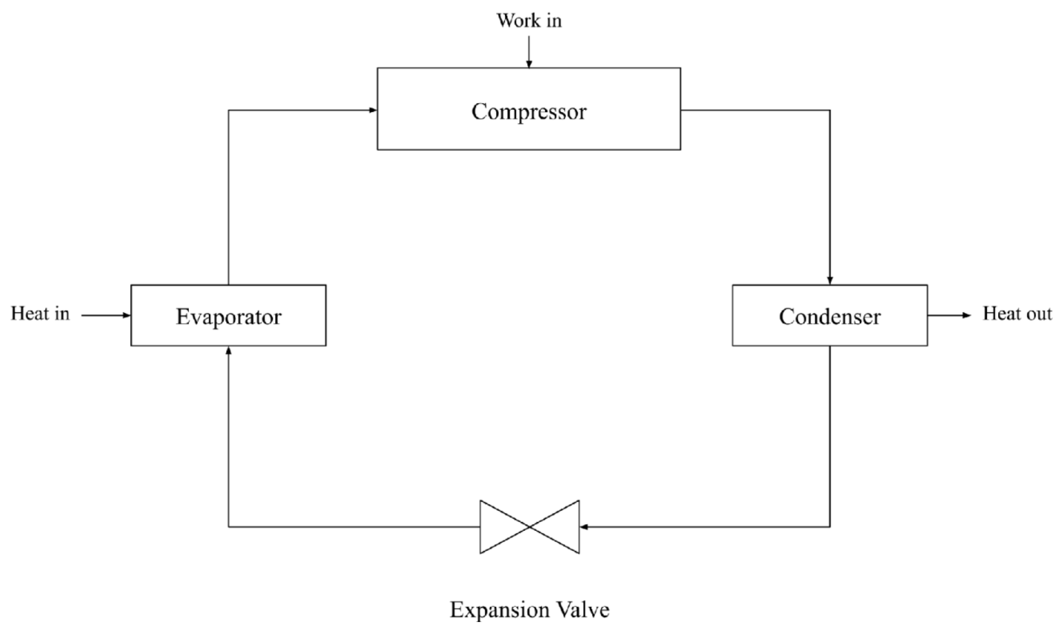
CHAPTER 1

INTRODUCTION

Electrification of HVAC systems has serious potential for reducing greenhouse gas emissions, and thus aiding the fight against climate change. In Europe, it has been found that electrification of the heating sector could lead to up to a 17% reduction in emissions [2]. Likewise, Tarroja et al. found that electrified heating could result in a 30-40% emission reduction in the state of California [3]. Similarly, the International Energy Agency's (IEA) Sustainable Development Scenario, which has global net-zero carbon emissions by 2070, predicts that the adoption of heat pumps and other currently available sustainable cooling technologies could reduce cooling sector CO_2 emissions by 11.5 gigatons per year worldwide by 2070, while accounting for a projected increase in space cooling demand [4]. With the international push towards emission reductions, the potential benefits of heat pumps are apparent, due to their efficiency and energy savings potential. There are a variety of electric systems for heating and cooling, with heat pumps being a very common application because of their ability to provide heating and cooling. Ground source heat pumps (GSHP) with borehole heat exchangers (BHE) are one common application and are the focus of this analysis since they hold the highest potential performance of common electric systems.

1.1 Ground Source Heat Pump Basics

All heat pumps work on the same basic premise, in that they move heat from a cold reservoir to a warm reservoir using mechanical work. In the cycle, the working fluid absorbs energy to evaporate on the cool side, and then is moved to a higher energy state through a compressor. The fluid is then condensed on the warm side, thus providing energy, and then the fluid is put through an expansion valve to begin the process again. This process is shown below.



Both air and ground source heat pumps work as such, but with one key difference. Air source heat pumps use the outside air as their cold reservoir, which can cause extreme variance in their performance, as air temperature can change significantly throughout the year. Ground source heat pumps, however, utilize geothermal heat exchangers (GHE). Rather than using the outside air as their cold reservoir, GSHPs have another working fluid that moves heat to and from the ground, via the GHEs. Since the ground temperature remains relatively stable throughout the course of a year, GSHPs often see better performance than their air sourced counterparts, especially in colder climates. There are two commonly used types of GHEs – closed loop and open loop. An open loop is one in which ground water is pumped through the heat pump to either absorb or reject heat, this water is then recirculated directly into the same well or a separate well depending on the configuration. A closed loop system, however, does not directly utilized ground water from a well. Rather, it utilizes a field of boreholes, which can be drilled hundreds of feet into the ground. Cross-linked polyethylene (PEX) tubing is then run through the boreholes, forming the closed loop through which the working fluid circulates to exchange heat.

Closed loop systems typically use some form of glycol or other antifreeze solution to prevent freezing in the loop. Closed loop systems are popular as there are fewer geologic/hydrologic constraints (such as ground water availability and water quality concerns) and thus they are the system chosen for this analysis.

One key potential hurdle for ground source heat pumps with borehole heat exchangers is the thermal degradation of the system. Depending on the load profile seen by the system, ground temperatures can change over the years of operation, thus affecting the performance of the heat pumps and exchanger. Typically, installations have a fairly balanced load profile, meaning that the heat pump will reject and extract approximately equivalent amounts of energy from the storage medium. In these cases, the performance is unaffected, as the ground temperature remains the same. In a very cold climate, however, the load profile may be severely heating dominated, meaning that the ground temperature will drop over time, as the heat pump extracts more energy from the ground in the heating season than it rejects to the ground in the cooling season. Similarly, in a hot climate, the load profile could be heavily cooling dominated, resulting in an increase in ground temperature over time as the heat pump rejects more energy than it extracts. Changing ground temperature is a known issue with these types of systems, as it can negatively affect the heat pump performance. Previous work at the University of Massachusetts has shown that, due to the institution's cold climate and high heating loads relative to its' cooling loads, ground temperature would drop over time [5]. This change in ground temperature can make an impact on the heat pump performance, as it affects the source loop temperature for the heat pump. Likewise, long-term changes of the ground temperature can have far reaching impacts, with possible changes to soil biology and composition. Therefore, ground source heat pump installations aim to have as balanced a load as possible, and there are a number of ways to make that possible. One way to balance the load is to utilize air source heat pumps in conjunction with ground source, so that the air source can meet a portion of the load, allowing the ground source to have a balanced load profile. Similarly, when the load is heating dominated, solar thermal collectors can be used to provide the supplemental heating needed to balance the load met by the heat pumps. Likewise, when there is a cooling dominated load, there are methods of balancing the load in the other direction. For example, the cooling towers can be added to the system to reject excess heat, and thus balance the load. Furthermore, summer heat can be used for water heating through a desuperheater, which gives a secondary location to deposit energy rather than the ground for cooling dominated systems.

1.2 Issues of Electrification

While HVAC electrification is undoubtedly a beneficial idea, there are some challenges to implementing fully electrified systems. By far the biggest issue is the notable increase in electric load during the heating season, which can cause serious stress on the grid as well as increased costs for the operator. In California, it was found that electrified heating could increase future grid capacity needs by nearly 32% [3]. Throughout the U.S., the impact of electric heating is even greater. Studies have shown that replacing all fossil-fuel based heating with heat pumps would result in a nearly 70% increase in peak load, with up to 23 states potentially seeing a doubling of their respective peak load [6]. Similarly, previous studies at the University of Massachusetts have shown that the implementation of a GSHP with vertical borehole system would be financially difficult, due to the increase in peak demand charges [5].

Electricity rates on the commercial and industrial scale are typically based on two factors – usage and demand. Usage defines the total electricity used by the customer, while demand is based upon the highest usage for a defined time period, whether it be an hour, 15 minutes, or some other length defined by the utility. Due to the nature of the grid and energy planning, peak demand can be the driving force behind an energy bill, accounting for anywhere from 30-70% of a monthly electric bill [7]. Typically, the highest peak demand charges are seen during the summer, as most cooling systems are already electrified. During the summer, peak hours are usually towards the middle of the day, when temperatures rise and thus the cooling load is highest. During the winter, however, peak hours will typically occur either in the morning or evening, when there is a greater heating load to be met due to colder temperatures and less sunlight during the morning and evening [8]. Currently, winter peaks are not as high as summer peaks, since there is a litany of non-electric heating systems, such as gas boilers. This could change in the future, as a shift towards electrified heating would drastically increase the winter peak demand. Especially in colder climates, it is likely that electrified heating would result in the heating season seeing higher peak demand than the cooling season. For example, the state of New York found that, in their efforts to decarbonize, their highest peak demand will shift from summer to winter around the year 2040 [9]. While the decarbonization of heating is a vital component of our fight against climate change, the transition must be carefully implemented to ensure the viability of the efforts. Peak demand charges are a major hurdle for this endeavor, so any means to lessen their impact are highly valuable. In fact, it has been shown that keeping some fossil fuel backup can allow for 97% heating electrification in the United States without any changes to the current peak loads [6]. In this scenario, heat pumps are able to meet the majority of the heating load, with fossil fuel backup maintained for the coldest weather. By strategically using fossil fuels during times of high heating demand, the peak impacts on the grid from electrified heating can be nullified, allowing for adoption of these technologies with no need for greater grid capacity.

1.3 TES Basics

TES is a commonly used tool to mitigate peak demand and maintain operational flexibility. Kamal et al. were able to show that TES with HVAC applications could shift peak cooling electricity use by up to 78%, which would reduce operational costs up to 17%, [10]. Similarly, Jebamalai et al. showed that TES could reduce costs nearly 7% when operating with a fossil fuel based district heating network [11]. Furthermore, TES can also improve emission reduction efforts. A study has demonstrated that TES in Spain and Europe could reduce CO_2 emissions nearly 6% from 1990 levels. By reducing peak electric load as well as overall electricity consumption, thermal storage has been shown to be an effective way to reduce emissions [12]. Likewise, the reduction in peak demand corresponds to a decrease in the use of "peaker" plants. Peaker plants are typically fossil fuel fired plants that only operate during peak demand hours, which can be from 2-7% of the hours in a year [13]. It is possible to use thermal storage to shift those demand peaks, thus putting less reliance on the CO_2 intensive peaker plants and avoiding the high demand prices during those hours. Storage requires no fuel, has no independent emissions, requires minimal maintenance, and can be dispatched quickly and efficiently. TES also helps with the transition to renewable energy, as it provides a means of resiliency to aid in the inherent variability of renewable generation. TES is a key technology in the future of energy – in fact, it is projected that thermal storage capacity could triple from 2019 to 2030 [14].

There are a variety of TES systems, with sensible storage and latent storage being the most common. Sensible storage is the simplest method, where energy is distributed through the temperature change of a material, such as water or molten salt. An example of sensible storage is a storage tank, where hot or chilled water is stored for later use. Latent storage, conversely, utilizes the latent heat of transformation for substances, and thus stores energy in different material phases. An example of latent storage would be ice storage, where ice is melted to provide cooling. While latent storage has greater potential energy benefits, sensible storage is the more mature technology, and is the most common method in commercial applications. Thus, sensible heat storage, specifically in the form of tank thermal storage, is the primary system investigated in this analysis.

Sensible heat storage is fundamentally based on the temperature change of the storage material. The temperature is directly related to the inherent energy of the system, as well as the heat capacity of the storage material. This principle is defined below:

$$Q = \int_{T_i}^{T_f} mC_p dT = mC_p(T_f - T_i)$$

Where

Q	=	Sensible heat stored; J
T_f	=	Final temperature; ^oC
T_i	=	Initial temperature; ^oC
m	=	Mass of storage medium; kg
C_p	=	Specific heat of the storage medium; J/kg ^oC

Typically, sensible storage uses either solid or liquid substances. Solid materials include things such as rock beds or metal, while liquid materials are likely water or molten salt. Liquid water is often used as a sensible storage medium since it is relatively inexpensive and has a high specific heat capacity. Storage tanks can work with a wide array of temperatures, ranging anywhere from 90 C for the hottest storage, to 7 C for the coldest [15].

1.3.1 Stratified Water Storage

Water storage tanks are perhaps the most common methods for thermal storage and have been used with great success. They are a well-studied method of thermal storage, and are highly reliable, easily installed, and financially viable [16]. The most efficient method of water storage is a thermally stratified storage tank. Thermal stratification creates layers within the storage tank, so that the less dense, higher temperature water is on the top of the tank while the denser, lower temperature water is on the bottom. Stratification allows for improved efficiency of thermal storage systems, as it limits the mixing between the hot and cold water. Experimental studies have shown that thermally stratified storage tanks can have efficiencies of up to 90% [17]. The working limits to stratified storage tanks are centered on ways to mitigate mixing between the hot and cold layers. In general, it is known that lower inlet velocities and higher temperature differences between the hot and cold layers are best for stratified storage, to prevent mixing and maintain high energy efficiency [18].

1.4 Objectives of Research

TES is a key component of the transition to decarbonized heating and cooling systems. Previous studies have shown that thermal storage is an economically and operationally advantageous technology, which can elevate the appeal of electrified heating and cooling systems. This research proposes a coupled GSHP and TES system, to find a cost-effective way to make the conversion to fully electrified district heating and cooling system. This research looks at the benefits of both electrified systems and thermal storage, using available measured load data from the University of Massachusetts (UMass) campus. Similarly, by using UMass loads, it is possible to make a direct comparison to their combined heat and power plant (CHP), which will provide strong insight into the viability of a GSHP with TES system. The combined system design, and distinct characteristics given via the UMass campus operating data, make this research a unique and valuable analysis. Therefore, the primary objectives of this research are as follows:

- Measured data for heating and cooling loads were obtained from the campus Building Automation System
- Ground source heat pumps capable of providing said loads were simulated with and without TES, using an energy model built in TRNSYS
- The corresponding energy use and carbon emissions were determined
- Costs were compared for the storage and non-storage case versus the current CHP, using UMass rates for electricity and natural gas. A more generalized rate structure was used as well to provide analysis beneficiary to many facilities

The goal of this study was to determine a cost effective system design that could minimize the costs associated with the adoption of electrified heating and cooling systems, in order to meet the decarbonization milestones necessary to meet the climate goals of the 21st century.

CHAPTER 2

LITERATURE REVIEW

TES has been widely studied as an effective way to manage society's growing energy needs. As our thermal energy needs continue to grow, TES can effectively decouple our thermal needs from our power needs, thus improving the operation of all aspects of our energy infrastructure. With the growing interest in the decarbonization of our heating and cooling systems, TES will be a key tool in smoothing that transition in all ways, from operational to financial.

2.1 TRNSYS Simulations

TRNSYS is a well-regarded energy simulation software that can be used for a variety of different purposes. It has been used extensively to model many different technologies, including heat pumps and thermal storage.

Antoniadis [19] optimized the performance of a solar thermal system with seasonal storage in TRNSYS. The system used an array of solar thermal collectors combined with a seasonal water tank storage system to see how much of the hot water load could be maintained through solar integration. The TRNSYS simulation found that, for a typical building in Thessaloniki, Greece, the thermal storage system could cover nearly 67% of the heating load. For all cases investigated in the study, it was found that at least 39% of heating load needs could be covered by the system.

Similarly, Glembin [20] utilized TRNSYS to optimize the use of thermal storage tanks with high efficiency heat pumps. Based upon a building in Zurich, Switzerland, the study investigates how a thermal storage tank integrated with heat pump operation could affect electricity consumption. In their scenario, the thermal storage was charged by both heat pump operation and an array of solar collectors, with an optimization of the heat pump parameters.

They studied the impact of differing numbers of heating zones, heat pump flow rates, setpoint temperatures, and other key indicators. They found that the optimal scenario for heat pump operation with water tank storage could reduce electricity consumption by nearly 15%.

2.2 Financial Value of TES

TES is a proven method of reducing operational costs for heating and cooling systems. In particular, the combination of TES with electrified heating systems has been shown to be a thoughtful way to make the transition away from fossil fuel technologies.

Hutty [21] investigated the value of TES as a peak shaving mechanism with the electrification of heat. Using a designated area of 50 buildings in southern England, the authors compared the potential for peak load shaving using both adsorption energy storage and a hot water storage tank. Coupled with an array of air source heat pumps, the authors found that the use of $5m^3$ of hot water storage could result in a demand reduction of nearly 14%. Only $0.25m^3$ of adsorption storage was needed, but the charging of the adsorption storage accounted for a significant increase in electricity consumption, making that form of thermal storage less financially viable.

Facci [22]looked at the correlation between renewable production, electrified heating, and TES in the residential sector. They showed that the combination of photovoltaic generation, heat pumps, and thermal storage could have a significant benefit from both a financial and emissions standpoint, resulting in a 41% cost savings over natural gas boilers, as well as a 73% reduction in emissions. For the sake of their study, the system was effectively islanded, in that there was no benefit for excess generation that could potentially be sold to the grid.

Egging-Bratseth [23] investigated the value of TES in situations with relative demand uncertainty. They looked at how TES could be integrated with a district heating network, to reduce operational costs and emissions. Integrating with their district heating model required seasonal storage, in the form of hot or chilled-water storage tanks as well as borehole storage. Using a residential area in Trondheim, Norway as the location, it was shown that TES could reduce operational costs by 10%, as well as reduce CO_2 emissions by 37%.

2.3 Additional Benefits of TES

While TES has immense advantages from a financial perspective, there are also other ancillary benefits. TES helps in many other ways with electrified heating, from lessening peak impacts on the electric grid to improving resiliency with variable renewable generation sources.

Cooper [24] simulated the electric demand impacts of heating electrification in the United Kingdom. They found that, if 80% of dwellings in the nation were to switch to heat pumps, peak electric demand could increase by anywhere from 30-100%. The study also noted, however, that extensive thermal storage could reduce that increase by nearly 15%. The study utilized a variety of thermal storage techniques in their analysis, from hot water storage tanks to utilizing the building's thermal mass via preheating.

Schellenberg [25] investigated how TES could provide flexibility of electric heating systems dependent on variable renewable generation sources. Looking at wind energy shares of 7%, 25%, and 60%, the study examined how TES could impact the electric loads of the heat pumps. It was found that anywhere from 33-100% of the heat pump electrical load could be shifted to off-peak hours, which would provide a serious cost benefit to the operator, while also offsetting the inherent difficulties of variability in renewable energy generation.

Modi and Waite [6] looked at how the decarbonization of the heating sector would affect grid capacity and peak loads in the United States. They found that a direct transition to fully electrified heating would require a 70% increase in grid capacity for the country. Maintaining some fossil fuel backup for the coldest weather, however, can mitigate the impact on grid capacity. The authors showed that it is possible to reduce fossil fuel usage by 27% without increasing peak demand, based on currently available heat pump technologies. Similarly, they determined that, through strategic implementations of both electric and fossil fuel heating, it is possible to get the U.S.'s reliance on fossil fuels for heating to 1-3%, while not requiring any increase to our current electric capacity.

2.4 Previous Research at the University of Massachusetts

There has been a demonstrated interest in TES and electrified heating research at the University of Massachusetts, and this study builds upon those previous findings.

El Hasnaoui [26] investigated a central solar heating plant with seasonal thermal storage using borehole heat exchangers. Using a storage volume of 60,000 m^3 and 850 boreholes, the plant was able to provide 83% of a 3,306 MWh annual heating load using a 7,500 m^2 solar collector. The analysis showed that the first law efficiency of this system was 65%.

McDaniel & Kosanovic [27] utilized TRNSYS to analyze seasonal TES using excess heat generated by the UMass CHP system. Using generated steam and power data from the CHP plant, and a TRNSYS model built around the duct ground storage model, it was found that the borehole system could approach an efficiency of 90%. Likewise, cost and emissions savings were found when using the stored thermal energy in the winter, as opposed to burning ultra-low sulfur diesel during the winter.

Wagner et al [5] compared air source versus ground source heat pumps as a way to transition the UMass campus to electrified heating. It was shown that ground source heat pumps were more efficient and cost effective than air source, but the increase in peak demand charges due to electrification resulted in an increase in total costs compared to the existing CHP system. That said, there were meaning reductions in CO_2 emissions from the heat pumps utilizing electricity purchased from the grid over the base case with CHP.

As shown, electrified heating systems with TES hold great potential for the continued battle against climate change. The extensive emissions reductions are apparent for electrification, and the integration of thermal storage only increases those reductions, while also making the transition more financially palatable. The potential for such a system at the UMass is intriguing, due to its current CHP plant. UMass has shown an interest in decarbonization and thermal storage technologies, and this thesis builds on those previous findings to investigate ways for the campus to make that change.

CHAPTER 3

SIMULATION METHODOLOGY

In order to effectively analyze how TES can be incorporated into an electrified heating and cooling system, a model was built that can simulate the operation of these kinds of systems. First, the initial parameters were established, in order to define a boundary for the simulation. Then, data was gathered to provide a realistic load case for the application of these systems. Finally, specific relevant components were investigated, to gain greater insight into the operation and mechanics of the key system components. This combination of studies results in a functioning model that allows for the simulation of a ground source heat pump system coupled with stratified water storage tanks.

3.1 University Building Background

Having established TRNSYS as an effective way to model electrified heating with TES, it is necessary to generate a realistic load profile based on measured heating and cooling loads from UMass. For this purpose, the southwestern quadrant of campus was chosen, which includes the Mullins Center, the Recreation Center, the Commonwealth Honors College Residential Complex, and the Southwest Residential Area, among others. A full list of buildings used can be found in Appendix A. This array of buildings was chosen in coordination with the UMass Carbon Mitigation Plan Taskforce. UMass's goal with that plan is to be carbon neutral and 100% renewable by 2030, and it is likely to take a phased approach to meet that goal. The southwestern quadrant was identified as likely to be the first phase of that transition, and thus was selected to develop the load profile.

3.2 Definition of Case Studies

For this analysis, two distinct case studies were analyzed using the data about the defined section of the UMass campus. The UMass case looks at the cost of the heat pump and storage system under the current UMass electricity rate structure, which is unique because UMass has a large generation facility on campus. In the UMass case, monthly demand charges are based on a defined hour chosen by the utility. The monthly demand charge is defined as $11.53/kW. For 2019, those monthly peaks are defined as such:

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 1: UMass Utility Peak Hours

Similarly, the UMass case contains a capacity charge, which is a yearly charge based on the electric usage during the peak hour of the regional grid. For 2019, this peak capacity hour was July 30th, from 5:00 PM to 6:00 PM. Because of variability in this capacity charge cost, the average projection for the years 2020-2025 was used, giving an annual capacity charge cost of $71.66/kW-yr. The volumetric electric prices for UMass change monthly, with the average on peak electric cost being $0.0765/kWh and the average off peak cost being $0.0668/kWh, with on peak hours being from 7:00AM to 8:00 PM.

The second case is a general case, where all electricity is bought from the grid. The peak period for this case is defined as 7:00 AM to 8:00 PM, and the facility is charged for their peak monthly usage during these hours. Using published 2019 electric rates, the peak demand charge under the generalized case is $14.94/kW, and the volumetric on peak electric cost is $0.1074/kWh and the off peak cost is $0.0841/kWh[1]. A summary of the different cases, and their corresponding electric prices, is shown in the table below.

[1] https://www.eversource.com/clp/vpp/vpphistory.aspx#

	Rate Structure	System	On Pk $/kWh	Off Pk $/kWh	Demand $/kW	Capacity $/kW	Fuel $/MMBTU
Case 1	UMass	Heat pumps w/ storage	$0.0765	$0.0668	$11.53	$71.66	-
Case 2	UMass	Heat pumps no storage	$0.0765	$0.0668	$11.53	$71.66	-
Case 3	UMass	Heat pumps w/ storage and CHP generation	$0.0765	$0.0668	$11.53	$71.66	$6.44
Case 4	General	Heat pumps w/ storage	$0.1074	$0.0841	$14.94	-	-
Case 5	General	Heat pumps no storage	$0.1074	$0.0841	$14.94	-	-
Base	UMass	Conventional CHP	$0.0765	$0.0668	$11.53	$71.66	$6.44

Table 2: Definition of Cases

3.3 Data Acquisition

Heating and cooling load data for the defined buildings was collected from Johnson Controls' Metasys, the building automation system (BAS) used by UMass. This system can provide data on pounds of steam delivered to a building for heating, as well as the supply and return temperatures and flowrates for any hot water heating. Similarly, there is information on chilled water flowrates and temperatures related for cooling. The flow rates are measured using Venturi flow meters and the temperatures are collected with temperature sensors, and all data is recorded in 15-minute intervals. Data from the year 2019 was chosen for this analysis, as that represents the most recent "typical" year that was unaffected by campus capacity limits imposed in 2020 and 2021. The heating and cooling load delivered by either hot or chilled water can be calculated as follows:

$$\dot{\mathbf{Q}} = \boldsymbol{\rho} \times \dot{\mathbf{m}} \times \mathbf{C_P} \times \Delta\mathbf{T}$$

Where ρ is the density of water, ṁ 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 supply to return. The heating load delivered directly by steam can be calculated as such:

$$\dot{\mathbf{Q}} = \dot{\mathbf{m}} \times \mathbf{h_{fg}}$$

Where ṁ is the amount of steam delivered, and h_{fg} is the heat of evaporation for steam. 939 $\frac{\mathbf{Btu}}{\mathbf{Lb}}$ was used for h_{fg}, as that corresponds to the 20 psig steam that the CHP provides for heating.

There was not sufficient data for every building in the defined portion of campus, so any missing data was estimated using the building's square footage and the ratio of BTU per square foot found from the buildings with a complete load data set. The total heating and cooling load for this section of campus is shown in Figure 1 below.

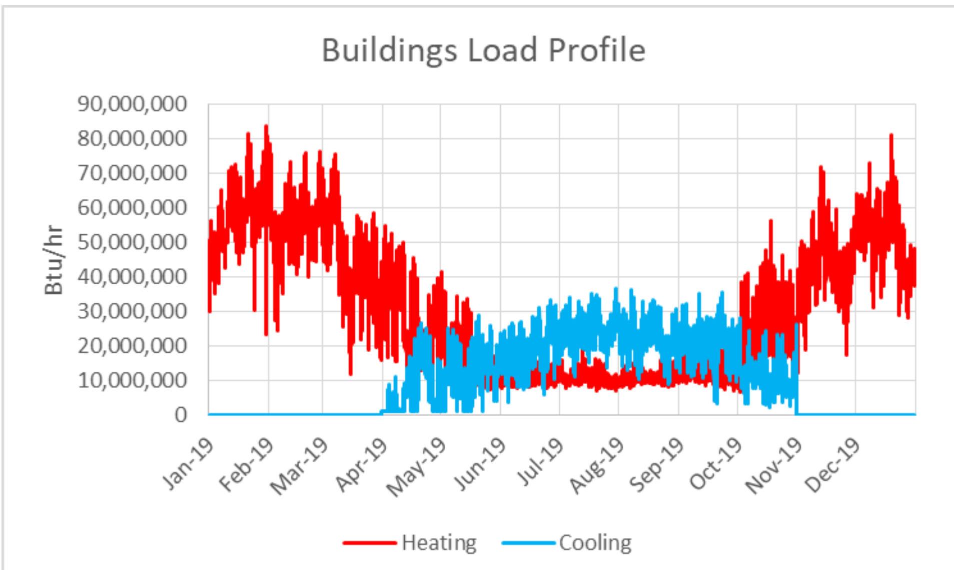


Figure 1: Heating and Cooling Loads for Southwest Quadrant

Currently, not all buildings in the defined area have cooling, contributing to the significant difference in heating versus cooling loads. Heat pumps can provide both heating and cooling, and therefore were UMass to install an array of heat pumps, they would likely provide cooling to buildings that do not have any currently. Using a similar method of estimating loads based on square footage and a ratio of BTU per square foot for cooling, the cooling loads were adjusted to include buildings that would likely have cooling installed should heat pumps be implemented. These buildings include academic and facility buildings such as Boyden Gymnasium, Curry Hicks, Machmer Hall and Memorial Hall. The adjusted loads accounting for this potential addition of cooling capacity is shown below in Figure 2. These adjusted loads were used in the TRNSYS simulation to provide the most accurate prediction of the system performance. The total heating load for the year is 263,464 MMBTU, while the total cooling load is 106,385 MMBTU.

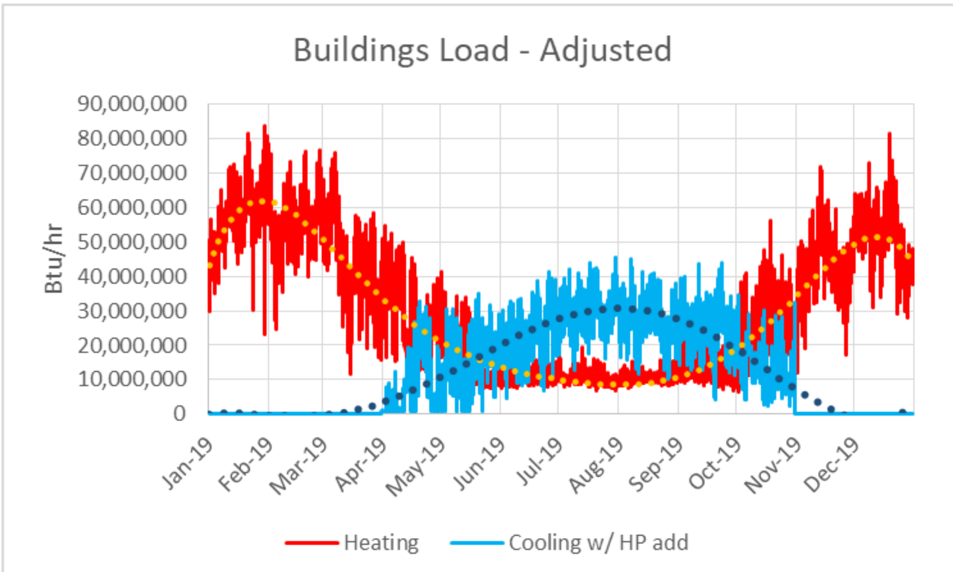


Figure 2: Adjusted Loads for Added Heat Pump Cooling Capacity

Along with the heating and cooling loads, there is also an electric load associated with lighting, ventilation, and plug load. This is defined as the "building load" and is assumed to be constant throughout all scenarios. The total yearly building load is 26,584,856 kWh.

3.4 Heat Pump Characteristics

Heat pumps were simulated in TRNSYS to provide the described heating and cooling loads. This was accomplished using TRNSYS's Multidimensional Interpolator, which interpolates manufacturer provided performance data based on inlet flowrate and temperature conditions. A Trane Axiom Water to Water 20 Ton Heat Pump was chosen for this application, and the tabular performance data can be found in Appendix B. The inlet conditions that define the performance of the heat pump are the water temperature and flow rate on the load (building) side, as well as the water temperature and flow rate on the source (ground) side. This simulation assumes that the flow rate is equal on both sides of the heat pump, as that was a commonly described mode of operation in different manufacturers' data. In general, water to water heat pumps operate more efficiently at higher flows, with their best COP coming when both the load and source side flowrate is maximized. Likewise, water to water heat pumps operate more efficiently at lower temperatures. Figure 3 below shows the heating COP of the heat pumps versus flow rate for a constant entering water temperatures, and Figure 4 shows the heating COP versus load entering water temperature with a constant flow.

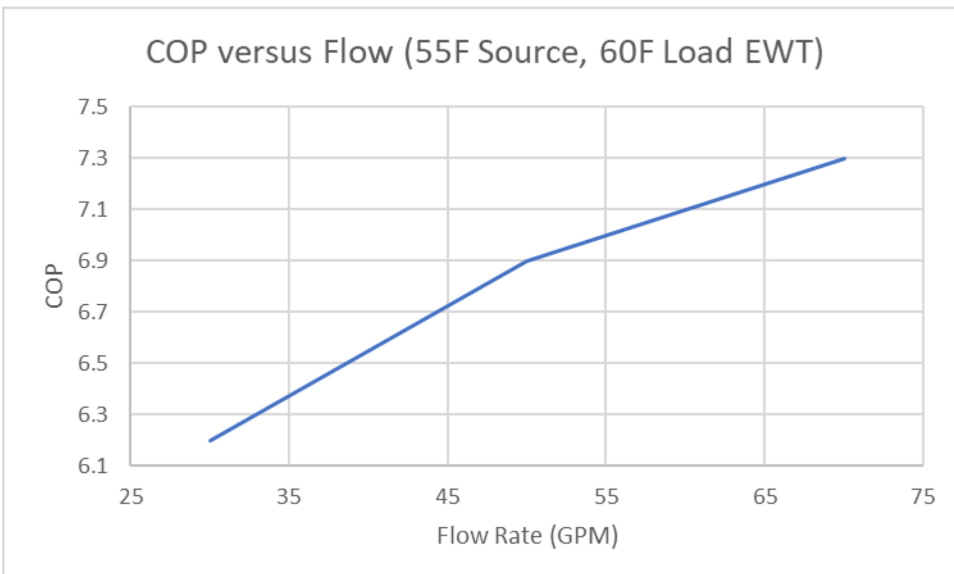


Figure 3: Heating COP versus Flow with constant entering water temperatures

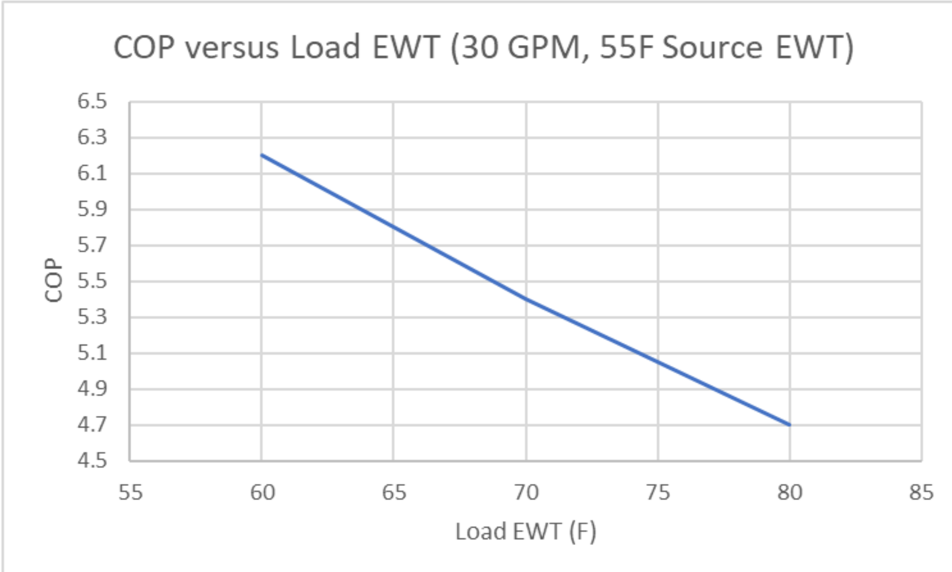


Figure 4: Heating COP versus Load EWT with constant flow

3.5 Borehole Parameters

The borehole heat exchanger that is connected to the array of ground source heat pumps was also simulated in TRNSYS. This was done using TRNSYS Type 557, which simulates a borehole heat exchanger based on the duct ground heat storage model [28]. This methodology is a widely accepted way of simulating borehole heat exchangers and is typically used for analysis of borehole heat exchangers in TRNSYS, including previous work done at UMass [5][26]. The model assumes that the heat exchangers are uniformly distributed in the ground storage region, with homogenous thermal properties. The temperature at any given point in the storage volume is calculated based on a superposition of three distinct solutions for the heat flow: the global solution, a steady heat-flux solution that happens near the borehole pipes, and a local solution solely based on the radial component. This results in the following equation:

$$C\frac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T) + Q_{sf} + Q_I$$

Where Q_{sf} is the source term of the steady-flux solution, Q_I is the source term for the heat from the local solution, C is the volumetric heat capacity, and λ is the thermal conductivity.

The design factors for the boreholes and ground heat exchanger were defined within the International Ground Source Heat Pump Association (IGSHPA) *Closed-Loop/Geothermal Heat Pump Systems, Design and Installation Standards* [29]. This allows for a pipe material of cross-linked polyethylene (PEX), and a U-tube pipe nominal diameter of 2.371 in. With a dimension ratio of 9 to 1, the minimum wall thickness is 0.26 in. The pipe's minimum pressure rating is 160 psi, and the classification is PEX 1006 or PEX 1008. The borehole radius is defined as 4.7 in**,** and the borehole depth is 328 feet.

A thermal grout with thermal conductivity of 1 $\frac{\mathbf{BTU}}{\mathbf{hr\ ft}\ {}^{\circ}\mathrm{F}}$ was used, which represents a medium grade thermally enhanced bentonite grout typically used in modern borehole systems. The ground thermal conductivity and volumetric heat capacity for soil on the UMass campus has been previously defined [26]. Therefore, the ground thermal conductivity of 0.71 $\frac{\mathbf{BTU}}{\mathbf{hr\ ft}\ {}^{\circ}\mathrm{F}}$ and volumetric heat capacity of 59.05 $\frac{\mathbf{BTU}}{\mathbf{ft^3}\ {}^{\circ}\mathrm{F}}$ are used in the simulation model.

The borehole fluid used was a 20% by weight ethylene glycol to water mixture. The addition of an antifreeze like ethylene glycol is needed in cold climates to prevent freezing of the borehole fluid during the winter. A direct exchange system using refrigerant such as R-410a could be used, but this methodology was not examined in this analysis.

The number of boreholes in the borehole field has a significant impact on the total operating cost of the ground source heat pump system. Higher number of boreholes have a higher installation cost, but also improve heat pump efficiency. By operating the heat pumps more efficiently, it is possible to reduce electric use and costs. Similarly, improving heat pump efficiency can reduce the size of the heat pump array, as less heat pumps are needed to meet the load.

Using average cost data from studies at similar large institutions [30] as well as regional costs reported by the MassCEC [31], an install cost of $14.68/ft was determined. Similarly, average costs reported by the MassCEC [31] and similar large institutional installations [30] define an average cost of $3,517.65/ton for the installation cost of the water-to-water heat pumps. Figure 5 below shows the total year 1 cost for a system based on the number of boreholes, which includes the borehole install cost, the heat pump install cost, as well as electricity cost from system operation.

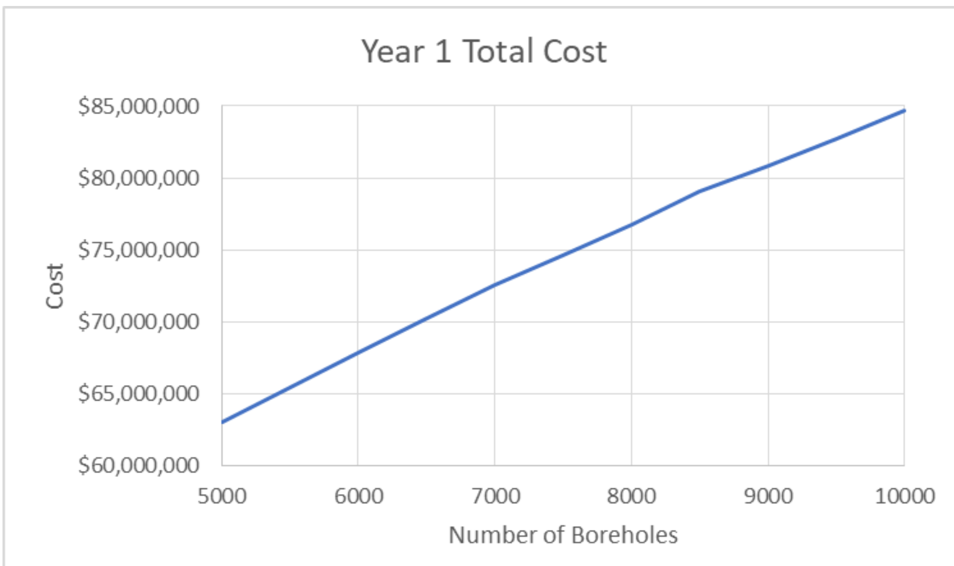


Figure 5: Year 1 Total Cost vs Number of Boreholes

As shown, an increase in the number of boreholes increases the year one cost, due to the high capital cost of borehole installation. Therefore, it is necessary to investigate the cost effectiveness of increasing the borehole field size. Figure 6 below shows the cost system cost increase associated with an addition of 500 boreholes to the system, along with the number of heat pumps removed from the array associated with the larger borehole system. Figure 7 highlights the ratio of cost increase to total heat pump array size, and Table 3 shows the relevant data in tabular form.

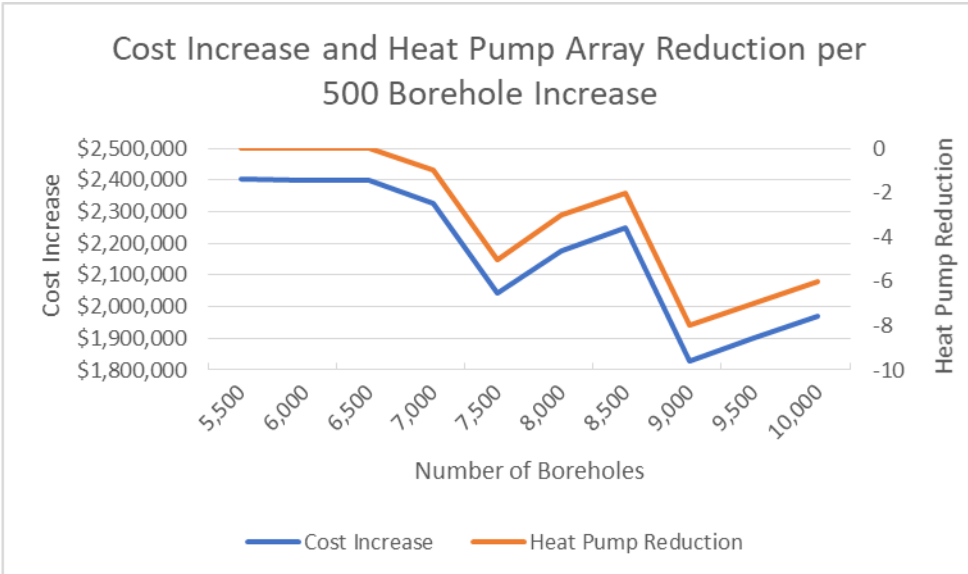


Figure 6: Cost Increase and Heat Pump Reduction vs Number of Boreholes

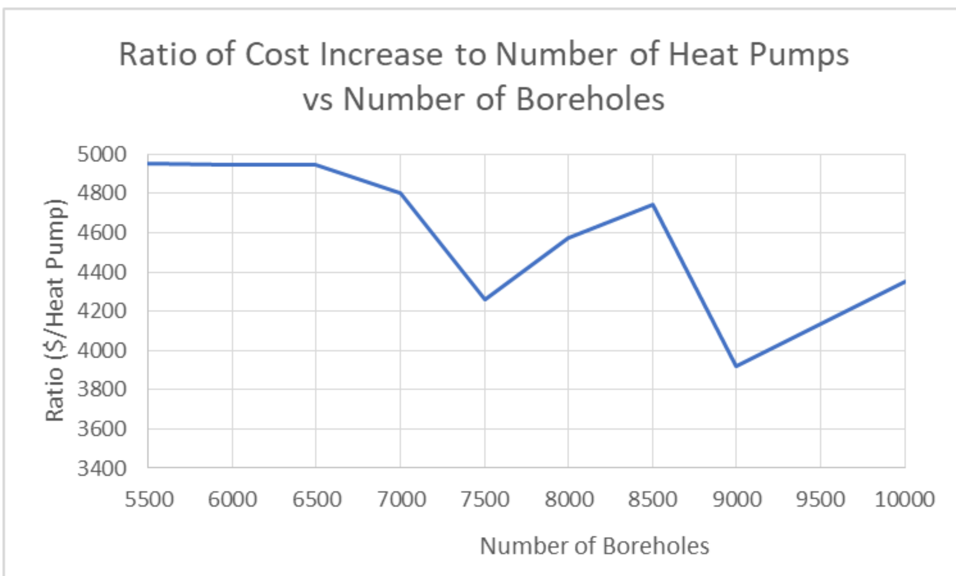


Figure 7: Ratio of Cost Increase and Heat Pump Array vs Number of Boreholes

Boreholes	#HP	Install Cost	Cost Increase
5000	485	$63,034,246	-
5500	485	$65,435,981	$2,401,735
6000	485	$67,835,744	$2,399,762
6500	485	$70,233,681	$2,397,938
7000	484	$72,558,882	$2,325,201
7500	479	$74,599,750	$2,040,868
8000	476	$76,778,066	$2,178,316
8500	474	$79,026,520	$2,248,454
9000	466	$80,853,851	$1,827,331
9500	459	$82,753,219	$1,899,368
10000	453	$84,724,775	$1,971,557

Table 3: Borehole cost numbers

As seen above, a 9,000 borehole system is the most cost effective, as that size of borehole field reduces the heat pump array by 8 heat pumps, and thus limits the cost increase to approximately $1,800,000 relative to a borehole field of 8,500 boreholes. Therefore, a borehole system size of 9,000 boreholes was used for this analysis, which corresponds to a borehole field area of 2,886,455 square feet, with an installation cost of $43,335,360. This system has a heat pump array of 466 20-ton heat pumps, which has an install cost of $32,784,498, for a total system install cost of $76,119,858.

3.6 Stratified Storage Parameters

Stratified thermal storage tanks for either hot or chilled water were also incorporated into the TRNSYS model. This was done using TRNSYS Type 4, the Stratified Fluid Storage Tank. This component models a constant volume closed storage tank divided into N segments, called nodes. Each node is considered fully mixed, and it is assumed that the flowrates between nodes are fully mixed before they enter each segment. Theoretically, the greater number of nodes in the tank, the greater the stratification that can be simulated. Ahmed [32] showed that a 15 node tank is most efficient in terms of stratification and computational power, and thus the tanks were modeled with 15 nodes.

Charging of the thermal storage tanks was done using the water output from the ground source heat pumps. During off-peak hours, defined as 8:00 PM to 7:00AM, the temperature setpoint for the supply water would be changed to charge the tanks. For hot water, the temperature setpoint was raised, from 95°F to 100°F, and a portion of the output water was used to charge the storage tank, with the remaining water being used to meet the heating load. This operation was maintained until the storage tank was filled with hot water at the higher temperature setpoint. The hot water temperature setpoint and storage temperature have a significant impact on the system operational cost, and they are further explored in Chapter 4. Similarly, for chilled water, the setpoint temperature was lowered during off peak hours, and the tank was charge until it was filled with chilled water at the lower temperature setpoint. The chilled water setpoint temperature was 44°F and the chilled water storage temperature was 40°F, both of which are standard temperatures for their respective systems.

Type 4 also allows for a definition of thermal losses for the storage medium. Karim [17] demonstrated that stratified storage tanks could reach efficiencies approaching 90%, so the tank model was tuned to have a similar efficiency. The efficiency of the storage medium can be calculated as follows:

$$\eta_{ST} = \frac{Q_{Discharge}}{Q_{Charge}}$$

Where η_{ST} is the storage tank efficiency, $Q_{Discharge}$ is the energy output from the storage tank, and Q_{Charge} is the energy input into the storage tank. The difference between the energy input and output from the storage tank can be attributed to losses to the through the tank to the ambient air, as well as losses due to mixing between the upper and lower portions of the stratified water.

Discharge strategy also impacts the efficiency of the storage tanks, and two different strategies were investigated related to the UMass case versus the generalized case. Therefore, for the UMass case, the discharge strategy is focused on reducing the energy use during those defined peak hours. Discharge was done over the course of 4 hours, to simulate a realistic discharge strategy. The stratification profile for February 16th with the UMass hot water storage tank is shown below, where each line represents a node of the storage tank

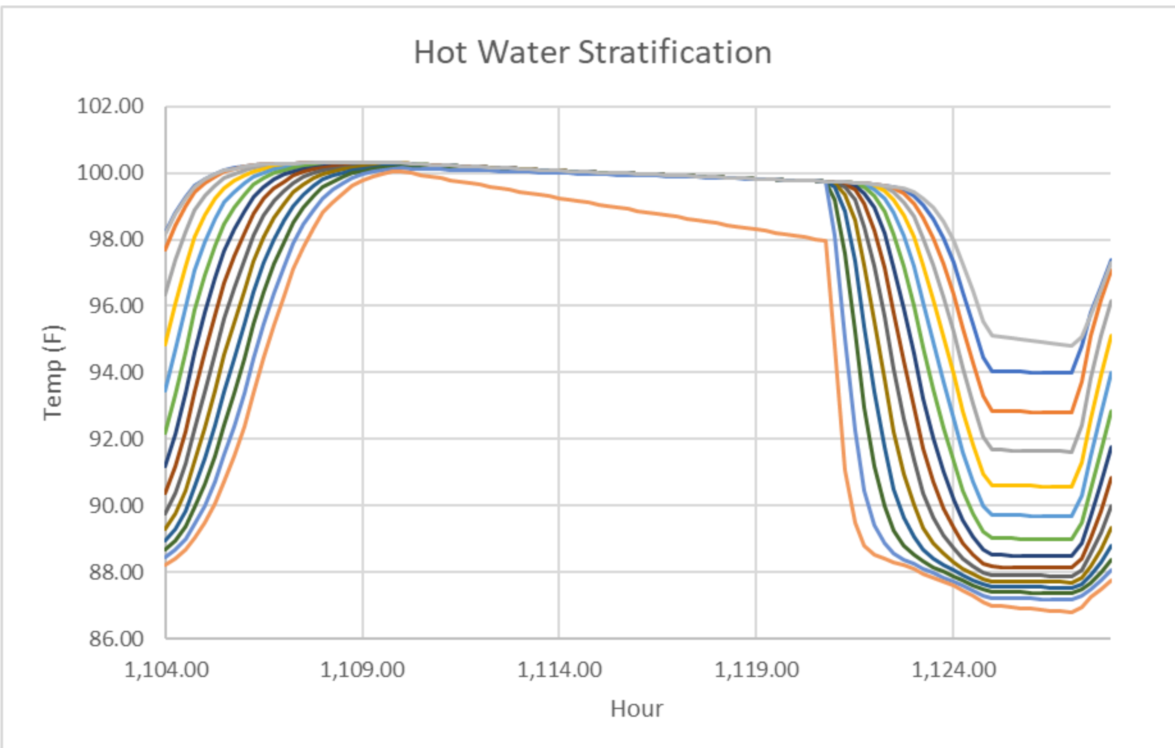


Figure 8: Hot Water Stratification - UMass Case

The efficiencies for the storage tanks in the UMass case by month are shown in the tables below.

	Average Daily Charge MBTU	Average Daily Discharge MBTU	Average Daily Losses	Efficiency %
Jan	366,601	326,376	41,335	89.03%
Feb	373,876	331,141	41,629	88.57%
Mar	348,553	305,963	41,708	87.78%
Apr	315,803	271,244	42,950	85.89%
May	245,941	204,246	41,881	83.05%
Jun	212,824	172,283	40,854	80.95%
Jul	209,391	168,905	40,664	80.66%
Aug	212,002	171,658	40,122	80.97%
Sep	240,806	200,700	40,816	83.35%
Oct	259,859	221,913	38,975	85.40%
Nov	352,068	311,765	41,151	88.55%
Dec	365,318	323,376	41,764	88.52%

Table 4: Average Daily Hot Water Storage Efficiency - UMass

	Average Daily Charge MBTU	Average Daily Discharge MBTU	Average Daily Losses	Efficiency %
Jan	0	0	6,732	0.00%
Feb	0	0	6,732	0.00%
Mar	0	0	2,059	0.00%
Apr	119,119	105,578	33,338	88.63%
May	194,756	153,448	42,548	78.79%
Jun	290,451	246,706	43,867	84.94%
Jul	326,942	292,601	44,336	89.50%
Aug	334,000	290,805	43,094	87.07%
Sep	311,147	266,055	44,080	85.51%
Oct	190,282	148,690	41,791	78.14%
Nov	0	0	17,831	0.00%
Dec	0	0	4,821	0.00%

Table 5: Average Daily Chilled Water Storage Efficiency - UMass

For the generalized case, the discharge strategy was aimed at lowering the peak load during the entire on peak hour period from 7:00 AM to 8:00 PM. Since the load at every interval is known, it is possible to develop a dispatch strategy that utilizes storage during the highest load periods, and thus lower the peak electric demand from the heat pumps. Therefore, the dispatch strategy could vary from day to day in the generalized case, whereas the UMass strategy would vary from month to month. The stratification profile for February 16th but with the general case is shown in Figure 9.

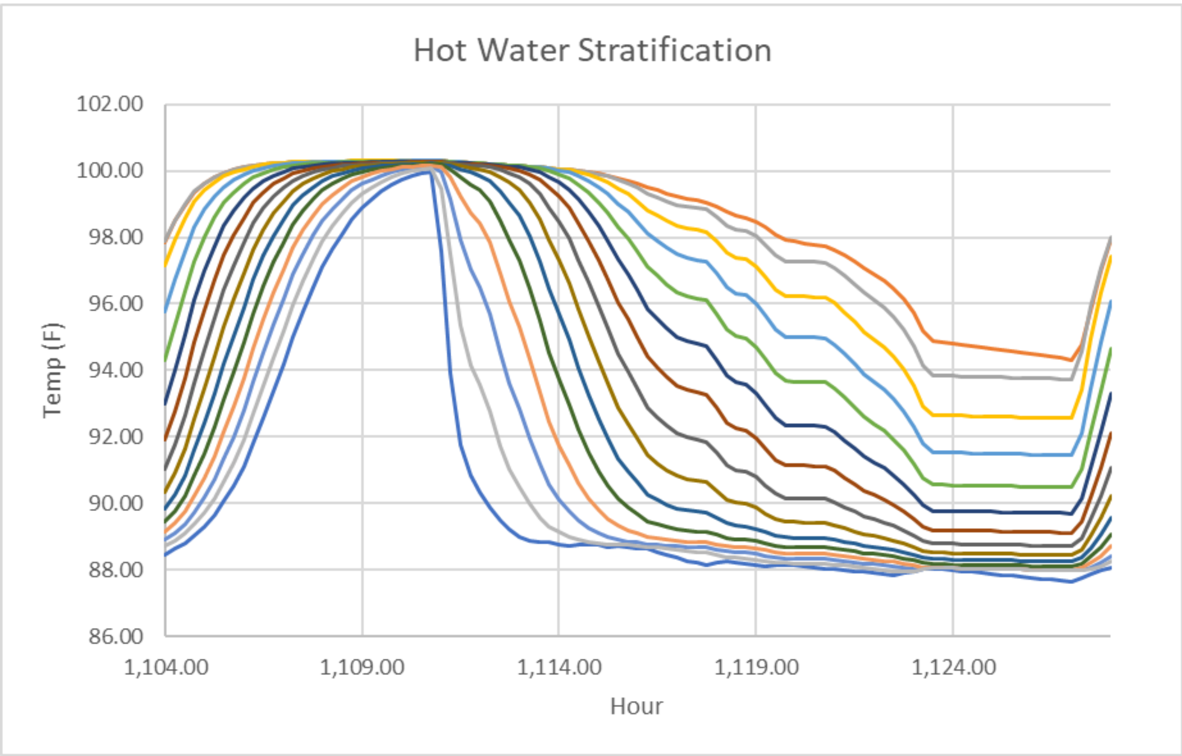


Figure 9: Hot Water Stratification - General Case

The stratification profile for the generalized case is much different than the UMass case, due to the different dispatch strategies. The storage efficiencies for the general case are shown in Tables 6 and 7. It should be noted that the month of April has a purge period for chilled water, where the storage tank must be purged of its room temperature water before it can meet any cooling load. This contributes to the outlier average efficiency for that month, which is high due to the averaging across the entire month. The cumulative efficiency for the system during the month of April is 55.71%.

	Average Daily Charge MBTU	Average Daily Discharge MBTU	Average Daily Losses	Efficiency %
Jan	355,940	319,262	36,748	89.70%
Feb	359,140	321,990	36,710	89.66%
Mar	338,838	301,686	36,654	89.04%
Apr	330,130	290,927	37,746	88.12%
May	287,815	251,862	37,628	87.51%
Jun	252,027	215,100	36,958	85.35%
Jul	242,995	206,035	36,919	84.79%
Aug	247,271	210,422	36,960	85.10%
Sep	274,873	238,401	36,766	86.73%
Oct	265,208	230,471	35,633	86.90%
Nov	343,830	306,573	36,805	89.16%
Dec	356,006	319,595	36,906	89.77%

Table 6: Average Daily Hot Water Storage Efficiency - General

	Average Daily Charge MBTU	Average Daily Discharge MBTU	Average Daily Losses	Efficiency %
Jan	0	0	6,732	0.00%
Feb	0	0	6,732	0.00%
Mar	0	0	2,059	0.00%
Apr	126,408	124,283	31,370	98.32%
May	189,900	153,442	41,237	80.80%
Jun	276,091	233,677	42,331	84.64%
Jul	310,547	268,437	42,511	86.44%
Aug	302,645	259,976	42,780	85.90%
Sep	288,593	245,247	42,871	84.98%
Oct	193,161	147,304	41,044	76.26%
Nov	0	0	17,905	0.00%
Dec	0	0	4,833	0.00%

Table 7: Average Daily Chilled Water Storage Efficiency - General

The different dispatch strategies have a direct impact on the heat pump power draw, and thus the peak demand charge. In the case of no storage, the heat pump power is directly related to the heating or cooling load that needs to be met, as shown in Figures 10 and 11 below.

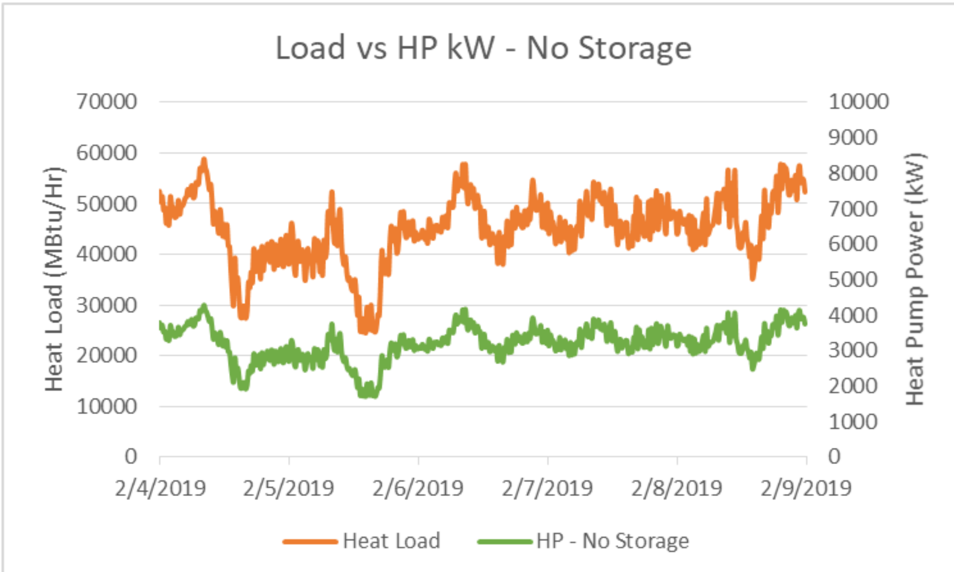


Figure 10: Heat Pump Power vs Heating Load

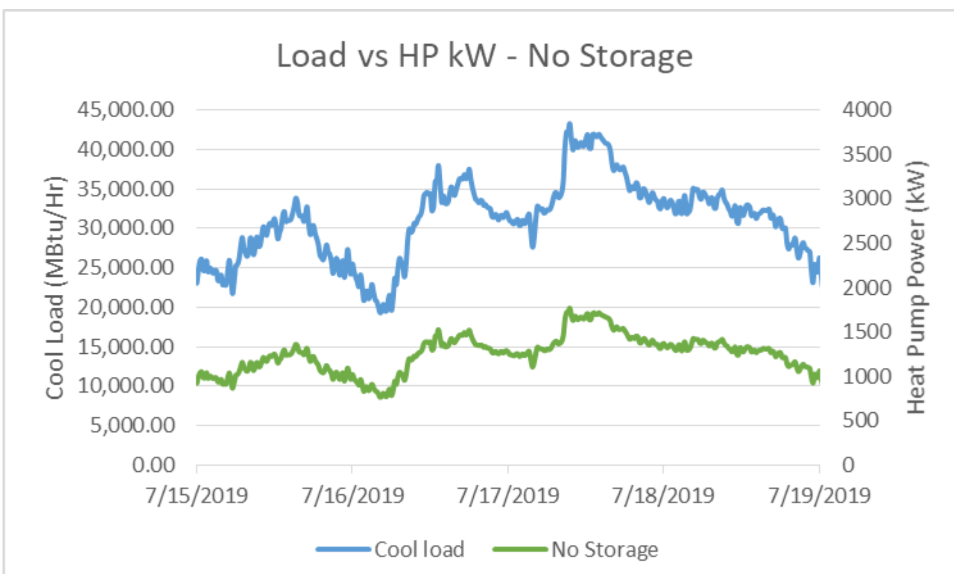


Figure 11: Heat Pump Power vs Cooling Load

The addition of storage, however, shifts the heating or cooling load, and thus shifts the heat pump power draw. Figures 12 through 15 below show the different dispatch strategies and their respective heat pump power compared to the case with no storage, for both the heating and cooling season.

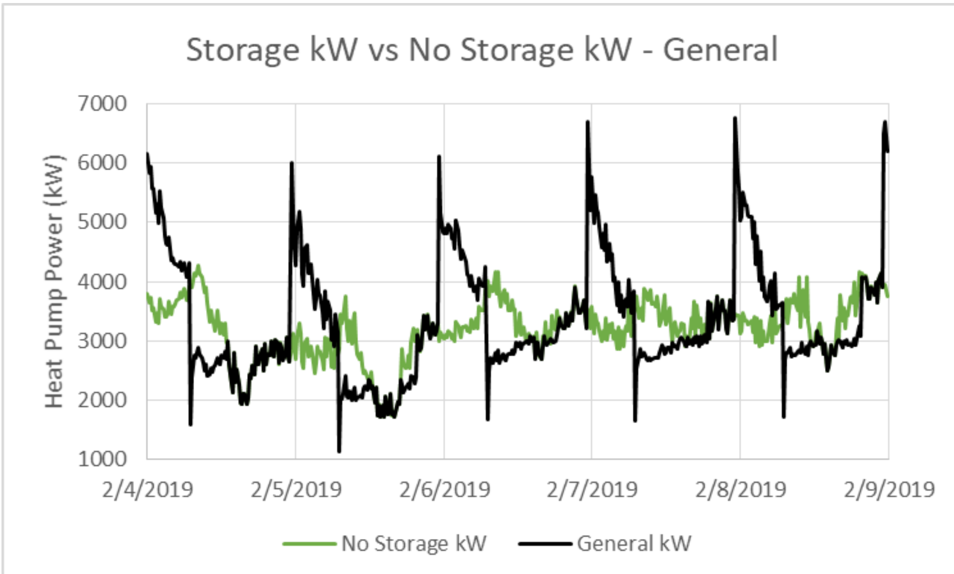


Figure 12: Storage Power vs No Storage Power - General, Heating

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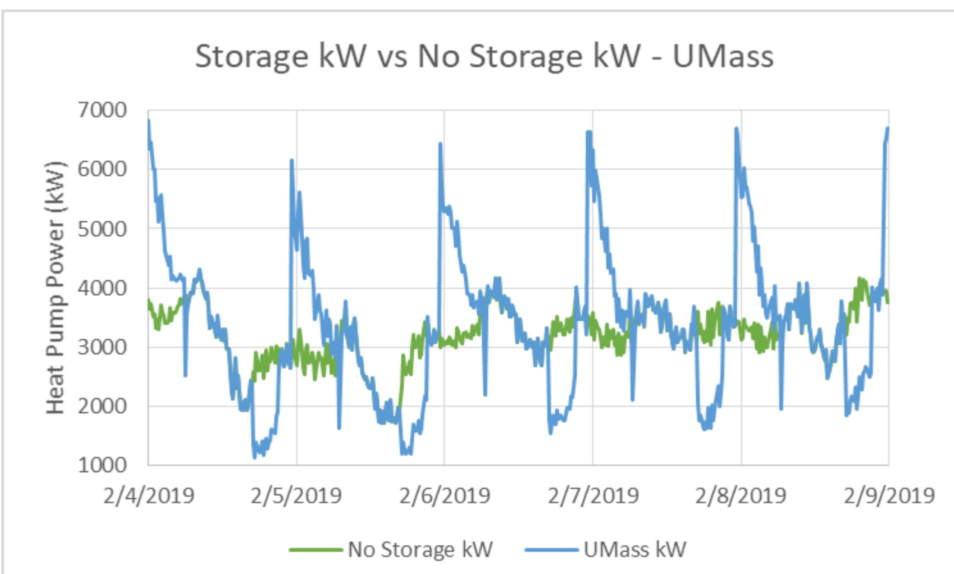

Figure 13: Storage Power vs No Storage Power - UMass, Heating

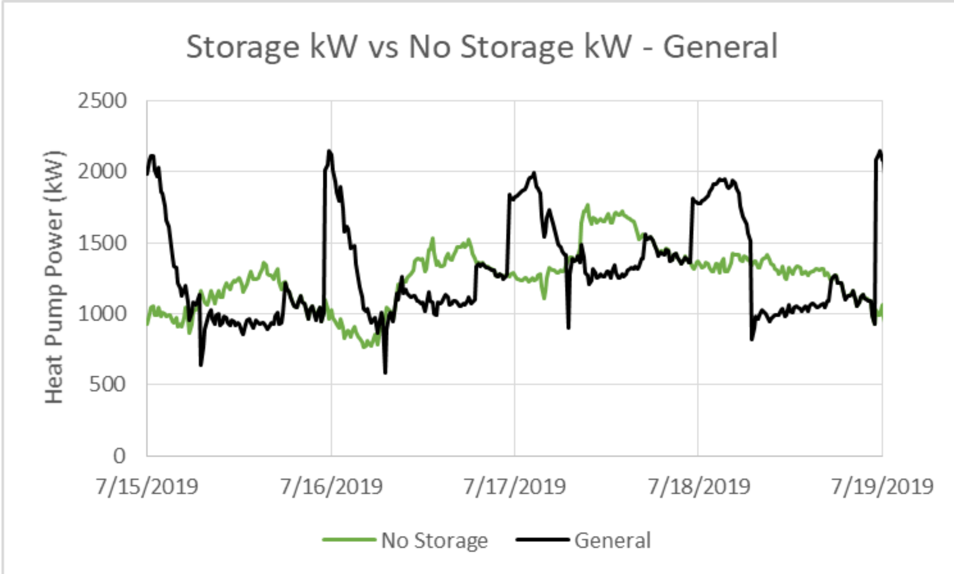

Figure 14: Storage Power vs No Storage Power - General, Cooling

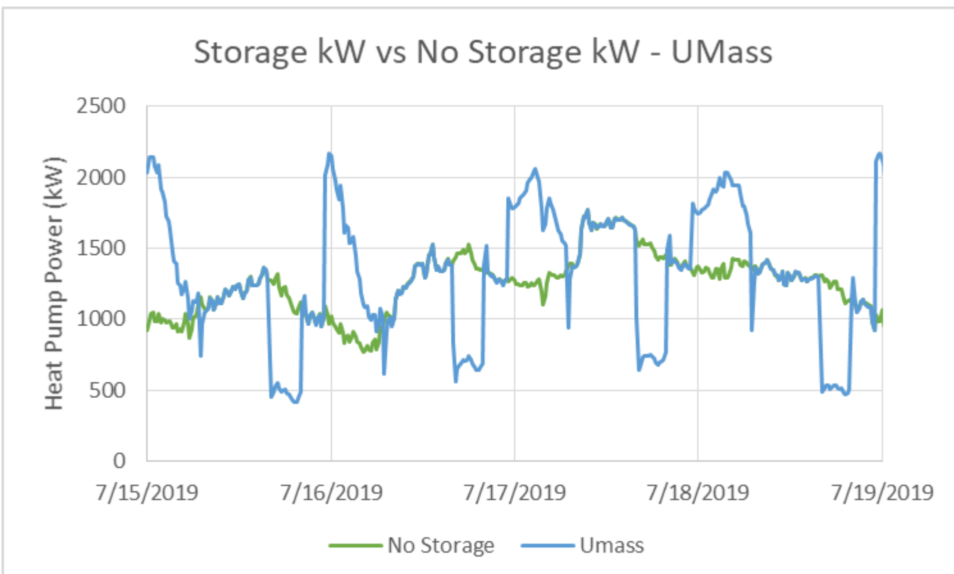

Figure 15: Storage Power vs No Storage Power - UMass, Cooling

As shown above, the charging strategy can result in significant peaks during off hours. This sort of operation could invoke a 24 hour demand window, due to the severity of the spikes. Adjusting the charging strategy to mitigate the charging peaks can be done and is shown below for the UMass case.

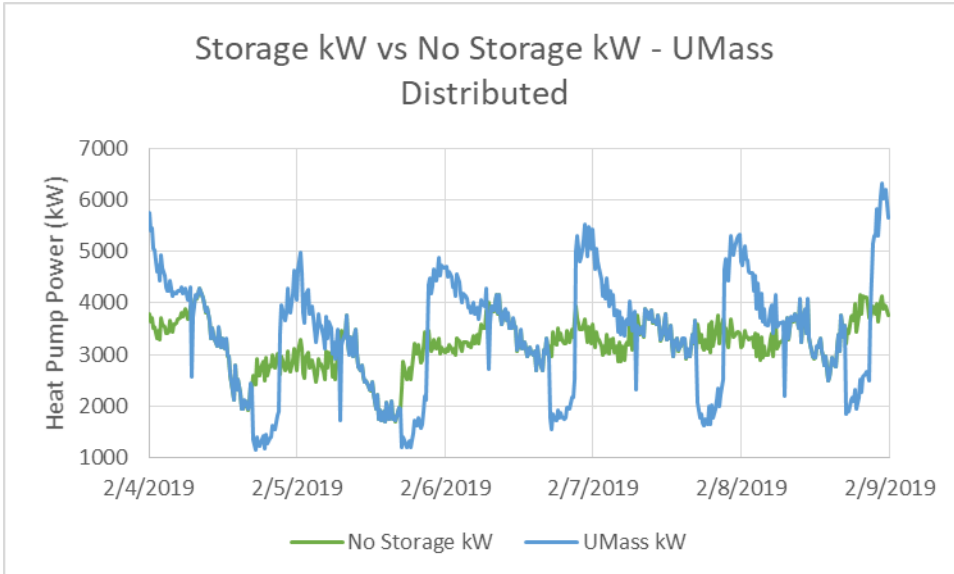

Figure 16: UMass Heating Distributed Charge Peak

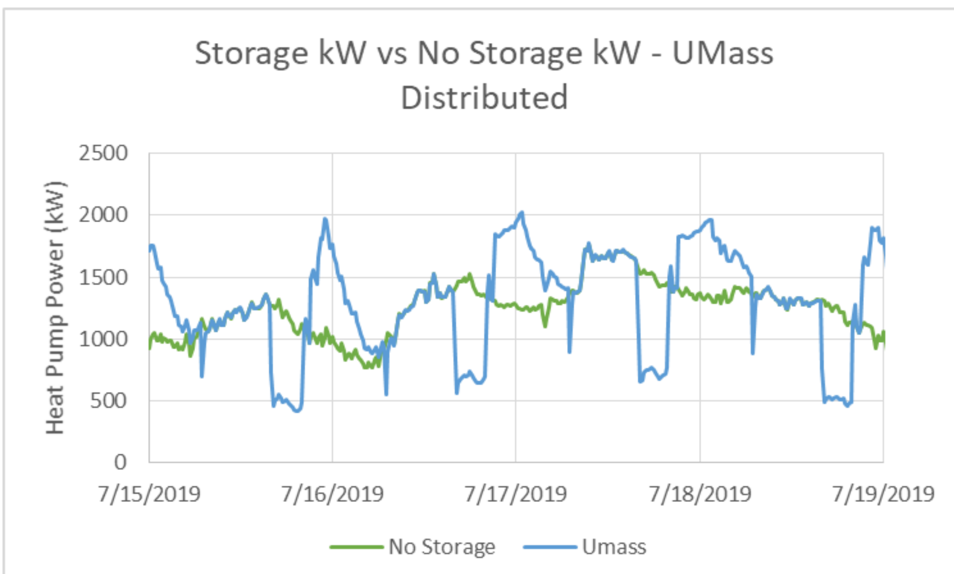

Figure 17: UMass Cooling Distributed Charge Peak

Adjusting the charging strategy, however, accrues an additional penalty of 872,207 kWh, due to increased pumping energy as well as longer time spent at the storage temperature needed for charging.

As indicated, the unique dispatch strategies result in different power profiles for the heat pumps. The UMass case, with the defined peak window, has a consistent daily discharge, which creates a significant reduction compared to the general case, which has a more distributed discharge and thus a lower reduction.

3.7 TRNSYS Simulation

The ground source heat pump system with and without thermal storage was simulated in TRNSYS for an energy comparison. In the case of no storage, the heat pumps worked to maintain a 95°F temperature setpoint for heating and 44°F setpoint for cooling, with the total number of heat pumps and total flowrate determined by the heating or cooling load needed. For simulation purposes, one array of heat pumps was dedicated to the cooling loads, while the other was dedicated to the heating loads. The generated hot or chilled water was then sent to the load and returned to the heat pump after meeting the load. On the source side, water was sent from the heat pumps to the borehole heat exchangers, which calculates the ground temperature and resulting water temperature using the duct storage model that has been previously described. That outlet water is then provided to the heat pumps on the source side. These water temperatures and flowrates are used in conjunction with heat pump data from a manufacturer to examine the heat pump performance. When storage was used, the heat pumps charged the storage during off peak hours. This was done by changing the setpoint and increasing the flowrate for the heat pumps, to fill the storage tank with hot or chilled water. The storage tank is constant volume, so equal amounts of water enter and leave the tank. During charging, the water that leaves the tank bypasses the load and goes directly on return to the heat pumps. During discharging, the water that leaves the tank goes to meet a portion of the load and is replaced with return water from the load. This gives a TRNSYS simulation of a water-to-water ground source heat pump that provides hot or chilled water to a storage tank, to meet a defined heating or cooling load. An image of the TRNSYS model can be found below. Within the model, the yellow represents the source fluid leaving the heat pumps and entering the borehole heat exchangers, and green represents source fluid exiting the heat exchangers and returning to the heat pumps. The red represents the loop dedicated to the heating load, with pink being the hot water storage loop. The blue represents the dedicated cooling loop, with the lighter blue representing the chilled water storage. The model also includes necessary components and functions needed for model operation and data management.

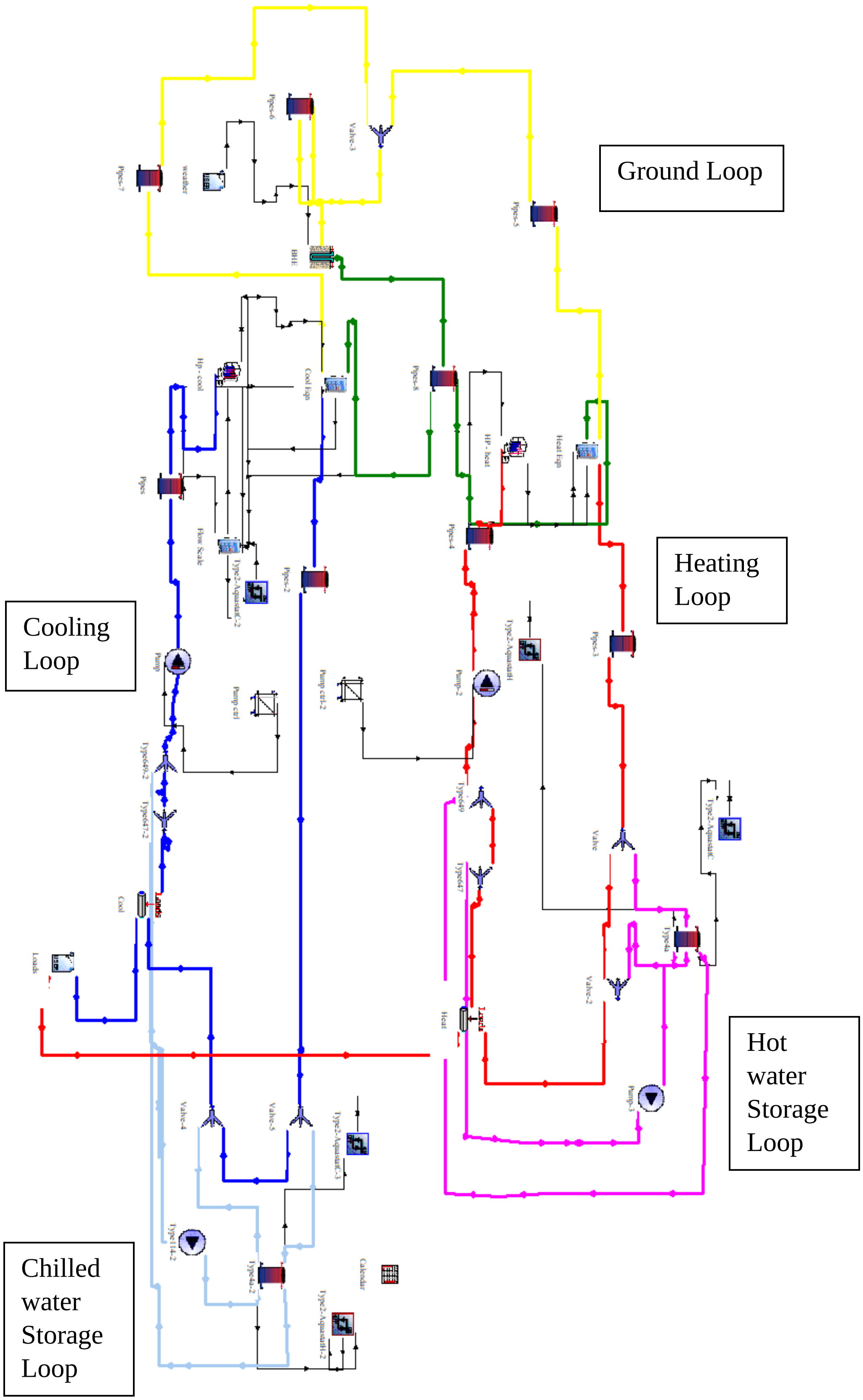

Figure 18: TRNSYS Model

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Current System

The current heating and cooling systems for the outlined campus buildings define the base case for comparison to the heat pump system with TES. The buildings are cooled by a variety of air-cooled and water-cooled chillers, which have an average EER of 11.1, which is equivalent to a COP of 3.25 [33]. Heating is achieved by steam distribution from the UMass CHP plant, which burns primarily natural gas, along with liquified natural gas and ultra-low sulfur diesel when needed during the winter months. The plant also generates electricity while meeting the campus heating load. The plant consists of a combined heat and power (CHP) system including a 10 MW combustion gas turbine, 4 MW low-pressure steam turbine, a 2 MW high-pressure steam turbine, and a heat recovery steam generator (HRSG). Exhaust from the turbine is routed to the HRSG capable of producing 37,000 pounds per hour (PPH) of steam at 600 PSI without any additional firing, and up to 100,000 PPH with additional duct burners. The steam enters the 2 MW high-pressure steam turbine, is expanded to 200 psi, and is then routed to the high-pressure campus steam line and to the 4 MW low-pressure steam turbine. Steam exits the low-pressure turbine at about 17 PSI and is routed to the low-pressure campus steam line. Single-effect absorption chillers, which run off of the low-pressure steam line, produce up to 5,730 tons of cooling. There are three additional boilers on-site, each capable of producing 125,000 PPH of steam. One of these boilers (HPB) is designed to run at 600 PSI, and the other two at 200 PSI (LPB1 and LPB2). The CHP plant generates approximately 66% of the annual electric load for the campus, and thus it currently generates 66% of the electric load for the defined buildings. The CTG produces waste heat as a byproduct of its electricity generation, which is recovered by the HRSG to meet part of the campus heating load. Further heating is provided by duct burners on the HRSG, as well as the low and high-pressure boilers. Fuel is required by the CTG to produce electricity, as well as for the HRSG and boilers to produce heat. The efficiencies of these systems are defined below [34]

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

$$\eta_{\mathrm{heat}} = \frac{Q_{\mathrm{additional\ heat}}}{Q_{\mathrm{fuel,heat}}}$$

Where η_{CTG} is the electric generation efficiency of the CTG, $E_{\mathrm{electricity,CTG}}$ is the amount of electricity produced, $Q_{\mathrm{fuel,CTG}}$ is the amount of energy in fuel used by the CTG, η_{heat} is the efficiency of the heating components, $Q_{\mathrm{additional\ heat}}$ is the heating needed beyond that recovered from the CTG, and $Q_{\mathrm{fuel,heat}}$ is the amount of energy in fuel used by the additional heating components.

Using production data from the CHP plant for 2019, the efficiencies described above were determined. For the year, the average efficiencies were η_{CTG} = 28.2% and η_{heat} = 85.9%. This average heating efficiency is a weighted average efficiency for the 4 supplementary heating components, which are the duct burners on the HRSG along with the 3 packaged boilers. The average efficiencies during additional firing are η_{HRSG} = 84.7% for the HRSG, and η_{Boilers} = 87.8% for the 3 packaged boilers. Using these efficiencies and the electric and heating loads of the building profile, the fuel required by the CHP to serve this portion of the campus was found and is shown in Table 8.

4.2 Proposed Heat Pump System Layout

For both heat pump cases, it is assumed that the load is met by a distributed, terminal heat pump system, where multiple small heat pumps provide heating and cooling to distinct HVAC zones throughout all the buildings. This is a commonly used system layout, and notably is how the UMass Police Station utilizes ground source heat pumps for their heating and cooling needs. To meet the described heating and cooling loads, a system of 466 heat pumps with a nominal capacity of 20 tons is needed. With hot water setpoints of 95°F and storage temperature of 100°F, and chilled water setpoints of 44°F and 40°F, the average COP_{Heat} =4.24 and the average COP_{Cool} = 7.11 for the year. Since the load profile is so heavily imbalanced towards the heating load, the heat pump system is sized based on the peak heating load. The cooling load only requires 227 heat pumps, however that is insufficient to meet the full heating load. Using average costs reported by the MassCEC [31] and similar large institutional installations [30], it was determined that an average cost of $3,517.65/ton can be used for the installation cost of the water-to-water heat pumps. Therefore, the total installation cost for the 466 heat pump array comes to $32,784,498. When considered with the installation cost of $43,335,360 for the borehole heat exchanger that is described in Chapter 3.5, the total system installation cost comes to $76,119,858.

4.3 Energy Comparison of Storage, No Storage, and Current Case

The first relevant metric for comparison of the different case is the overall annual energy usage for the defined systems. Total energy consumption is one of the major drivers of the system cost for these systems, and thus it is necessary to examine the addition of storage will impact overall electric usage. Storage incurs an increase in total electric usage due to the inherent inefficiencies of storing energy, but that increase corresponds to a reduction in peak demand that is defined further in Chapter 4.4.

Using the described TRNSYS model, the electric consumption of the heat pumps both with and without storage can be found. Similarly, TRNSYS can provide the energy used by the associated water pumps needed for this system, to provide an overall view of the electricity usage of the proposed system. The conventional case energy usage is defined as the amount of fuel input into the CHP to meet the heating load, as well as electricity used to power the chillers to meet the cooling load. The conventional case fuel and electric usage, as well as the no storage case electric usage, do not change from the UMass rate case to the generalized rate case, as the different demand structure only affects the storage charge and discharge strategy. The heat pump cases energy use is defined as the electric consumption of the heat pumps needed to meet the heating and cooling loads, along with the additional pumping energy needed to utilize water-to-water ground source heat pumps. A table summarizing the different cases can be found in Chapter 3.2.

Both the UMass case and general case use a baseline of 95F hot water supply temperature and 44F chilled water supply temperature, with a 1,000,000 gallon storage tank at a 5F temperature differential for the storage analysis. The results in Figures 19 show cooling energy input for each of the 4 cases, which is the electricity needed by the heat pumps or conventional chillers to meet the defined cooling load. Figure 20 shows the heating energy input for all cases in kWh, with the electrified cases using electricity as the energy input and the conventional case using CHP fuel as input. Figure 21 summarizes the additional pumping energy needed for each of the electrified cases, as water-to-water heat pumps require significant pumping for operation that is not necessary under the conventional case. Tables 8 and 9 show the respective comparative summary of the UMass discharge strategy case and the general strategy case versus the CHP and no storage case.

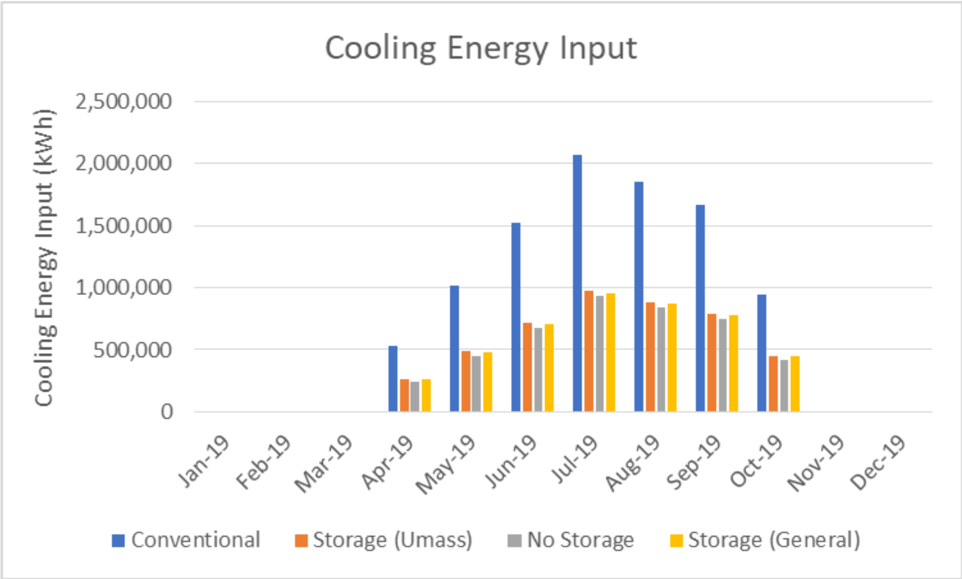

Figure 19: Cooling Energy Input

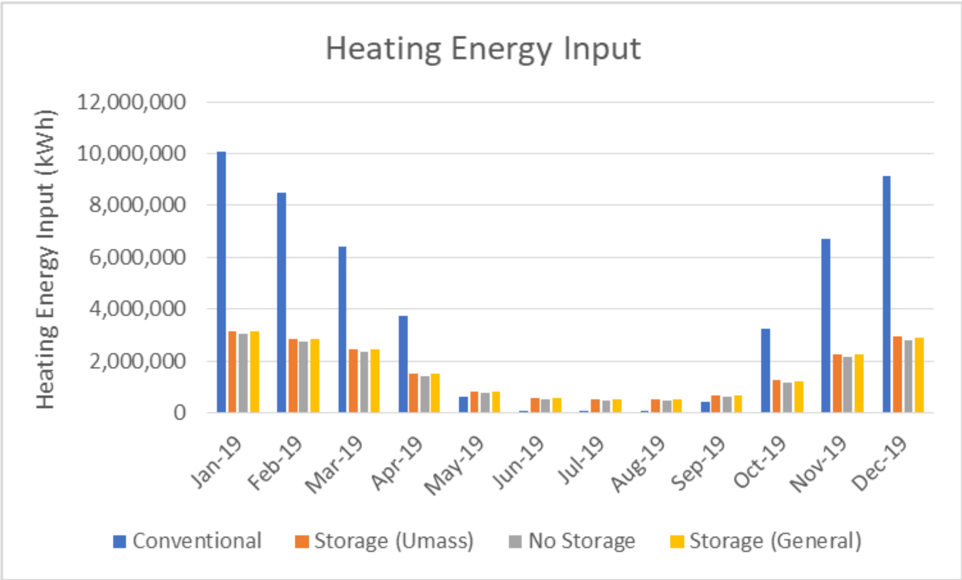

Figure 20: Heating Energy Input

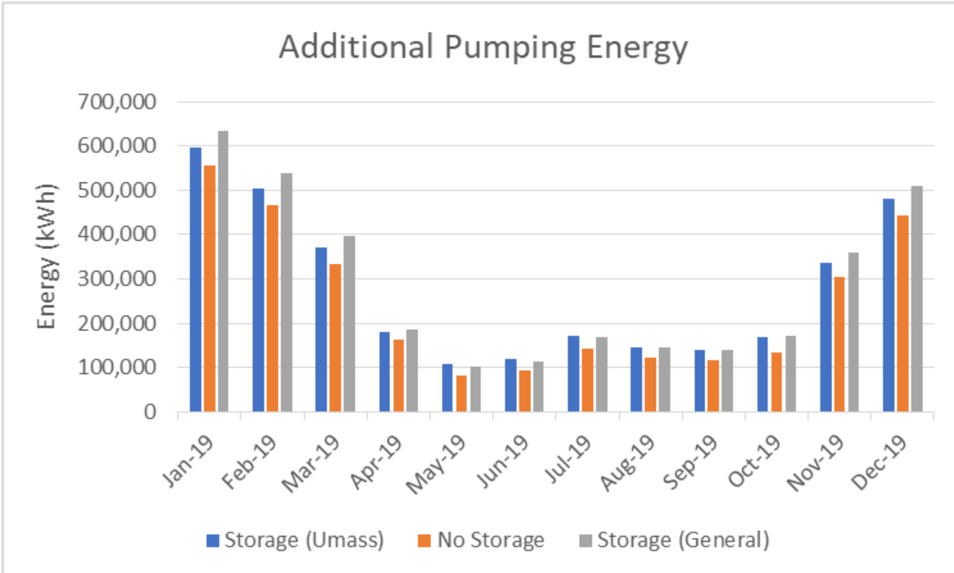

Figure 21: Additional Pumping Energy Input

Month	Heating Load (MMBtu)	Heating Energy Input (kWh)						Cooling Load (MMBtu)	Cooling Electricity (kWh)				Additional Pumping Electricity (kWh)		
					Base										
		Case 1	Case 2	Case 3	Heating Fuel	Heat Recovery	Extra Heat		Case 1	Case 2	Case 3	Base	Case 1	Case 2	Case 3
Jan	42,708	3,123,268	3,025,288	3,123,268	10,431,917	3,631,699	0	0	0	0	0	0	149,217	139,115	149,217
Feb	37,255	2,834,792	2,726,630	2,834,792	8,739,673	3,414,695	0	0	0	0	0	0	126,136	116,682	126,136
Mar	32,125	2,438,273	2,324,398	2,438,273	6,639,154	3,687,789	-2,601	0	0	0	0	0	92,680	83,115	92,680
Apr	20,367	1,487,127	1,405,898	1,487,127	3,823,680	2,625,514	-21,964	5,860	267,637	237,040	267,637	527,361	45,023	40,353	45,023
May	11,301	808,773	745,693	808,773	638,493	3,164,689	-423,096	11,267	486,242	449,628	486,242	1,014,045	26,821	20,394	26,821
Jun	7,783	543,733	495,194	543,733	61,499	2,536,834	-306,540	16,852	715,469	672,217	715,469	1,516,682	29,521	23,223	29,521
Jul	7,712	526,056	478,857	526,056	83,326	2,869,031	-681,348	22,935	968,419	926,528	968,419	2,064,145	43,112	35,811	43,112
Aug	7,852	532,910	485,650	532,910	36,670	2,760,469	-489,707	20,545	883,316	834,386	883,316	1,849,021	36,609	30,215	36,609
Sep	9,599	646,784	596,041	646,784	282,439	2,794,419	-220,473	18,478	791,066	745,934	791,066	1,662,985	35,213	29,309	35,213
Oct	17,995	1,232,942	1,163,653	1,232,942	3,331,131	2,419,385	-57,126	10,432	451,215	416,866	451,215	940,274	42,422	33,736	42,422
Nov	30,790	2,250,576	2,146,955	2,250,576	6,933,690	2,958,362	-12,613	0	0	0	0	0	84,092	76,072	84,092
Dec	37,977	2,908,003	2,787,456	2,908,003	9,420,981	2,958,987	0	0	0	0	0	0	120,277	110,817	120,277
Total:	**263,464**	**19,333,237**	**18,381,713**	**19,333,237**	**50,422,652**	**35,821,874**	**-2,215,468**	**106,369**	**4,563,364**	**4,282,599**	**4,563,364**	**9,574,513**	**831,123**	**738,842**	**831,123**

Month	CHP Generated Electricity (kWh)		CHP Fuel Used for Electric Generation (kWh)		Total Purchased Electricity On Peak (kWh)				Total Purchased Electricity Off Peak (kWh)				Total Fuel Usage (MMBtu)	
	Case 3	Base	Case 3	Base	Case 1	Case 2	Case 3	Base	Case 1	Case 2	Case 3	Base	Case 3	Base
Jan	2,110,236	2,110,236	7,818,660	7,818,660	3,317,108	3,469,621	2,507,622	417,008	3,152,704	2,892,109	1,851,954	670,084	26,677	62,271
Feb	2,027,878	2,027,878	7,395,207	7,395,207	3,115,052	3,256,850	2,339,988	399,275	2,918,418	2,659,005	1,665,604	645,389	25,232	55,052
Mar	2,137,549	2,137,549	7,934,137	7,934,137	2,900,381	3,036,897	2,101,613	411,487	2,869,283	2,609,327	1,530,502	689,675	27,071	49,714
Apr	1,565,034	1,729,230	5,323,511	5,856,099	2,328,802	2,410,711	1,725,189	655,939	2,244,920	2,046,514	1,283,499	916,126	18,164	32,937
May	1,686,712	2,032,632	5,854,371	7,006,994	1,624,591	1,762,651	1,015,493	401,136	1,762,944	1,518,764	685,330	645,977	19,975	24,347
Jun	1,249,770	1,773,874	4,085,841	5,761,353	1,129,812	1,278,957	691,028	365,222	1,329,918	1,082,683	518,932	548,592	13,941	18,601
Jul	1,350,680	2,051,158	4,328,076	6,560,795	1,214,907	1,377,959	743,606	437,050	1,428,604	1,169,161	549,225	681,860	14,767	19,956
Aug	1,351,033	1,979,381	4,325,848	6,318,377	1,168,570	1,351,941	717,931	392,436	1,434,305	1,148,351	533,910	627,246	14,760	19,694
Sep	1,423,965	1,992,032	4,576,263	6,384,392	1,371,680	1,539,441	853,626	418,246	1,456,629	1,187,088	550,717	607,952	15,614	21,852
Oct	1,342,410	1,613,885	4,526,276	5,416,754	1,833,805	1,999,863	1,294,934	545,482	1,898,852	1,620,470	1,095,313	786,642	15,444	29,619
Nov	1,778,318	1,778,318	6,428,369	6,428,369	2,528,595	2,698,028	1,915,430	315,873	2,500,495	2,219,420	1,335,341	600,231	21,934	45,540
Dec	1,817,817	1,817,817	6,468,850	6,468,850	2,965,275	3,118,102	2,231,884	377,808	2,817,274	2,534,439	1,732,849	558,643	22,072	54,216
Total:	**19,841,403**	**23,043,991**	**69,065,408**	**79,349,986**	**25,498,578**	**27,301,021**	**18,138,344**	**5,136,962**	**25,814,346**	**22,687,331**	**13,333,177**	**7,978,417**	**235,651**	**433,800**

Table 8: Energy Usage - UMass

Month	Heating Load (MMBtu)	Heating Energy Input (kWh)		Cooling Load (MMBtu)	Cooling Electricity (kWh)		Additional Pumping Electricity (kWh)		Building Fixed Electric Load (kWh)	Total Purchased Electricity On Peak (kWh)		Total Purchased Electricity Off Peak (kWh)	
		Case 4	Case 5		Case 4	Case 5	Case 4	Case 5		Case 4	Case 5	Case 4	Case 5
Jan	42,708	3,123,257	3,025,288	0	0	0	158,106	139,115	3,197,327	3,269,884	3,469,621	3,208,806	2,892,109
Feb	37,255	2,829,898	2,726,630	0	0	0	134,595	116,682	3,072,543	3,065,510	3,256,850	2,971,527	2,659,005
Mar	32,125	2,430,036	2,324,398	0	0	0	99,396	83,115	3,238,711	2,846,505	3,036,897	2,921,638	2,609,327
Apr	20,367	1,483,972	1,405,898	5,860	265,718	237,040	46,688	40,353	2,773,934	2,228,256	2,410,711	2,342,057	2,046,514
May	11,301	810,719	745,693	11,267	480,177	449,628	25,718	20,394	2,065,700	1,574,538	1,762,651	1,807,776	1,518,764
Jun	7,783	547,015	495,194	16,852	703,979	672,217	28,106	23,223	1,171,006	1,091,357	1,278,957	1,358,748	1,082,683
Jul	7,712	528,726	478,857	22,935	954,527	926,528	41,890	35,811	1,105,924	1,178,385	1,377,959	1,452,682	1,169,161
Aug	7,852	536,016	485,650	20,545	867,714	834,386	36,057	30,215	1,150,041	1,153,287	1,351,941	1,436,541	1,148,351
Sep	9,599	649,099	596,041	18,478	777,440	745,934	34,830	29,309	1,355,246	1,338,639	1,539,441	1,477,976	1,187,088
Oct	17,995	1,229,748	1,163,653	10,432	446,456	416,866	42,659	33,736	2,006,078	1,820,832	1,999,863	1,904,110	1,620,470
Nov	30,790	2,243,482	2,146,955	0	0	0	89,506	76,072	2,694,078	2,517,195	2,698,028	2,510,214	2,219,420
Dec	37,977	2,898,348	2,787,456	0	0	0	127,681	110,817	2,754,268	2,909,627	3,118,102	2,870,671	2,534,439
Total:	**263,464**	**19,310,316**	**18,381,713**	**106,369**	**4,496,011**	**4,282,599**	**865,234**	**738,842**	**26,584,856**	**24,994,015**	**27,301,021**	**26,262,746**	**22,687,331**

Table 9: Energy Use - General

As shown, the addition of a thermal storage system results in an increase in energy usage compared to a no storage system. The highlighted columns represent the heating and cooling energy input along with additional pumping energy for the storage (Case 1, Case 4) and no storage (Case 2, Case 5) cases across the different rate structures. The addition of storage incurs an increase in heating and cooling energy due to inefficiencies in the storage medium, and storage allows increases the pumping energy due to pumps associated with the storage medium. The overall energy increase is expected for the use of a storage system and is offset by the corresponding reduction in peak demand.

4.4 Peak Demand Comparison of Storage, No Storage, and Current Case

Energy consumption is only one portion of the profile that needs to be examined when evaluating an energy storage application. Figures 22 and 23 below shows the comparison of the peak demand in the CHP, no storage, and storage case for both the UMass rate structure and the generalized rate structure. These figures show the charged monthly peak demand for each of the cases, which corresponds to the defined peak hours in the UMass case, or the maximum demand during the on-peak window in the generalized case.

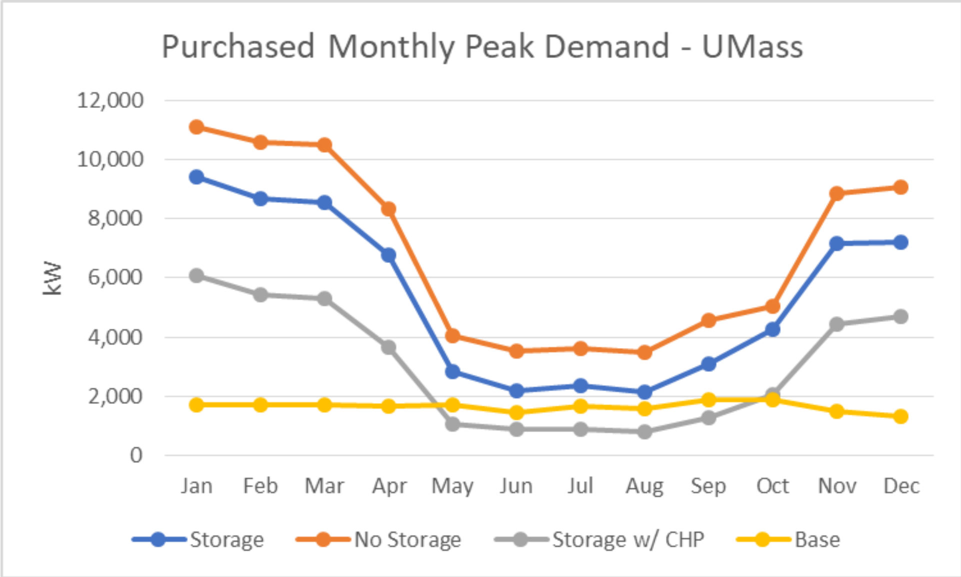

Figure 22: Purchased Monthly Peak Demand - UMass

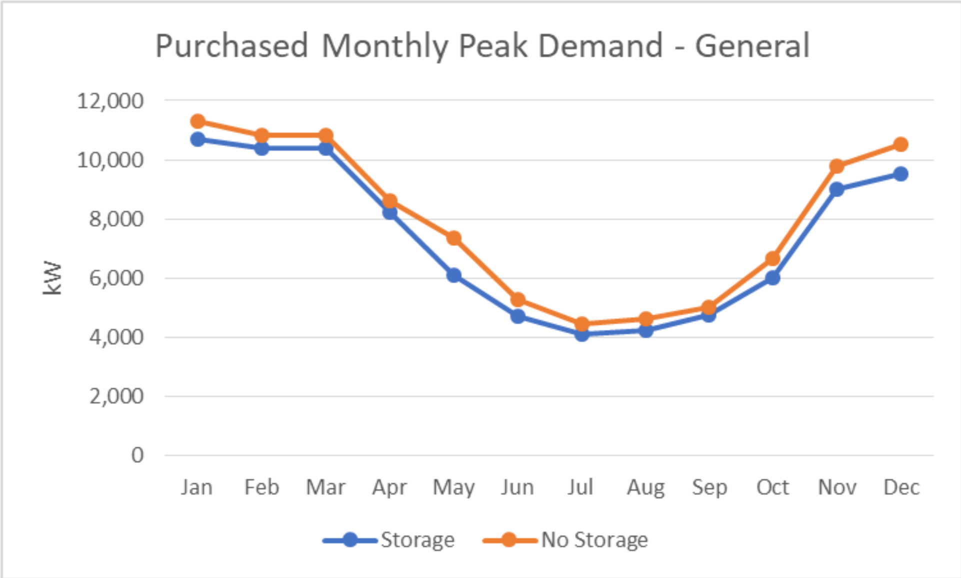

Figure 23: Purchased Monthly Peak Demand - General

As can be seen above, the addition of a thermal storage system allows for a reduction in the monthly peak demand. In the UMass case, the reduction is much greater, with an average monthly reduction of 1,503 kW with storage, as opposed to a 595 kW monthly average in the generalized case. This is due to the differences in discharge strategy between the rate structures, for in the UMass case the known demand hour allows for a concentrated discharge, instead of the distributed distribution that happens in the generalized case. Similarly, the purchased demand under the current CHP case changes with the rate structure. This corresponds to shutdowns of the CHP during the year, during which 100% of the campus electric load will be purchased from the grid. This does not affect the demand structure under the UMass case, due to the shutdowns happening at a different time than the defined demand hours. Furthermore, it is noteworthy that Case 3, which represents the phased transition that maintains CHP generation, actually can reduce peak demand in the summer months relative to the traditional CHP case. This is due to the modern heat pumps being more efficient at cooling than the current UMass chillers, which allows for the reduction when kept with CHP generation.

Specifically for the UMass case, there is also an annual capacity charge, which relates to the yearly peak on the regional grid. Under the conventional case, that peak capacity is 1,614 kW. The heat pump case without storage results in a capacity charge of 3,155 kW and the addition of storage reduces that to 1,933 kW. The phased transition, which has both heat pumps and CHP generation, has a peak capacity of only 733 kW.

4.5 Overall Emissions Comparison

The carbon footprint and other emissions output related to the heat pump cases come from the energy sources that generate the electricity to run the heat pumps. ISO New England, the grid operator that serves the UMass region, provides emissions factors for electricity, which can be used to calculate the emissions associated with the heat pump cases. These factors are as follows [35]:

	CO_2 (lb/kWh)	NO_x (lb/kWh)	SO_2 (lb/kWh)
ISO-NE Electricity	0.81700	0.00048	0.00012

Table 10: Average Emissions Factor for grid electricity in Massachusetts

For an emissions comparison to the current CHP, emissions factors for the UMass plant from the 2019 Massachusetts Greenhouse Gas report were used. The CHP utilizes a selective catalytic reduction system to reduce NO_x emissions.

	CO_2 (lb/MMBtu)	NO_x (lb/MMBtu)	SO_2 (lb/MMBtu)
CTG Fuel Input	111.48	0.00943	0.00216

Table 11: Emissions Factors for CHP CTG per MMBtu of Fuel

	CO_2 (lb/MMBtu)	NO_x (lb/MMBtu)	SO_2 (lb/MMBtu)
Boiler Fuel Input	120.44	0.00681	0.00068

Table 12: Emissions Factors for CHP Boilers per MMBtu of Fuel

The cumulative heat pump emissions come from those related to generating the electricity used to power the heat pumps. The conventional case emissions are a combination of the emissions for the fuel to the CTG, the fuel to the boilers for heating, and emissions from the current purchased electricity. The table below shows the yearly emissions for each of the 5 described cases.

System	Heating System CO2 (tons)	Cooling System CO2 (tons)	Pumping System CO2 (tons)	Additional Builiding Electric Usage CO2 (tons)	Total System + Building CO2 (tons)	Total System + Building NOx (lbs)	Total System + Building SO2 (lbs)
Case 1	7,898	1,864	340	10,860	20,961	24,630	6,158
Case 2/5	7,509	1,749	340	10,860	20,458	23,994	5,999
Case 3	7,898	1,864	340	6,869	16,970	17,328	4,286
Case 4	7,888	1,837	353	10,860	20,938	24,603	6,151
Base	20,539	3,911	-	5,830	30,280	10,020	2,276

Table 11: Emissions for all cases

Case 1 and 4, which represent the storage cases with all electricity bought from the grid, have an increase in pollutant emissions relative to the no storage case, due to the increased electricity usage. All electrification cases, however, reduce the amount of carbon emissions relative to the conventional case. This emissions analysis, however, assumes that the carbon and other pollutant intensity is constant throughout the day. The actual emissions factors associated with grid electricity varies throughout the day, and thus there is potential that shifting more demand to off-peak hours could increase the overall emissions profile for the electrified cases. These emissions could also be reduced further by the integration of renewable generation sources, such as wind or solar, to cover some of the electric load and reduce the amount that is purchased from the grid. Furthermore, the impacts of the CHP emissions could be expanded, due to the use of ultra-low sulfur diesel (ULSD) as a fuel in the winter months. The plant utilizes this during very cold periods that result in restrictions on natural gas, and the carbon emissions associated with this fuel type are much greater than natural gas. Additional firing of ULSD could heighten the CO_2 emissions associated with the conventional case, depending on the plant operation. Furthermore, the electrified cases result in an increase in NO_x and SO_2 emissions, caused by the increased purchase of electricity from the grid, where the majority of electricity is produced in fossil fuel power plants. Similarly, Case 3, which maintains some CHP generation, had the lowest associated carbon emissions, due to the higher emissions factors for electricity purchased from the grid than from that generated by the CHP. However, as the grid begins to decarbonize to meet the Massachusetts state target of net zero greenhouse gas emissions by 2050, the emissions associated with purchased electricity will diminish, thus lessening the environmental impacts of the electrified cases.

4.6 Cost Comparison

For the heat pump cases, it was assumed that all electricity was purchased from the grid, at the respective rates described in Chapter 3.2. The heat pump case has three major cost components, being the on peak consumption cost, the off peak consumption cost, and the monthly peak demand cost. Additionally, the UMass rate structure has a fourth component, which is the yearly capacity charge. In the conventional case, the costs stem from the cost of fuel to operate the plant, along with the cost of the additional purchased electricity necessary to meet the campus electric load. A blended fuel cost that accounts for the cost of natural gas as well as fuel oil and ULSD needed to run the plant was used for this analysis. A summary of the cases and rates can be found in Table 2 and Chapter 3.2, and are reshown below

	Rate Structure	System	On Pk $/kWh	Off Pk $/kWh	Demand $/kW	Capacity $/kW	Fuel $/MMBTU
Case 1	UMass	Heat pumps w/ storage	$0.0765	$0.0668	$11.53	$71.66	-
Case 2	UMass	Heat pumps no storage	$0.0765	$0.0668	$11.53	$71.66	-
Case 3	UMass	Heat pumps w/ storage and CHP generation	$0.0765	$0.0668	$11.53	$71.66	$6.44
Case 4	General	Heat pumps w/ storage	$0.1074	$0.0841	$14.94	-	-
Case 5	General	Heat pumps no storage	$0.1074	$0.0841	$14.94	-	-
Base	UMass	Conventional CHP	$0.0765	$0.0668	$11.53	$71.66	$6.44

Table 13 below shows the direct cost comparison between the conventional system, a heat pump system with no storage, and a heat pump system with storage under the UMass rate structure.

Month	Fuel Cost				On Peak Electric Cost				Off Peak Electric Cost			
	Case 1	Case 2	Case 3	Base	Case 1	Case 2	Case 3	Base	Case 1	Case 2	Case 3	Base
Jan	$0	$0	$312,116	$728,552	$328,231	$343,322	$248,132	$41,263	$280,436	$257,256	$164,733	$59,605
Feb	$0	$0	$293,552	$640,472	$298,540	$312,130	$224,260	$38,266	$250,511	$228,244	$142,972	$55,399
Mar	$0	$0	$195,972	$359,883	$236,155	$247,270	$171,117	$33,504	$204,930	$186,363	$109,312	$49,258
Apr	$0	$0	$104,251	$171,851	$176,423	$182,628	$130,695	$49,692	$147,619	$134,573	$84,399	$60,242
May	$0	$0	$108,389	$110,380	$112,636	$122,208	$70,406	$27,812	$104,599	$90,111	$40,662	$38,327
Jun	$0	$0	$89,407	$84,603	$71,489	$80,926	$43,725	$23,109	$70,851	$57,680	$27,646	$29,226
Jul	$0	$0	$106,411	$94,865	$84,941	$96,341	$51,990	$30,557	$85,596	$70,051	$32,907	$40,854
Aug	$0	$0	$102,471	$93,608	$80,498	$93,130	$49,455	$27,033	$84,460	$67,622	$31,440	$36,936
Sep	$0	$0	$97,529	$97,834	$89,237	$100,151	$55,534	$27,210	$80,198	$65,358	$30,321	$33,472
Oct	$0	$0	$85,503	$137,025	$119,027	$129,805	$84,050	$35,406	$104,260	$88,975	$60,140	$43,192
Nov	$0	$0	$123,381	$256,174	$195,407	$208,501	$148,023	$24,410	$168,231	$149,320	$89,840	$40,383
Dec	$0	$0	$181,365	$445,499	$260,846	$274,290	$196,332	$33,235	$219,654	$197,603	$135,105	$43,556
Capacity												
Total:	**$0**	**$0**	**$1,800,347**	**$3,220,745**	**$2,053,432**	**$2,190,704**	**$1,473,720**	**$391,497**	**$1,801,347**	**$1,593,156**	**$949,478**	**$530,450**

Month	Demand Cost				Total Cost			
	Case 1	Case 2	Case 3	Base	Case 1	Case 2	Case 3	Base
Jan	$108,728	$127,983	$70,173	$19,601	**$717,395**	**$728,561**	**$795,153**	**$849,021**
Feb	$100,150	$121,895	$62,632	$19,601	**$649,201**	**$662,269**	**$723,416**	**$753,738**
Mar	$98,605	$121,353	$61,234	$19,601	**$539,689**	**$554,987**	**$537,635**	**$462,246**
Apr	$78,047	$95,930	$42,174	$19,179	**$402,089**	**$413,130**	**$361,519**	**$300,964**
May	$32,445	$46,639	$12,057	$19,601	**$249,681**	**$258,958**	**$231,514**	**$196,120**
Jun	$25,251	$40,609	$10,191	$16,629	**$167,591**	**$179,215**	**$170,969**	**$153,568**
Jul	$26,934	$41,877	$10,333	$19,036	**$197,472**	**$208,270**	**$201,641**	**$185,312**
Aug	$24,513	$39,905	$9,282	$18,271	**$189,471**	**$200,657**	**$192,648**	**$175,848**
Sep	$35,893	$52,542	$14,476	$21,766	**$205,328**	**$218,051**	**$197,861**	**$180,282**
Oct	$49,141	$58,146	$23,599	$21,783	**$272,428**	**$276,926**	**$253,293**	**$237,405**
Nov	$82,474	$102,029	$50,997	$17,050	**$446,112**	**$459,850**	**$412,241**	**$338,017**
Dec	$83,143	$104,427	$54,023	$15,264	**$563,644**	**$576,320**	**$566,825**	**$537,553**
Capacity	$138,534	$226,071	$52,508	$115,660	**$138,534**	**$226,071**	**$52,508**	**$115,660**
Total:	**$883,856**	**$1,179,405**	**$473,679**	**$343,043**	**$4,738,635**	**$4,963,265**	**$4,697,224**	**$4,485,735**

Table 13: System Operating Costs - UMass

Both heat pump cases, with and without storage, are more operationally expensive than the current system. The storage case (Case 1), however, saves approximately 4.5% over the no storage case (Case 2), due to the reduction in peak demand and capacity charges. Likewise, the phased case (Case 3) that maintains CHP generation is able to reduce operating cost by 5.4% versus the no storage case, and about 1% from the storage case where all electricity is purchased from the grid. It is also necessary to quantify the cost of carbon reduction with the electrified systems. For the UMass cases, the associated cost per ton of CO_2 reduction can be seen in the table below, and Figure 24 shows the associated CO_2 emissions versus the overall system operating cost.

	Rate Structure	System	Cost Increase ($)	CO2 Savings (Tons)	CO2 Cost ($/Ton)
Case 1	UMass	Heat pumps w/ storage	$252,900	9,319	$27.14
Case 2	UMass	Heat pumps no storage	$477,530	9,823	$48.62
Case 3	UMass	Heat pumps w/ storage and CHP generation	$211,490	13,310	$15.89

Table 14: Cost per Ton of CO2 Reduced

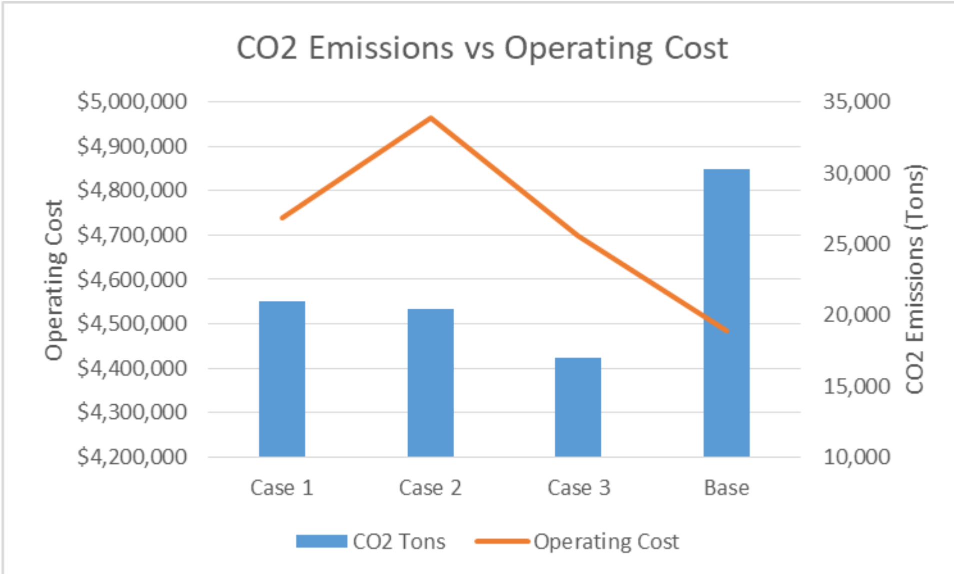

Figure 24: CO2 Emissions vs Operating Cost

Table 15 below shows a similar cost analysis using the generalized electric rate structure and discharge method.

Month	On Peak Electric Cost		Off Peak Electric Cost		Demand Cost		Total Cost	
	Case 4	Case 5	Case 4	Case 5	Case 4	Case 5	Case 4	Case 5
Jan	$630,695	$669,220	$487,161	$439,080	$159,798	$169,046	**$1,277,654**	**$1,277,347**
Feb	$401,674	$426,745	$355,365	$317,990	$155,077	$161,830	**$912,116**	**$906,566**
Mar	$284,565	$303,599	$280,156	$250,208	$155,286	$161,755	**$720,007**	**$715,562**
Apr	$208,832	$225,932	$189,871	$165,911	$122,956	$129,037	**$521,659**	**$520,880**
May	$137,268	$153,668	$128,298	$107,787	$91,448	$109,824	**$357,014**	**$371,279**
Jun	$85,311	$99,976	$77,095	$61,431	$70,606	$78,614	**$233,013**	**$240,022**
Jul	$105,489	$123,355	$102,458	$82,461	$61,314	$66,857	**$269,260**	**$272,672**
Aug	$114,014	$133,653	$85,776	$68,568	$63,450	$69,038	**$263,240**	**$271,259**
Sep	$110,438	$127,004	$97,635	$78,419	$70,935	$75,193	**$279,008**	**$280,616**
Oct	$146,486	$160,889	$119,940	$102,073	$89,610	$99,515	**$356,036**	**$362,478**
Nov	$286,381	$306,955	$185,354	$163,882	$134,789	$146,532	**$606,524**	**$617,368**
Dec	$409,501	$438,842	$288,560	$254,762	$142,617	$157,363	**$840,678**	**$850,967**
Total:	**$2,920,655**	**$3,169,837**	**$2,397,668**	**$2,092,573**	**$1,317,887**	**$1,424,604**	**$6,636,210**	**$6,687,014**

Table 15: System Operating Costs – General

In the general scenario, the storage case (Case 4) only saves about 1% relative to the no storage case (Case 5). This is primarily due to the distributed demand profile, which lessens the overall demand reduction in the generalized case. Similarly, the general case does not include a capacity charge, which represents a significant portion of the savings in the UMass case. A summary of all the cases, and their respective rate structures and operating costs, can be found in Table 16.

	Rate Structure	System	Operating Cost	% Increase from Base
Case 1	UMass	Heat pumps w/ storage	$4,738,635	5.64%
Case 2	UMass	Heat pumps no storage	$4,963,265	10.65%
Case 3	UMass	Heat pumps w/ storage and CHP generation	$4,697,224	4.71%
Case 4	General	Heat pumps w/ storage	$6,636,210	47.94%
Case 5	General	Heat pumps no storage	$6,687,014	49.07%
Base	UMass	Conventional CHP	$4,485,735	-

Table 16: Summary of Total System Operating Costs

4.7 Sensitivity Analysis

While the storage case has cost benefits versus the non-storage case, there a litany of factors that influence that analysis. Heat pump operation, electricity and natural gas costs, storage size, and technological advancements could all impact that cost comparison, and thus change the internal calculus for a facility that wants to adopt an electrified heating system. Therefore, it is necessary to do a sensitivity analysis of these major components, in order to develop a broader understanding of how electrified heating and thermal storage may fare currently and into the future.

The sensitivity analyses revolve around the UMass rate case, with the initial analysis examining the impacts of different setpoint temperatures and storage temperature differentials on the system cost. The figure shows operating costs for the no storage case (no st), along with two examples for the storage cases, with one case having a storage delta T of 5 and the other having a storage delta T of 10. The storage delta T defines the difference between the setpoint and storage temperature – for example, st – 5T at a hot water setpoint of 90°F means that the storage is charged to 95°F.

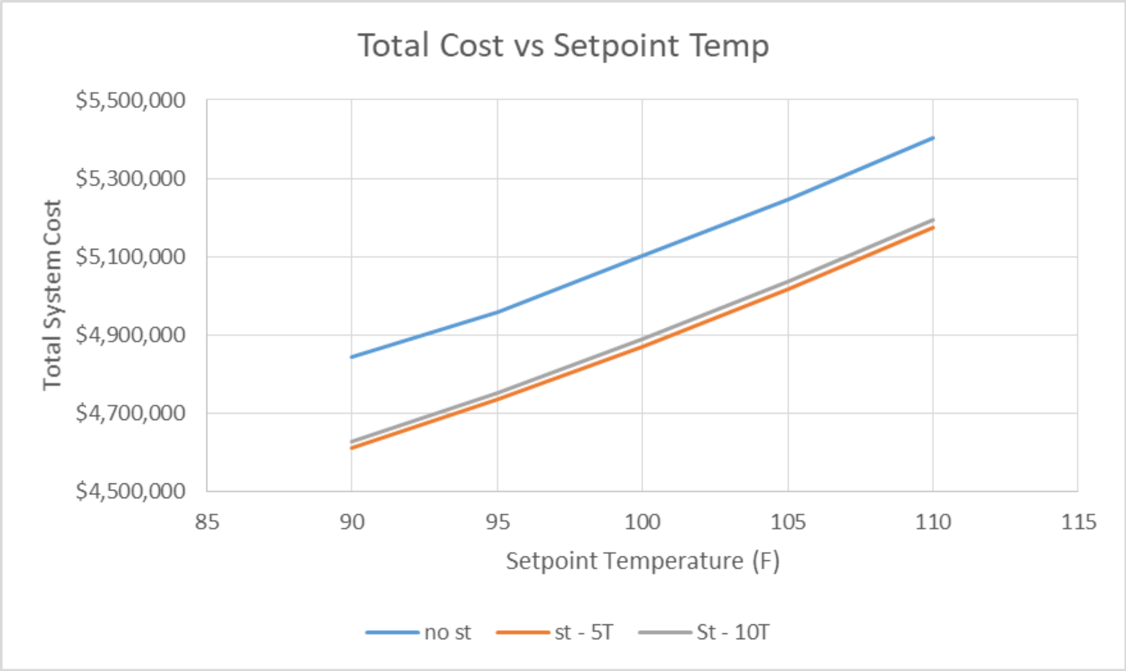

Figure 25: System Cost versus Setpoint Temperature and Storage Delta T

The increase in setpoint temperature corresponds to an increase in system cost, due to an increase in electric usage by the heat pumps. The COP of the heat pumps goes down at higher outlet temperatures, and thus creates the cost increase shown. Similarly, an increase in storage temperature differential has a slight cost increase as well. Charging to a higher temperature still requires a higher temperature output, which lowers the efficiency of the heat pumps and thus increases total cost. Therefore, to have the most efficient operation of the heat pump system, a lower hot water supply temperature is preferred. However, the implications of low temperature hot water heating are wide, and the building space impacts and usability of that type of water may vary depending on the building profile.

The next sensitivity analysis in Table 16 looks at the impacts of an increase in storage size, and how that would affect the cost savings versus the non-storage scenario. These are then used with install costs taken from *RSMeans Mechanical Cost Data* [36] to examine what the simple payback is for different storage volumes.

Storage Volume (gal)	Operation Cost	Savings	Install cost	Payback (Yrs)
500,000	$4,816,380	$141,529	$917,000	6.48
1,000,000	$4,733,995	$223,914	$1,451,000	6.48
1,500,000	$4,678,081	$279,828	$1,873,500	6.70
2,000,000	$4,698,787	$259,122	$2,296,000	8.86

Table 17: Storage Volume Cost Sensitivity

An increase in storage volume beyond 1,000,000 gallons incurs an increase in the payback for installation, due to an increase in the pumping energy necessary to charge and discharge the storage, along with an increase in hours spent at higher temperatures for the charging of the storage medium. At higher storage volumes, it becomes more difficult to fully charge the storage tank, as there is an upper limit to the heat pump array output. This partial charging also contributes to the diminished cost effectiveness at greater volumes, as the system cannot fully utilize the entire tank.

Electricity costs are also a significant variable in the analysis of the heat pump case since the transition to electrified heating and cooling systems results in a major increase in electric consumption and peak demand. Figure 26 below shows the change in system operating cost related to a change in the price of on-peak and off-peak electricity consumption, and Figure 33 examines the impact of peak demand price on the system operational cost.

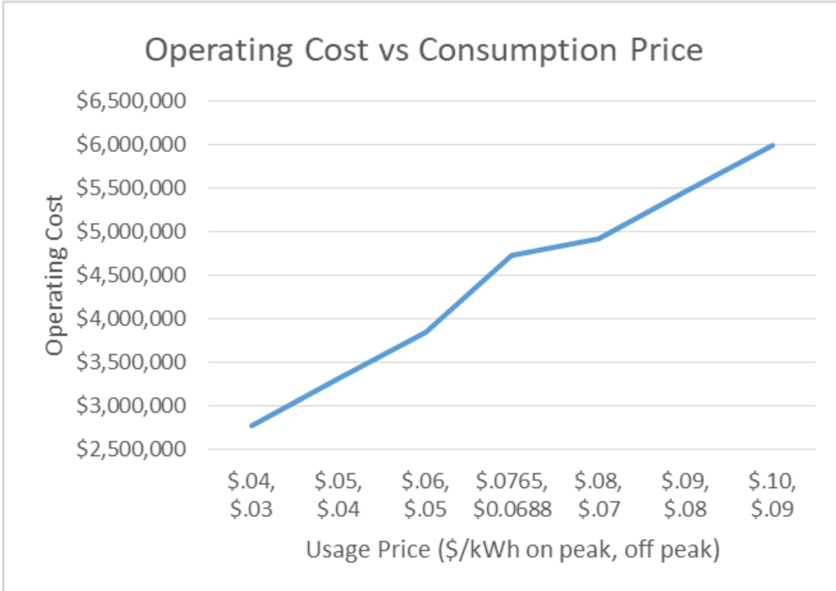

Figure 26: Storage Cost vs Consumption Price

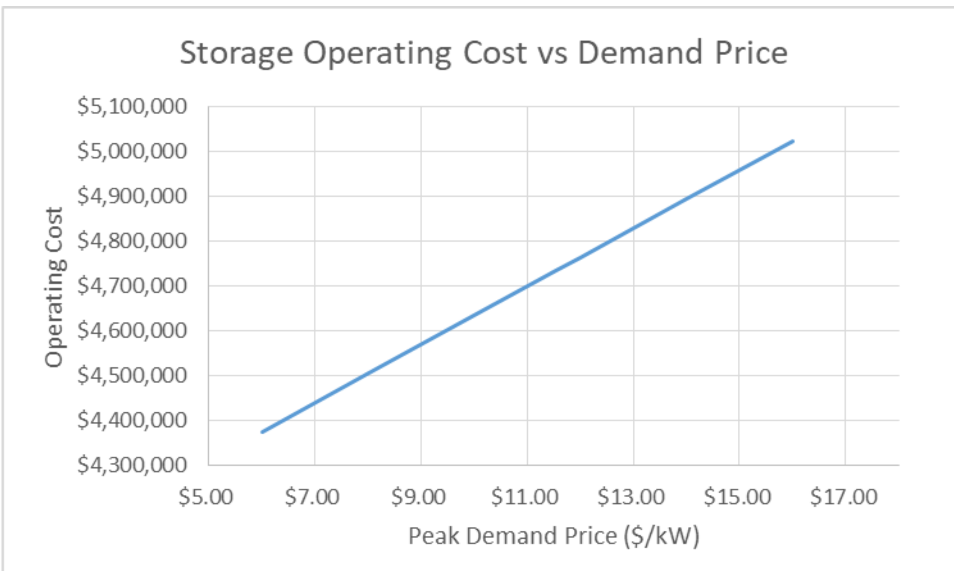

Figure 27: Storage Cost vs Demand Price

An increase or decrease in electricity prices relates to an increase or decrease in system operating cost for the heat pump with TES case. Changes in the price of consumption have a more significant impact on the system cost, since those costs represent a higher percentage of the total system cost than the demand charges.

Similar to changes in electricity prices, changes in the cost of fuel will affect the cost of the conventional CHP system. Figure 28 shows how changes in average price of fuel will affect the cost to run the CHP system.

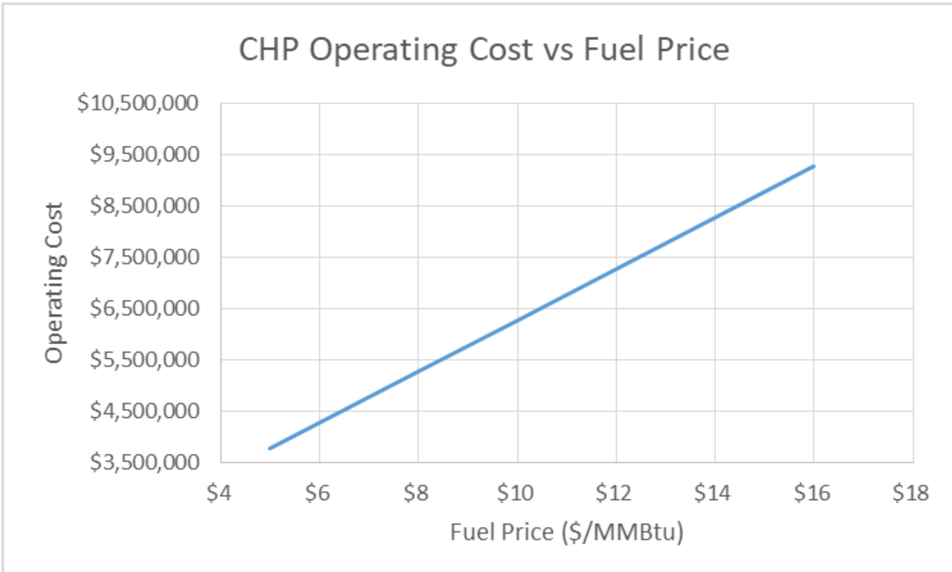

Figure 28: Conventional System Cost vs Fuel Price

Any change in the cost of fuel has an impact on the cost of the conventional CHP system. With the current volatility in the natural gas markets, this is a key consideration for facilities when examining the cost effectiveness of their transition to a decarbonized heating system.

Technological advancements will also impact the bottom line of the heat pump scenarios. As the transition to a fully decarbonized heating sector commences, the average COP of heat pumps will likely increase with market growth. Figure 29 demonstrates the cost value of higher efficiency of heat pumps, where “H” denotes the average COP of the heat pump when heating, and “C” denotes the average COP of the heat pump when cooling. Average COP_H and COP_C of 4.22 and 6.82 respectively represent the current heat pumps modeled in this analysis.

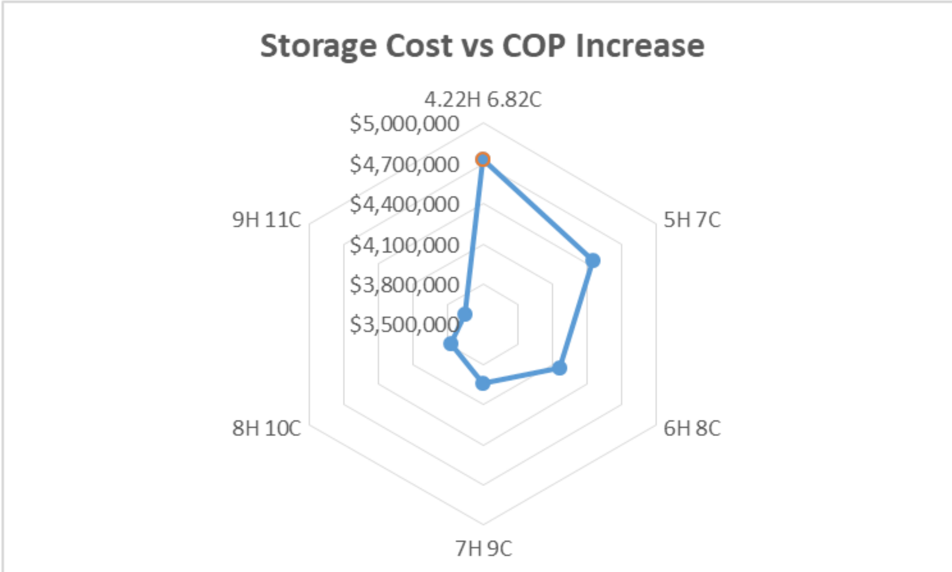

Figure 29: Storage Cost vs COP Increase

As expected, improving the efficiency of the heat pumps reduces the overall operating costs of the electrified system. Likewise, with technological improvements, the transition to electrified systems becomes more palatable from a cost perspective. Figure 30 shows the system cost of improved COPs compared to the current conventional system cost.

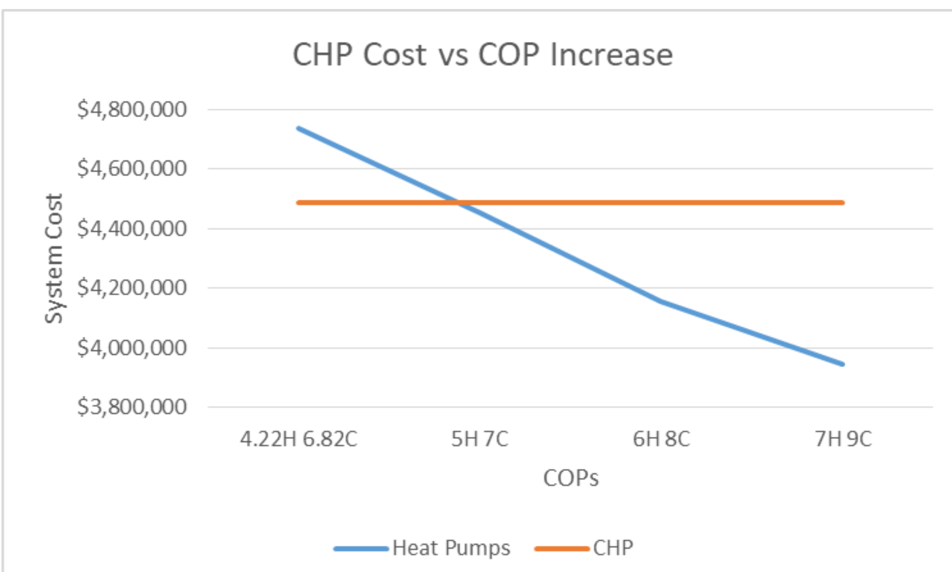

Figure 30: CHP Cost vs COP Increase

Improvements in heat pump efficiency can make them a more cost friendly option than the conventional system, with an average COP_H of 6 and COP_C of 8 having a lower operating cost than the conventional system. A comparison of all the different sensitivity analyses is shown in the figure below.

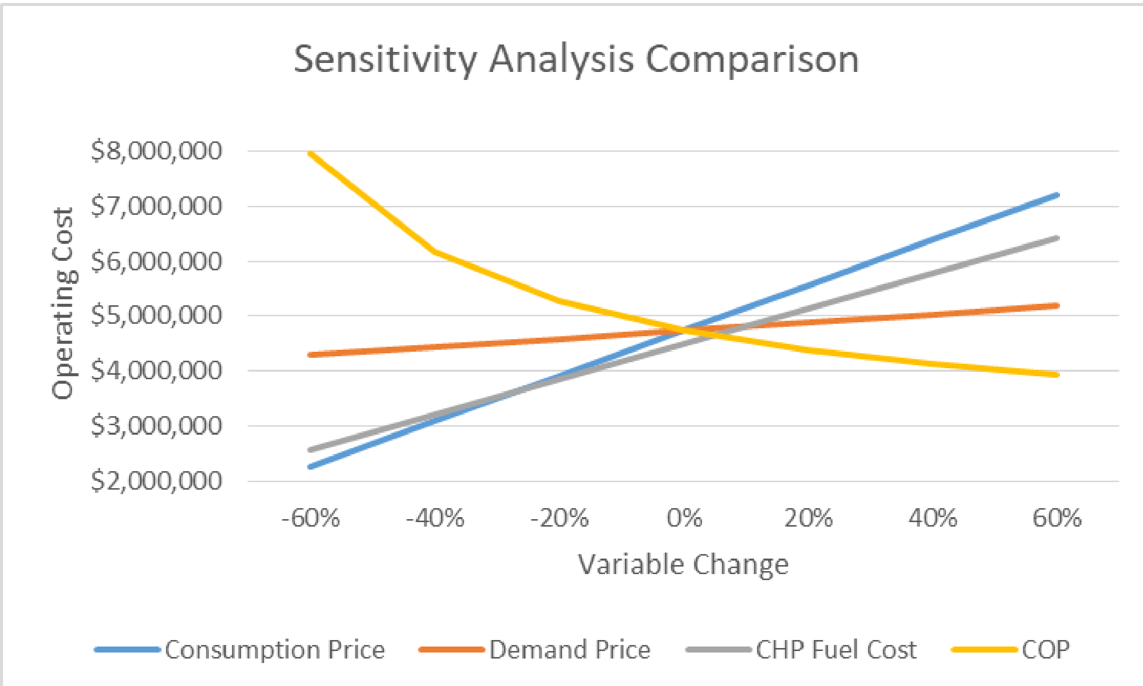

Figure 31: Overall Sensitivity Analysis Comparison

As shown, consumption price and heat pump COP are the major drivers of the operating cost for the storage system. Changes in heat pump performance and consumption price will have a noticeable impact on the operating cost of the electrified system, while changes to CHP fuel cost can also impact the economic decision making for the fossil fuel fired equipment. Demand prices have less of an impact on the total cost, due to the addition of storage that works to limit the overall demand charges.

CHAPTER 5

CONCLUSIONS

5.1 Summary

This thesis investigated the application of thermal energy storage, in the form of stratified water tanks, in conjunction with electrified heating and cooling systems. Thermal storage has proven to be an effective means of reducing peak demand charges, which are one of the major financial hurdles when transitioning from a fossil fuel based heating system to an electrified one. Utilizing UMass load data taken from the campus building management system, an energy model was built in TRNSYS to simulate the operation of a ground source heat pump array with stratified water storage to meet a portion of the campus heating and cooling loads. Two methodologies were investigated, related to different electric rates and their peak demand structure. Under the general rate case, based a typical large industrial rate structure, storage had some cost savings, reducing the system operating cost from $6,687,014 without storage to $6,636,210 with storage. Under the current UMass rate, with its defined peak and capacity hours, the addition of thermal storage had much greater cost benefits, as it reduced the system operating cost from $4,963,265 without storage to $4,738,635 with storage. The current CHP base case, however, has an annual operating cost of $4,485,735, meaning that the heat pump with storage system has a higher operational cost. This is due to the increase in purchased grid electricity, with 51,312,924 kWh being purchased in the storage case versus only 5,136,962 kWh in the base case. This difference can be further mitigated, however, through a phased approach to heat pump adoption, where the CHP is maintained and able to provide some electricity generation. Under that scenario, the operating costs are reduced to $4,697,224, which is the most economical of all the heat pump cases. Looking beyond costs, there are also significant emissions impacts associated with transitioning to electrified heating and cooling systems. The electrified case with storage results in a 9,319 ton reduction in CO_2 emission, due to the elimination of fossil fuel fired equipment. However, there is also a 14,611 lb increase in NO_X emissions and a 3,882 lb increase in SO_2 emissions, due to the increase in purchased electricity. The phased approach had the greatest emissions savings, with that transition reducing CO_2 emissions by 13,310 tons and increasing NO_X emissions by 7,309 lbs and SO_2 emissions by 2,010 lbs.

In summary, based on known simulation methods for ground source heat pumps and thermal energy storage, the addition of stratified water storage to an array of ground source heat pumps can reduce overall operating cost. Despite that reduction, these systems will still incur a greater annual operating cost than the current UMass CHP, due to the increased peak demand and electric usage. The maintenance of fossil fuel fired equipment can help mitigate some of these demand increases, by covering a portion of the heating load that would be met by the heat pumps. Modi and Waite showed that keeping fossil fuel backup could ease the transition to electrified heating by limiting increases in grid capacity [6], and recent installations at Amherst College noted their plan to maintain fossil fuel boiler backup [30]. By phasing the transition to include elements of both heat pumps and the CHP's capabilities, the economics become more favorable, while still achieving the carbon reductions desired by the 21st century climate goals.

5.2 Future Work

As described in Chapter 3.3, the load profile used in this analysis is severely unbalanced, with a much greater heating load than cooling load. This could result in the thermal degradation of the source medium, which would in turn impact the heat pump performance, along with other biological and geological concerns. Balancing this load would be paramount to the long term success of this system, and could be done by using air source heat pumps to meet some of the heating load while remaining fully electrified, or using solar thermal collectors to provide the supplemental heating needed. Similarly, using heat recovery during periods of simultaneous heating and cooling to internally balance the load can be done, and installations of electrified systems at Amherst College project to recover 13,700 MMBtu via this methodology [30].

Likewise, the adoption of heat pumps would require the implementation of low temperature hot water heating. The current campus distribution system is primarily steam, as well as steam to hot water heat exchangers. The heat pump system described in this thesis outputs low temperature hot water, and the ability to use that for heating has far reaching impacts. Investigation into the capability of utilizing that temperature water, and the potential implications of doing so, could provide further insight into the viability of these systems.

Furthermore, the move towards efficient electrified systems encompasses more than just heat pump technology. For example, new chillers available on the market are increasing in efficiency every year, with some having COPs higher than that of ground source heat pumps. Transitioning a large campus or other facility to a fully electrified system will require coordination to meet the heating and cooling needs of the space and could thus incorporate a variety of different efficient technologies. While heat pumps are a major piece of equipment in the future of energy efficient buildings, there are advancement in other technologies that should be considered to make a thoughtful and effective transition.

Finally, the carbon emissions associated with electrified heating could be further reduced. While the electrification case reduces carbon output related to the CHP case, it still has a notable emissions profile due to grid emissions factors. Coupling these electrified heating systems with renewable generation such as rooftop solar could cover a portion of the electric load generated by the heat pumps, and thus further reduce their associated pollutant emissions. Furthermore, as the grid integrates more renewable energy sources and further decarbonizes energy production, the emissions associated with the heat pumps will lower as emissions associated with grid purchased electricity reduce.

APPENDIX A

FULL BUILDING LIST

- Bartlett
- Berkshire DC
- Berkshire House
- Blaisdell house
- Boyden gym
- Cance
- Commonwealth Honors College Residential Complex
- Coolidge
- Curry hicks
- Dickinson hall
- Goodell
- Grinnell
- Hampden dc
- Hampshire House
- Hampshire DC
- J Adams
- JQ adams
- Kennedy
- Kennedy champions center
- Machmer
- Memorial Hall
- Middlesex
- Moore
- Mullins center
- Munson
- Old Chapel
- Patterson
- Photo Lab
- Pierpont
- Prince
- Rec center
- South college
- Thompson
- Thoreau
- Tobin
- Washington
- WEB Dubois Library

APPENDIX B

HEAT PUMP DATA

Table 7. Cooling capacities 20 tons - EXW240

Source			Load																		
				Flow 30 GPM						Flow 50 GPM						Flow 70 GPM					
EWT °F	Flow GPM	WPD FT	EWT °F	TC Mbtuh	Power kW	HR Mbtuh	LWT °F	EER	WPD FT	TC Mbtuh	Power kW	HR Mbtuh	LWT °F	EER	WPD FT	TC Mbtuh	Power kW	HR Mbtuh	LWT °F	EER	WPD FT
50	30.0	3.4	50	189.1	9.57	221.8	37.4	19.8	3.6	208.5	9.68	241.6	41.7	21.5	8.7	218.5	9.74	251.7	43.8	22.4	15.7
50	50.0	8.1	50	195.3	8.89	225.7	37.0	22.0	3.6	215.3	8.99	246.0	41.4	24.0	8.7	225.6	9.04	256.5	43.6	25.0	15.7
50	70.0	14.1	50	197.9	8.63	227.3	36.8	22.9	3.6	218.1	8.72	247.9	41.3	25.0	8.7	228.5	8.77	258.5	43.5	26.0	15.7
50	30.0	3.4	60	220.9	9.88	254.6	45.3	22.4	3.5	243.6	9.98	277.6	50.3	24.4	8.4	255.2	10.05	289.5	52.7	25.4	15.2
50	50.0	8.1	60	228.1	9.17	259.4	44.8	24.9	3.5	251.5	9.27	283.1	49.9	27.1	8.4	263.5	9.33	295.4	52.5	28.3	15.2
50	70.0	14.1	60	231.1	8.90	261.5	44.6	26.0	3.5	254.8	8.99	285.5	49.8	28.3	8.4	266.9	9.05	297.8	52.4	29.5	15.2
50	30.0	3.4	70	256.3	10.26	291.3	52.9	25.0	3.3	282.5	10.37	317.9	58.7	27.2	8.2	296.0	10.43	331.6	61.5	28.4	14.8
50	50.0	8.1	70	264.6	9.52	297.1	52.4	27.8	3.3	291.7	9.63	324.6	58.3	30.3	8.2	305.7	9.69	338.7	61.3	31.6	14.8
50	70.0	14.1	70	268.1	9.24	299.6	52.1	29.0	3.3	295.5	9.34	327.4	58.2	31.6	8.2	309.6	9.40	341.7	61.2	32.9	14.8
50	30.0	3.4	80	296.6	10.73	333.2	60.2	27.7	3.2	327.0	10.84	364.0	66.9	30.2	8.0	342.6	10.91	379.9	70.2	31.4	14.5
50	50.0	8.1	80	306.3	9.96	340.3	59.6	30.8	3.2	337.7	10.07	372.1	66.5	33.5	8.0	353.8	10.13	388.4	69.9	34.9	14.5
50	70.0	14.1	80	310.3	9.66	343.3	59.3	32.1	3.2	342.1	9.77	375.4	66.3	35.0	8.0	358.4	9.83	392.0	69.8	36.5	14.5
50	30.0	3.4	85	319.1	11.00	356.7	63.7	29.0	3.2	351.9	11.11	389.8	70.9	31.7	7.9	368.7	11.18	406.8	74.5	33.0	14.3
50	50.0	8.1	85	329.6	10.21	364.4	63.0	32.3	3.2	363.3	10.32	398.6	70.5	35.2	7.9	380.7	10.38	416.1	74.1	36.7	14.3
50	70.0	14.1	85	333.8	9.91	367.7	62.7	33.7	3.2	368.1	10.01	402.2	70.3	36.8	7.9	385.6	10.08	420.0	74.0	38.3	14.3
60	30.0	3.0	50	181.9	10.88	219.0	37.9	16.7	3.6	200.6	11.00	238.1	42.0	18.2	8.7	210.1	11.07	247.9	44.0	19.0	15.7
60	50.0	7.4	50	187.8	10.10	222.3	37.5	18.6	3.6	207.1	10.21	241.9	41.7	20.3	8.7	217.0	10.27	252.0	43.8	21.1	15.7
60	70.0	13.0	50	190.3	9.80	223.7	37.3	19.4	3.6	209.8	9.91	243.6	41.6	21.2	8.7	219.8	9.97	253.8	43.7	22.0	15.7
60	30.0	3.0	60	213.1	11.19	251.3	45.8	19.0	3.5	234.9	11.31	273.6	50.6	20.8	8.4	246.2	11.38	285.0	53.0	21.6	15.2
60	50.0	7.4	60	220.1	10.39	255.5	45.3	21.2	3.5	242.6	10.50	278.5	50.3	23.1	8.4	254.2	10.57	290.3	52.7	24.0	15.2

Source			Load																		
				Flow 30 GPM						Flow 50 GPM						Flow 70 GPM					
EWT °F	Flow GPM	WPD FT	EWT °F	TC Mbtuh	Power kW	HR Mbtuh	LWT °F	EER	WPD FT	TC Mbtuh	Power kW	HR Mbtuh	LWT °F	EER	WPD FT	TC Mbtuh	Power kW	HR Mbtuh	LWT °F	EER	WPD FT
60	70.0	13.0	60	222.9	10.08	257.3	45.1	22.1	3.5	245.8	10.19	280.5	50.2	24.1	8.4	257.5	10.26	292.5	52.6	25.1	15.2
60	30.0	3.0	70	247.6	11.59	287.1	53.5	21.4	3.3	272.9	11.72	312.9	59.1	23.3	8.2	286.0	11.79	326.2	61.8	24.3	14.8
60	50.0	7.4	70	255.6	10.76	292.4	53.0	23.8	3.3	281.9	10.88	319.0	58.7	25.9	8.2	295.3	10.95	332.7	61.6	27.0	14.8
60	70.0	13.0	70	259.0	10.44	294.6	52.7	24.8	3.3	285.5	10.56	321.5	58.6	27.0	8.2	299.1	10.62	335.4	61.5	28.2	14.8
60	30.0	3.0	80	286.8	12.09	328.0	60.9	23.7	3.2	316.2	12.22	357.9	67.4	25.9	8.0	331.3	12.29	373.2	70.5	26.9	14.5
60	50.0	7.4	80	296.1	11.22	334.4	60.3	26.4	3.2	326.5	11.34	365.2	66.9	28.8	8.0	342.1	11.41	381.0	70.2	30.0	14.5
60	70.0	13.0	80	300.0	10.89	337.2	60.0	27.6	3.2	330.8	11.00	368.3	66.8	30.1	8.0	346.5	11.07	384.3	70.1	31.3	14.5
60	30.0	3.0	85	308.6	12.37	350.9	64.4	25.0	3.2	340.3	12.50	382.9	71.4	27.2	7.9	356.5	12.58	399.5	74.8	28.3	14.3
60	50.0	7.4	85	318.7	11.48	357.9	63.8	27.8	3.2	351.4	11.61	391.0	70.9	30.3	7.9	368.1	11.68	408.0	74.5	31.5	14.3
60	70.0	13.0	85	322.9	11.14	360.9	63.5	29.0	3.2	356.0	11.26	394.4	70.8	31.6	7.9	372.9	11.33	411.6	74.3	32.9	14.3
70	30.0	2.8	50	174.7	12.28	216.6	38.4	14.2	3.6	192.6	12.41	234.9	42.3	15.5	8.7	201.8	12.49	244.4	44.2	16.2	15.7
70	50.0	6.9	50	180.4	11.40	219.3	38.0	15.8	3.6	198.9	11.52	238.2	42.0	17.3	8.7	208.3	11.59	247.9	44.0	18.0	15.7
70	70.0	12.3	50	182.7	11.06	220.5	37.8	16.5	3.6	201.4	11.18	239.6	41.9	18.0	8.7	211.1	11.25	249.5	44.0	18.8	15.7
70	30.0	2.8	60	205.1	12.59	248.1	46.3	16.3	3.5	226.2	12.72	269.6	51.0	17.8	8.4	237.0	12.80	280.7	53.2	18.5	15.2
70	50.0	6.9	60	211.8	11.69	251.7	45.9	18.1	3.5	233.5	11.81	273.9	50.7	19.8	8.4	244.7	11.89	285.3	53.0	20.6	15.2
70	70.0	12.3	60	214.6	11.34	253.3	45.7	18.9	3.5	236.6	11.46	275.7	50.5	20.6	8.4	247.9	11.53	287.2	52.9	21.5	15.2
70	30.0	2.8	70	238.6	12.99	283.0	54.1	18.4	3.3	263.1	13.13	307.9	59.5	20.0	8.2	275.6	13.21	320.7	62.1	20.9	14.8
70	50.0	6.9	70	246.4	12.06	287.6	53.6	20.4	3.3	271.7	12.19	313.3	59.1	22.3	8.2	284.6	12.27	326.5	61.9	23.2	14.8
70	70.0	12.3	70	249.6	11.70	289.5	53.4	21.3	3.3	275.2	11.83	315.6	59.0	23.3	8.2	288.3	11.90	329.0	61.8	24.2	14.8
70	30.0	2.8	80	276.6	13.49	322.6	61.6	20.5	3.2	304.9	13.64	351.5	67.8	22.4	8.0	319.5	13.72	366.3	70.9	23.3	14.5
70	50.0	6.9	80	285.6	12.53	328.3	61.0	22.8	3.2	314.9	12.66	358.1	67.4	24.9	8.0	329.9	12.74	373.4	70.6	25.9	14.5
70	70.0	12.3	80	289.3	12.16	330.8	60.7	23.8	3.2	319.0	12.29	360.9	67.2	26.0	8.0	334.2	12.36	376.4	70.5	27.0	14.5
70	30.0	2.8	85	297.7	13.78	344.7	65.2	21.6	3.2	328.2	13.93	375.7	71.9	23.6	7.9	343.9	14.02	391.7	75.2	24.5	14.3
70	50.0	6.9	85	307.4	12.80	351.1	64.5	24.0	3.2	338.9	12.93	383.0	71.4	26.2	7.9	355.1	13.02	399.5	74.9	27.3	14.3
70	70.0	12.3	85	311.4	12.42	353.8	64.2	25.1	3.2	343.3	12.55	386.1	71.3	27.4	7.9	359.7	12.63	402.8	74.7	28.5	14.3
80	30.0	2.7	50	167.2	13.81	214.3	38.9	12.1	3.6	184.3	13.95	231.9	42.6	13.2	8.7	193.1	14.04	241.0	44.5	13.8	15.7
80	50.0	6.6	50	172.6	12.82	216.4	38.5	13.5	3.6	190.3	12.95	234.5	42.4	14.7	8.7	199.4	13.04	243.9	44.3	15.3	15.7
80	70.0	11.8	50	174.9	12.44	217.3	38.3	14.1	3.6	192.8	12.57	235.7	42.3	15.3	8.7	202.0	12.65	245.2	44.2	16.0	15.7
80	30.0	2.7	60	196.8	14.10	244.9	46.9	14.0	3.5	217.0	14.25	265.6	51.3	15.2	8.4	227.3	14.34	276.3	53.5	15.9	15.2
80	50.0	6.6	60	203.2	13.09	247.9	46.5	15.5	3.5	224.1	13.23	269.2	51.0	16.9	8.4	234.7	13.31	280.2	53.3	17.6	15.2
80	70.0	11.8	60	205.9	12.70	249.2	46.3	16.2	3.5	227.0	12.84	270.8	50.9	17.7	8.4	237.8	12.92	281.9	53.2	18.4	15.2
80	30.0	2.7	70	229.1	14.49	278.6	54.7	15.8	3.3	252.6	14.65	302.6	59.9	17.2	8.2	264.7	14.74	315.0	62.4	18.0	14.8
80	50.0	6.6	70	236.6	13.45	282.5	54.2	17.6	3.3	260.9	13.60	307.3	59.6	19.2	8.2	273.3	13.69	320.0	62.2	20.0	14.8
80	70.0	11.8	70	239.7	13.06	284.3	54.0	18.4	3.3	264.3	13.20	309.3	59.4	20.0	8.2	276.9	13.28	322.2	62.1	20.8	14.8
80	30.0	2.7	80	265.7	14.99	316.8	62.3	17.7	3.2	292.9	15.15	344.6	68.3	19.3	8.0	306.9	15.25	358.9	71.2	20.1	14.5
80	50.0	6.6	80	274.4	13.92	321.9	61.7	19.7	3.2	302.5	14.07	350.5	67.9	21.5	8.0	316.9	14.16	365.2	70.9	22.4	14.5

Source			Load																		
				Flow 30 GPM						Flow 50 GPM						Flow 70 GPM					
EWT °F	Flow GPM	WPD FT	EWT °F	TC Mbtuh	Power kW	HR Mbtuh	LWT °F	EER	WPD FT	TC Mbtuh	Power kW	HR Mbtuh	LWT °F	EER	WPD FT	TC Mbtuh	Power kW	HR Mbtuh	LWT °F	EER	WPD FT
80	70.0	11.8	80	277.9	13.50	324.0	61.5	20.6	3.2	306.4	13.65	353.0	67.7	22.4	8.0	321.0	13.74	367.9	70.8	23.4	14.5
80	30.0	2.7	85	286.0	15.28	338.1	65.9	18.7	3.2	315.3	15.44	368.0	72.4	20.4	7.9	330.4	15.54	383.4	75.6	21.3	14.3
80	50.0	6.6	85	295.3	14.19	343.7	65.3	20.8	3.2	325.6	14.34	374.5	72.0	22.7	7.9	341.1	14.43	390.4	75.3	23.6	14.3
80	70.0	11.8	85	299.2	13.77	346.2	65.1	21.7	3.2	329.8	13.91	377.3	71.8	23.7	7.9	345.6	14.00	393.4	75.1	24.7	14.3
90	30.0	2.6	50	159.2	15.50	212.1	39.4	10.3	3.6	175.5	15.67	229.0	43.0	11.2	8.7	183.9	15.77	237.7	44.7	11.7	15.7
90	50.0	6.4	50	164.4	14.40	213.5	39.0	11.4	3.6	181.2	14.55	230.9	42.8	12.5	8.7	189.9	14.64	239.9	44.6	13.0	15.7
90	70.0	11.4	50	166.5	13.97	214.2	38.9	11.9	3.6	183.6	14.12	231.8	42.7	13.0	8.7	192.4	14.21	240.9	44.5	13.5	15.7
90	30.0	2.6	60	187.8	15.77	241.6	47.5	11.9	3.5	207.1	15.94	261.5	51.7	13.0	8.4	217.0	16.04	271.7	53.8	13.5	15.2
90	50.0	6.4	60	194.0	14.64	243.9	47.1	13.2	3.5	213.8	14.80	264.3	51.4	14.5	8.4	224.0	14.89	274.9	53.6	15.0	15.2
90	70.0	11.4	60	196.5	14.20	245.0	46.9	13.8	3.5	216.6	14.36	265.6	51.3	15.1	8.4	227.0	14.45	276.3	53.5	15.7	15.2
90	30.0	2.6	70	218.9	16.13	274.0	55.4	13.6	3.3	241.4	16.31	297.0	60.3	14.8	8.2	252.9	16.41	308.9	62.8	15.4	14.8
90	50.0	6.4	70	226.0	14.98	277.2	54.9	15.1	3.3	249.2	15.14	300.9	60.0	16.5	8.2	261.1	15.24	313.1	62.5	17.1	14.8
90	70.0	11.4	70	229.0	14.54	278.6	54.7	15.8	3.3	252.5	14.69	302.6	59.9	17.2	8.2	264.5	14.79	315.0	62.4	17.9	14.8
90	30.0	2.6	80	253.9	16.61	310.6	63.1	15.3	3.2	279.9	16.79	337.3	68.8	16.7	8.0	293.3	16.90	351.0	71.6	17.4	14.5
90	50.0	6.4	80	262.2	15.42	314.8	62.5	17.0	3.2	289.1	15.59	342.3	68.4	18.5	8.0	302.9	15.69	356.4	71.3	19.3	14.5
90	70.0	11.4	80	265.6	14.97	316.7	62.3	17.7	3.2	292.8	15.13	344.5	68.3	19.4	8.0	306.8	15.22	358.8	71.2	20.2	14.5
90	30.0	2.6	85	273.4	16.90	331.0	66.8	16.2	3.2	301.4	17.08	359.7	72.9	17.6	7.9	315.8	17.19	374.4	76.0	18.4	14.3
90	50.0	6.4	85	282.3	15.69	335.8	66.2	18.0	3.2	311.2	15.85	365.3	72.6	19.6	7.9	326.1	15.96	380.5	75.7	20.4	14.3
90	70.0	11.4	85	285.9	15.22	337.9	65.9	18.8	3.2	315.3	15.39	367.8	72.4	20.5	7.9	330.3	15.48	383.1	75.6	21.3	14.3
100	30.0	2.5	50	150.4	17.41	209.9	40.0	8.6	3.6	165.9	17.60	225.9	43.4	9.4	8.7	173.8	17.71	234.2	45.0	9.8	15.7
100	50.0	6.2	50	155.4	16.17	210.5	39.6	9.6	3.6	171.3	16.34	227.1	43.1	10.5	8.7	179.5	16.45	235.6	44.9	10.9	15.7
100	70.0	11.2	50	157.4	15.69	210.9	39.5	10.0	3.6	173.5	15.86	227.6	43.1	10.9	8.7	181.8	15.96	236.3	44.8	11.4	15.7
100	30.0	2.5	60	178.0	17.63	238.1	48.1	10.1	3.5	196.2	17.82	257.0	52.2	11.0	8.4	205.6	17.93	266.8	54.1	11.5	15.2
100	50.0	6.2	60	183.8	16.37	239.6	47.7	11.2	3.5	202.6	16.54	259.1	51.9	12.2	8.4	212.3	16.65	269.1	53.9	12.8	15.2
100	70.0	11.2	60	186.2	15.88	240.4	47.6	11.7	3.5	205.2	16.05	260.0	51.8	12.8	8.4	215.0	16.16	270.2	53.9	13.3	15.2
100	30.0	2.5	70	207.7	17.96	268.9	56.2	11.6	3.3	228.9	18.15	290.9	60.8	12.6	8.2	239.9	18.27	302.2	63.1	13.1	14.8
100	50.0	6.2	70	214.4	16.67	271.3	55.7	12.9	3.3	236.4	16.85	293.9	60.5	14.0	8.2	247.7	16.96	305.6	62.9	14.6	14.8
100	70.0	11.2	70	217.2	16.18	272.4	55.5	13.4	3.3	239.5	16.35	295.3	60.4	14.6	8.2	250.9	16.46	307.1	62.8	15.2	14.8
100	30.0	2.5	80	241.0	18.40	303.8	63.9	13.1	3.2	265.7	18.60	329.2	69.4	14.3	8.0	278.4	18.72	342.3	72.0	14.9	14.5
100	50.0	6.2	80	248.9	17.08	307.2	63.4	14.6	3.2	274.4	17.27	333.3	69.0	15.9	8.0	287.5	17.38	346.8	71.8	16.5	14.5
100	70.0	11.2	80	252.1	16.58	308.7	63.2	15.2	3.2	277.9	16.76	335.1	68.9	16.6	8.0	291.2	16.86	348.8	71.7	17.3	14.5
100	30.0	2.5	85	259.5	18.67	323.2	67.7	13.9	3.2	286.1	18.87	350.5	73.6	15.2	7.9	299.8	18.99	364.6	76.4	15.8	14.3
100	50.0	6.2	85	268.0	17.33	327.1	67.1	15.5	3.2	295.4	17.52	355.2	73.2	16.9	7.9	309.5	17.63	369.7	76.2	17.6	14.3
100	70.0	11.2	85	271.5	16.82	328.9	66.9	16.1	3.2	299.3	17.00	357.3	73.0	17.6	7.9	313.6	17.11	372.0	76.0	18.3	14.3
110	30.0	2.5	50	140.7	19.57	207.5	40.6	7.2	3.6	155.1	19.78	222.6	43.8	7.8	8.7	162.5	19.91	230.5	45.4	8.2	15.7
110	50.0	6.1	50	145.3	18.17	207.3	40.3	8.0	3.6	160.2	18.37	222.9	43.6	8.7	8.7	167.8	18.48	230.9	45.2	9.1	15.7

Source			Load																		
				Flow 30 GPM						Flow 50 GPM						Flow 70 GPM					
EWT °F	Flow GPM	WPD FT	EWT °F	TC Mbtuh	Power kW	HR Mbtuh	LWT °F	EER	WPD FT	TC Mbtuh	Power kW	HR Mbtuh	LWT °F	EER	WPD FT	TC Mbtuh	Power kW	HR Mbtuh	LWT °F	EER	WPD FT
110	70.0	10.9	50	147.2	17.63	207.4	40.2	8.3	3.6	162.3	17.82	223.1	43.5	9.1	8.7	170.0	17.94	231.2	45.1	9.5	15.7
110	30.0	2.5	60	167.0	19.73	234.3	48.9	8.5	3.5	184.1	19.94	252.1	52.6	9.2	8.4	192.9	20.07	261.4	54.5	9.6	15.2
110	50.0	6.1	60	172.4	18.31	234.9	48.5	9.4	3.5	190.1	18.51	253.3	52.4	10.3	8.4	199.2	18.63	262.7	54.3	10.7	15.2
110	70.0	10.9	60	174.7	17.77	235.3	48.4	9.8	3.5	192.6	17.96	253.9	52.3	10.7	8.4	201.8	18.08	263.5	54.2	11.2	15.2
110	30.0	2.5	70	195.1	20.00	263.4	57.0	9.8	3.3	215.1	20.21	284.1	61.4	10.6	8.2	225.4	20.34	294.8	63.6	11.1	14.8
110	50.0	6.1	70	201.5	18.57	264.9	56.6	10.9	3.3	222.2	18.77	286.2	61.1	11.8	8.2	232.8	18.89	297.2	63.3	12.3	14.8
110	70.0	10.9	70	204.1	18.02	265.6	56.4	11.3	3.3	225.1	18.21	287.2	61.0	12.4	8.2	235.8	18.33	298.3	63.3	12.9	14.8
110	30.0	2.5	80	226.7	20.40	296.3	64.9	11.1	3.2	249.9	20.62	320.3	70.0	12.1	8.0	261.9	20.75	332.7	72.5	12.6	14.5
110	50.0	6.1	80	234.1	18.94	298.7	64.4	12.4	3.2	258.1	19.14	323.4	69.7	13.5	8.0	270.4	19.26	336.1	72.3	14.0	14.5
110	70.0	10.9	80	237.1	18.38	299.8	64.2	12.9	3.2	261.4	18.57	324.8	69.5	14.1	8.0	273.9	18.69	337.7	72.2	14.7	14.5
110	30.0	2.5	85	244.2	20.64	314.6	68.7	11.8	3.2	269.2	20.86	340.4	74.2	12.9	7.9	282.1	21.00	353.7	76.9	13.4	14.3
110	50.0	6.1	85	252.2	19.17	317.6	68.2	13.2	3.2	278.0	19.37	344.1	73.9	14.4	7.9	291.3	19.49	357.8	76.7	14.9	14.3
110	70.0	10.9	85	255.4	18.60	318.9	68.0	13.7	3.2	281.6	18.80	345.8	73.7	15.0	7.9	295.1	18.92	359.6	76.6	15.6	14.3
120	30.0	2.5	50	129.7	22.02	204.8	41.4	5.9	3.6	143.0	22.25	218.9	44.3	6.4	8.7	149.8	22.39	226.2	45.7	6.7	15.7
120	50.0	6.0	50	133.9	20.44	203.7	41.1	6.6	3.6	147.7	20.66	218.2	44.1	7.1	8.7	154.7	20.79	225.7	45.6	7.4	15.7
120	70.0	10.8	50	135.7	19.83	203.4	41.0	6.8	3.6	149.6	20.05	218.0	44.0	7.5	8.7	156.7	20.17	225.6	45.5	7.8	15.7
120	30.0	2.5	60	154.6	22.09	230.0	49.7	7.0	3.5	170.4	22.33	246.7	53.2	7.6	8.4	178.6	22.47	255.3	54.9	7.9	15.2
120	50.0	6.0	60	159.6	20.51	229.6	49.4	7.8	3.5	176.0	20.73	246.8	53.0	8.5	8.4	184.4	20.87	255.6	54.7	8.8	15.2
120	70.0	10.8	60	161.7	19.91	229.7	49.2	8.1	3.5	178.3	20.12	247.0	52.9	8.9	8.4	186.8	20.25	255.9	54.7	9.2	15.2
120	30.0	2.5	70	181.1	22.30	257.2	57.9	8.1	3.3	199.7	22.54	276.6	62.0	8.9	8.2	209.2	22.68	286.6	64.0	9.2	14.8
120	50.0	6.0	70	187.0	20.70	257.7	57.5	9.0	3.3	206.2	20.93	277.6	61.8	9.9	8.2	216.0	21.06	287.9	63.8	10.3	14.8
120	70.0	10.8	70	189.5	20.09	258.0	57.4	9.4	3.3	208.9	20.31	278.2	61.6	10.3	8.2	218.8	20.44	288.6	63.7	10.7	14.8
120	30.0	2.5	80	210.7	22.63	288.0	66.0	9.3	3.2	232.3	22.88	310.4	70.7	10.2	8.0	243.4	23.02	322.0	73.0	10.6	14.5
120	50.0	6.0	80	217.6	21.01	289.3	65.5	10.4	3.2	239.9	21.24	312.4	70.4	11.3	8.0	251.4	21.37	324.3	72.8	11.8	14.5
120	70.0	10.8	80	220.4	20.39	290.0	65.3	10.8	3.2	243.0	20.61	313.4	70.3	11.8	8.0	254.6	20.74	325.4	72.7	12.3	14.5
120	30.0	2.5	85	227.2	22.85	305.2	69.9	9.9	3.2	250.4	23.10	329.3	75.0	10.8	7.9	262.4	23.24	341.7	77.5	11.3	14.3
120	50.0	6.0	85	234.6	21.22	307.0	69.4	11.1	3.2	258.6	21.44	331.8	74.7	12.1	7.9	271.0	21.58	344.6	77.3	12.6	14.3
120	70.0	10.8	85	237.6	20.59	307.9	69.2	11.5	3.2	262.0	20.81	333.0	74.5	12.6	7.9	274.5	20.94	346.0	77.2	13.1	14.3

Table 8. Heating capacities 20 tons

Source			Load																		
				Flow 30 GPM						Flow 50 GPM						Flow 70 GPM					
EWT °F	Flow GPM	WPD FT	EWT °F	HC Mbtuh	Power kW	HA Mbtuh	LWT °F	COP	WPD FT	HC Mbtuh	Power kW	HA Mbtuh	LWT °F	COP	WPD FT	HC Mbtuh	Power kW	HA Mbtuh	LWT °F	COP	WPD FT
25	30.0	4.5	60	153.5	10.64	117.2	70.2	4.2	3.5	154.8	10.17	120.0	66.2	4.5	8.4	155.1	10.04	120.9	64.4	4.5	15.2
25	50.0	11.4	60	164.3	10.64	128.0	71.0	4.5	3.5	165.6	10.18	130.8	66.6	4.8	8.4	166.0	10.04	131.7	64.7	4.8	15.2
25	70.0	19.6	60	169.5	10.65	133.1	71.3	4.7	3.5	170.8	10.19	136.1	66.8	4.9	8.4	171.2	10.05	136.9	64.9	5.0	15.2
25	30.0	4.5	70	151.5	12.03	110.5	80.1	3.7	3.3	152.7	11.50	113.4	76.1	3.9	8.2	153.1	11.35	114.4	74.4	4.0	14.8
25	50.0	11.4	70	162.1	12.03	121.0	80.8	3.9	3.3	163.4	11.51	124.1	76.5	4.2	8.2	163.8	11.35	125.0	74.7	4.2	14.8
25	70.0	19.6	70	167.2	12.04	126.1	81.1	4.1	3.3	168.6	11.52	129.2	76.7	4.3	8.2	169.0	11.36	130.2	74.8	4.4	14.8
25	30.0	4.5	80	149.7	13.60	103.3	90.0	3.2	3.2	150.9	13.01	106.5	86.0	3.4	8.0	151.3	12.83	107.5	84.3	3.5	14.5
25	50.0	11.4	80	160.2	13.61	113.8	90.7	3.4	3.2	161.5	13.02	117.1	86.5	3.6	8.0	161.9	12.84	118.1	84.6	3.7	14.5
25	70.0	19.6	80	165.3	13.62	118.8	91.0	3.6	3.2	166.6	13.02	122.1	86.7	3.7	8.0	167.0	12.85	123.2	84.8	3.8	14.5
25	30.0	4.5	90	148.2	15.39	95.6	99.9	2.8	3.2	149.4	14.72	99.1	96.0	3.0	7.8	149.7	14.52	100.2	94.3	3.0	14.1
25	50.0	11.4	90	158.5	15.40	106.0	100.6	3.0	3.2	159.8	14.73	109.5	96.4	3.2	7.8	160.2	14.53	110.6	94.6	3.2	14.1
25	70.0	19.6	90	163.6	15.41	111.0	100.9	3.1	3.2	164.9	14.74	114.5	96.6	3.3	7.8	165.3	14.54	115.6	94.7	3.3	14.1
25	30.0	4.5	100	146.7	17.44	87.2	109.8	2.5	3.1	147.9	16.68	91.0	105.9	2.6	7.6	148.2	16.45	92.1	104.2	2.6	13.7
25	50.0	11.4	100	157.0	17.45	97.4	110.5	2.6	3.1	158.2	16.69	101.3	106.3	2.8	7.6	158.6	16.46	102.4	104.5	2.8	13.7
25	70.0	19.6	100	161.9	17.46	102.4	110.8	2.7	3.1	163.2	16.70	106.2	106.5	2.9	7.6	163.6	16.47	107.4	104.7	2.9	13.7
25	30.0	4.5	110	145.3	19.77	77.8	119.7	2.2	3.0	146.5	18.91	81.9	115.9	2.3	7.4	146.8	18.65	83.1	114.2	2.3	13.4
25	50.0	11.4	110	155.5	19.79	87.9	120.4	2.3	3.0	156.7	18.92	92.1	116.3	2.4	7.4	157.1	18.66	93.4	114.5	2.5	13.4
25	70.0	19.6	110	160.4	19.80	92.8	120.7	2.4	3.0	161.6	18.94	97.0	116.5	2.5	7.4	162.0	18.68	98.3	114.6	2.5	13.4
35	30.0	4.3	60	179.5	10.68	143.0	72.0	4.9	3.5	180.9	10.21	146.0	67.2	5.2	8.4	181.3	10.07	147.0	65.2	5.3	15.2
35	50.0	9.9	60	192.0	10.68	155.6	72.8	5.3	3.5	193.6	10.22	158.7	67.7	5.5	8.4	194.0	10.08	159.6	65.5	5.6	15.2
35	70.0	16.9	60	198.1	10.69	161.6	73.2	5.4	3.5	199.7	10.23	164.8	68.0	5.7	8.4	200.2	10.09	165.7	65.7	5.8	15.2
35	30.0	4.3	70	176.8	12.07	135.6	81.8	4.3	3.3	178.2	11.55	138.8	77.1	4.5	8.2	178.7	11.39	139.8	75.1	4.6	14.8
35	50.0	9.9	70	189.2	12.08	148.0	82.6	4.6	3.3	190.7	11.55	151.3	77.6	4.8	8.2	191.2	11.39	152.3	75.5	4.9	14.8
35	70.0	16.9	70	195.2	12.09	153.9	83.0	4.7	3.3	196.7	11.56	157.3	77.9	5.0	8.2	197.2	11.40	158.3	75.6	5.1	14.8
35	30.0	4.3	80	174.4	13.64	127.9	91.6	3.7	3.2	175.8	13.04	131.3	87.0	3.9	8.0	176.2	12.87	132.3	85.0	4.0	14.5
35	50.0	9.9	80	186.6	13.65	140.1	92.4	4.0	3.2	188.1	13.05	143.6	87.5	4.2	8.0	188.6	12.87	144.6	85.4	4.3	14.5
35	70.0	16.9	80	192.5	13.66	145.9	92.8	4.1	3.2	194.1	13.06	149.5	87.8	4.4	8.0	194.5	12.88	150.6	85.6	4.4	14.5
35	30.0	4.3	90	172.2	15.41	119.6	101.5	3.3	3.2	173.5	14.74	123.2	96.9	3.4	7.8	174.0	14.54	124.3	95.0	3.5	14.1
35	50.0	9.9	90	184.2	15.42	131.6	102.3	3.5	3.2	185.7	14.75	135.3	97.4	3.7	7.8	186.1	14.55	136.5	95.3	3.7	14.1
35	70.0	16.9	90	190.0	15.43	137.4	102.7	3.6	3.2	191.5	14.76	141.2	97.7	3.8	7.8	192.0	14.56	142.3	95.5	3.9	14.1
35	30.0	4.3	100	170.0	17.44	110.5	111.3	2.9	3.1	171.3	16.68	114.4	106.9	3.0	7.6	171.7	16.45	115.6	104.9	3.1	13.7
35	50.0	9.9	100	181.9	17.45	122.3	112.1	3.1	3.1	183.3	16.69	126.3	107.3	3.2	7.6	183.8	16.46	127.6	105.3	3.3	13.7
35	70.0	16.9	100	187.6	17.46	128.0	112.5	3.1	3.1	189.1	16.70	132.1	107.6	3.3	7.6	189.6	16.47	133.3	105.4	3.4	13.7
35	30.0	4.3	110	167.8	19.74	100.4	121.2	2.5	3.0	169.1	18.88	104.7	116.8	2.6	7.4	169.5	18.62	105.9	114.8	2.7	13.4
35	50.0	9.9	110	179.5	19.75	112.1	122.0	2.7	3.0	180.9	18.90	116.4	117.2	2.8	7.4	181.4	18.64	117.8	115.2	2.9	13.4
35	70.0	16.9	110	185.2	19.77	117.7	122.3	2.7	3.0	186.7	18.91	122.1	117.5	2.9	7.4	187.1	18.65	123.5	115.3	2.9	13.4

Source			Load																		
				Flow 30 GPM						Flow 50 GPM						Flow 70 GPM					
EWT °F	Flow GPM	WPD FT	EWT °F	HC Mbtuh	Power kW	HA Mbtuh	LWT °F	COP	WPD FT	HC Mbtuh	Power kW	HA Mbtuh	LWT °F	COP	WPD FT	HC Mbtuh	Power kW	HA Mbtuh	LWT °F	COP	WPD FT
35	30.0	4.3	120	165.5	22.37	89.1	131.0	2.2	2.9	166.8	21.39	93.8	126.7	2.3	7.2	167.2	21.10	95.2	124.8	2.3	13.1
35	50.0	9.9	120	177.0	22.38	100.7	131.8	2.3	2.9	178.4	21.41	105.4	127.1	2.4	7.2	178.9	21.11	106.8	125.1	2.5	13.1
35	70.0	16.9	120	182.6	22.40	106.2	132.2	2.4	2.9	184.1	21.42	111.0	127.4	2.5	7.2	184.5	21.13	112.4	125.3	2.6	13.1
45	30.0	3.6	60	206.6	10.89	169.5	73.8	5.6	3.5	208.3	10.42	172.7	68.3	5.9	8.4	208.8	10.27	173.7	66.0	6.0	15.2
45	50.0	8.5	60	221.1	10.90	183.9	74.7	5.9	3.5	222.8	10.42	187.3	68.9	6.3	8.4	223.4	10.28	188.3	66.4	6.4	15.2
45	70.0	14.8	60	228.1	10.90	190.9	75.2	6.1	3.5	229.9	10.43	194.3	69.2	6.5	8.4	230.4	10.29	195.3	66.6	6.6	15.2
45	30.0	3.6	70	203.2	12.28	161.2	83.5	4.8	3.3	204.8	11.75	164.7	78.2	5.1	8.2	205.3	11.59	165.7	75.9	5.2	14.8
45	50.0	8.5	70	217.4	12.29	175.4	84.5	5.2	3.3	219.1	11.75	179.0	78.8	5.5	8.2	219.6	11.59	180.0	76.3	5.6	14.8
45	70.0	14.8	70	224.2	12.30	182.3	84.9	5.3	3.3	226.0	11.76	185.9	79.0	5.6	8.2	226.6	11.60	187.0	76.5	5.7	14.8
45	30.0	3.6	80	199.9	13.84	152.6	93.3	4.2	3.2	201.5	13.24	156.3	88.1	4.5	8.0	201.9	13.06	157.4	85.8	4.5	14.5
45	50.0	8.5	80	213.8	13.85	166.6	94.3	4.5	3.2	215.5	13.25	170.3	88.6	4.8	8.0	216.1	13.06	171.5	86.2	4.8	14.5
45	70.0	14.8	80	220.6	13.86	173.3	94.7	4.7	3.2	222.4	13.26	177.1	88.9	4.9	8.0	222.9	13.07	178.3	86.4	5.0	14.5
45	30.0	3.6	90	196.7	15.60	143.4	103.1	3.7	3.2	198.3	14.92	147.3	97.9	3.9	7.8	198.7	14.72	148.5	95.7	4.0	14.1
45	50.0	8.5	90	210.4	15.61	157.2	104.0	4.0	3.2	212.1	14.93	161.2	98.5	4.2	7.8	212.6	14.73	162.4	96.1	4.2	14.1
45	70.0	14.8	90	217.1	15.62	163.8	104.5	4.1	3.2	218.8	14.94	167.8	98.8	4.3	7.8	219.4	14.74	169.1	96.3	4.4	14.1
45	30.0	3.6	100	193.5	17.60	133.5	112.9	3.2	3.1	195.1	16.83	137.6	107.8	3.4	7.6	195.5	16.60	138.9	105.6	3.5	13.7
45	50.0	8.5	100	207.1	17.61	147.0	113.8	3.4	3.1	208.7	16.84	151.2	108.3	3.6	7.6	209.2	16.61	152.5	106.0	3.7	13.7
45	70.0	14.8	100	213.6	17.62	153.5	114.2	3.6	3.1	215.3	16.85	157.8	108.6	3.7	7.6	215.8	16.62	159.1	106.2	3.8	13.7
45	30.0	3.6	110	190.3	19.87	122.5	122.7	2.8	3.0	191.8	19.00	127.0	117.7	3.0	7.4	192.3	18.74	128.3	115.5	3.0	13.4
45	50.0	8.5	110	203.6	19.88	135.8	123.6	3.0	3.0	205.2	19.01	140.3	118.2	3.2	7.4	205.7	18.75	141.7	115.9	3.2	13.4
45	70.0	14.8	110	210.1	19.89	142.2	124.0	3.1	3.0	211.7	19.03	146.8	118.5	3.3	7.4	212.2	18.77	148.2	116.1	3.3	13.4
45	30.0	3.6	120	187.0	22.45	110.3	132.5	2.4	2.9	188.4	21.47	115.2	127.5	2.6	7.2	188.9	21.18	116.6	125.4	2.6	13.1
45	50.0	8.5	120	200.0	22.46	123.4	133.3	2.6	2.9	201.6	21.48	128.3	128.1	2.7	7.2	202.1	21.19	129.8	125.8	2.8	13.1
45	70.0	14.8	120	206.4	22.48	129.6	133.8	2.7	2.9	208.0	21.50	134.6	128.3	2.8	7.2	208.5	21.20	136.1	126.0	2.9	13.1
55	30.0	3.2	60	235.9	11.23	197.6	75.7	6.2	3.5	237.8	10.74	201.1	69.5	6.5	8.4	238.4	10.59	202.2	66.8	6.6	15.2
55	50.0	7.7	60	252.4	11.24	214.1	76.8	6.6	3.5	254.4	10.75	217.7	70.2	6.9	8.4	255.0	10.60	218.8	67.3	7.0	15.2
55	70.0	13.5	60	260.4	11.25	222.0	77.4	6.8	3.5	262.5	10.76	225.8	70.5	7.1	8.4	263.1	10.61	226.9	67.5	7.3	15.2
55	30.0	3.2	70	231.4	12.62	188.3	85.4	5.4	3.3	233.2	12.07	192.0	79.3	5.7	8.2	233.8	11.91	193.1	76.7	5.8	14.8
55	50.0	7.7	70	247.6	12.63	204.5	86.5	5.7	3.3	249.5	12.08	208.3	80.0	6.1	8.2	250.1	11.91	209.5	77.1	6.2	14.8
55	70.0	13.5	70	255.4	12.64	212.3	87.0	5.9	3.3	257.4	12.09	216.2	80.3	6.2	8.2	258.0	11.92	217.4	77.4	6.3	14.8
55	30.0	3.2	80	227.0	14.17	178.6	95.1	4.7	3.2	228.8	13.55	182.5	89.2	4.9	8.0	229.3	13.37	183.7	86.6	5.0	14.5
55	50.0	7.7	80	242.9	14.18	194.5	96.2	5.0	3.2	244.8	13.56	198.5	89.8	5.3	8.0	245.4	13.37	199.7	87.0	5.4	14.5
55	70.0	13.5	80	250.6	14.19	202.1	96.7	5.2	3.2	252.5	13.57	206.2	90.1	5.5	8.0	253.2	13.38	207.5	87.2	5.5	14.5
55	30.0	3.2	90	222.7	15.91	168.4	104.8	4.1	3.2	224.4	15.21	172.5	99.0	4.3	7.8	225.0	15.01	173.8	96.4	4.4	14.1
55	50.0	7.7	90	238.2	15.92	183.9	105.9	4.4	3.2	240.1	15.22	188.2	99.6	4.6	7.8	240.7	15.02	189.5	96.9	4.7	14.1
55	70.0	13.5	90	245.8	15.93	191.4	106.4	4.5	3.2	247.7	15.23	195.7	99.9	4.8	7.8	248.3	15.03	197.0	97.1	4.8	14.1

Source			Load																		
				Flow 30 GPM						Flow 50 GPM						Flow 70 GPM					
EWT °F	Flow GPM	WPD FT	EWT °F	HC Mbtuh	Power kW	HA Mbtuh	LWT °F	COP	WPD FT	HC Mbtuh	Power kW	HA Mbtuh	LWT °F	COP	WPD FT	HC Mbtuh	Power kW	HA Mbtuh	LWT °F	COP	WPD FT
55	30.0	3.2	100	218.3	17.87	157.3	114.6	3.6	3.1	220.1	17.10	161.7	108.8	3.8	7.6	220.6	16.86	163.0	106.3	3.8	13.7
55	50.0	7.7	100	233.6	17.88	172.5	115.6	3.8	3.1	235.4	17.11	177.1	109.4	4.0	7.6	236.0	16.87	178.4	106.7	4.1	13.7
55	70.0	13.5	100	241.0	17.90	179.9	116.1	3.9	3.1	242.9	17.12	184.5	109.7	4.2	7.6	243.5	16.88	185.8	107.0	4.2	13.7
55	30.0	3.2	110	213.9	20.11	145.2	124.3	3.1	3.0	215.6	19.23	149.9	118.6	3.3	7.4	216.1	18.97	151.3	116.2	3.3	13.4
55	50.0	7.7	110	228.8	20.12	160.2	125.3	3.3	3.0	230.6	19.24	165.0	119.2	3.5	7.4	231.2	18.98	166.4	116.6	3.6	13.4
55	70.0	13.5	110	236.1	20.13	167.3	125.7	3.4	3.0	237.9	19.26	172.2	119.5	3.6	7.4	238.5	18.99	173.7	116.8	3.7	13.4
55	30.0	3.2	120	209.2	22.64	132.0	133.9	2.7	2.9	210.9	21.65	137.0	128.4	2.9	7.2	211.4	21.36	138.5	126.0	2.9	13.1
55	50.0	7.7	120	223.8	22.65	146.5	134.9	2.9	2.9	225.6	21.67	151.7	129.0	3.1	7.2	226.2	21.37	153.2	126.5	3.1	13.1
55	70.0	13.5	120	230.9	22.67	153.6	135.4	3.0	2.9	232.8	21.68	158.8	129.3	3.1	7.2	233.3	21.38	160.3	126.7	3.2	13.1
65	40.0	4.9	60	279.5	11.66	239.7	78.6	7.0	3.5	281.7	11.16	243.7	71.3	7.4	8.4	282.4	11.00	244.9	68.1	7.5	15.2
65	60.0	9.6	60	292.1	11.68	252.3	79.5	7.3	3.5	294.5	11.17	256.4	71.8	7.7	8.4	295.2	11.01	257.6	68.4	7.9	15.2
65	30.0	2.9	60	268.3	11.66	228.5	77.9	6.7	3.5	270.4	11.16	232.3	70.8	7.1	8.4	271.1	11.00	233.5	67.7	7.2	15.2
65	30.0	2.9	70	262.5	13.05	217.9	87.5	5.9	3.3	264.6	12.48	222.0	80.6	6.2	8.2	265.2	12.31	223.2	77.6	6.3	14.8
65	50.0	7.1	70	280.8	13.06	236.3	88.7	6.3	3.3	283.1	12.49	240.4	81.3	6.6	8.2	283.7	12.32	241.7	78.1	6.8	14.8
65	70.0	12.6	70	289.7	13.06	245.1	89.3	6.5	3.3	292.0	12.50	249.4	81.7	6.8	8.2	292.7	12.32	250.6	78.4	7.0	14.8
65	30.0	2.9	80	256.7	14.58	207.0	97.1	5.2	3.2	258.8	13.94	211.2	90.4	5.4	8.0	259.4	13.75	212.5	87.4	5.5	14.5
65	50.0	7.1	80	274.7	14.59	224.9	98.3	5.5	3.2	276.9	13.95	229.3	91.1	5.8	8.0	277.5	13.76	230.6	87.9	5.9	14.5
65	70.0	12.6	80	283.4	14.60	233.6	98.9	5.7	3.2	285.6	13.96	238.0	91.4	6.0	8.0	286.3	13.77	239.3	88.2	6.1	14.5
65	30.0	2.9	90	251.0	16.29	195.4	106.7	4.5	3.2	253.0	15.59	199.8	100.1	4.8	7.8	253.6	15.37	201.2	97.2	4.8	14.1
65	50.0	7.1	90	268.6	16.30	212.9	107.9	4.8	3.2	270.7	15.59	217.5	100.8	5.1	7.8	271.4	15.38	218.9	97.8	5.2	14.1
65	70.0	12.6	90	277.1	16.32	221.4	108.5	5.0	3.2	279.3	15.61	226.0	101.2	5.2	7.8	280.0	15.39	227.4	98.0	5.3	14.1
65	30.0	2.9	100	245.3	18.23	183.1	116.4	3.9	3.1	247.2	17.44	187.7	109.9	4.2	7.6	247.8	17.20	189.1	107.1	4.2	13.7
65	50.0	7.1	100	262.4	18.24	200.2	117.5	4.2	3.1	264.5	17.45	205.0	110.6	4.4	7.6	265.1	17.21	206.4	107.6	4.5	13.7
65	70.0	12.6	100	270.7	18.25	208.4	118.0	4.3	3.1	272.9	17.46	213.3	110.9	4.6	7.6	273.5	17.22	214.8	107.8	4.7	13.7
65	30.0	2.9	110	239.3	20.42	169.7	126.0	3.4	3.0	241.3	19.53	174.6	119.7	3.6	7.4	241.8	19.26	176.1	116.9	3.7	13.4
65	50.0	7.1	110	256.1	20.43	186.4	127.1	3.7	3.0	258.1	19.54	191.4	120.3	3.9	7.4	258.7	19.27	193.0	117.4	3.9	13.4
65	70.0	12.6	110	264.2	20.45	194.4	127.6	3.8	3.0	266.3	19.56	199.5	120.7	4.0	7.4	266.9	19.29	201.1	117.6	4.1	13.4
65	30.0	2.9	120	233.2	22.90	155.0	135.5	3.0	2.9	235.0	21.90	160.3	129.4	3.1	7.2	235.6	21.60	161.9	126.7	3.2	13.1
65	50.0	7.1	120	249.5	22.91	171.3	136.6	3.2	2.9	251.5	21.92	176.7	130.1	3.4	7.2	252.1	21.62	178.3	127.2	3.4	13.1
65	70.0	12.6	120	257.4	22.93	179.1	137.2	3.3	2.9	259.4	21.93	184.6	130.4	3.5	7.2	260.1	21.63	186.2	127.4	3.5	13.1
75	30.0	2.7	60	304.7	12.14	263.2	80.3	7.4	3.5	307.1	11.62	267.4	72.3	7.7	8.4	307.8	11.46	268.7	68.8	7.9	15.2
75	50.0	6.7	60	326.0	12.15	284.5	81.7	7.9	3.5	328.6	11.62	288.9	73.1	8.3	8.4	329.4	11.46	290.2	69.4	8.4	15.2
75	70.0	12.0	60	336.3	12.16	294.8	82.4	8.1	3.5	339.0	11.63	299.3	73.6	8.5	8.4	339.8	11.47	300.6	69.7	8.7	15.2
75	30.0	2.7	70	297.3	13.52	251.2	89.8	6.4	3.3	299.7	12.93	255.6	82.0	6.8	8.2	300.4	12.75	256.9	78.6	6.9	14.8
75	50.0	6.7	70	318.1	13.53	272.0	91.2	6.9	3.3	320.7	12.94	276.5	82.8	7.3	8.2	321.4	12.76	277.9	79.2	7.4	14.8
75	70.0	12.0	70	328.2	13.54	282.0	91.9	7.1	3.3	330.8	12.95	286.6	83.2	7.5	8.2	331.6	12.77	288.0	79.5	7.6	14.8

Source			Load																		
				Flow 30 GPM						Flow 50 GPM						Flow 70 GPM					
EWT °F	Flow GPM	WPD FT	EWT °F	HC Mbtuh	Power kW	HA Mbtuh	LWT °F	COP	WPD FT	HC Mbtuh	Power kW	HA Mbtuh	LWT °F	COP	WPD FT	HC Mbtuh	Power kW	HA Mbtuh	LWT °F	COP	WPD FT
75	30.0	2.7	80	290.1	15.03	238.7	99.3	5.7	3.2	292.4	14.38	243.3	91.7	6.0	8.0	293.1	14.18	244.7	88.4	6.1	14.5
75	50.0	6.7	80	310.3	15.04	259.0	100.7	6.0	3.2	312.8	14.39	263.7	92.5	6.4	8.0	313.6	14.19	265.1	89.0	6.5	14.5
75	70.0	12.0	80	320.2	15.05	268.8	101.3	6.2	3.2	322.7	14.40	273.6	92.9	6.6	8.0	323.5	14.20	275.0	89.2	6.7	14.5
75	30.0	2.7	90	282.7	16.72	225.7	108.8	5.0	3.2	285.0	15.99	230.4	101.4	5.2	7.8	285.7	15.77	231.8	98.2	5.3	14.1
75	50.0	6.7	90	302.5	16.73	245.4	110.2	5.3	3.2	304.9	16.00	250.3	102.2	5.6	7.8	305.7	15.78	251.8	98.7	5.7	14.1
75	70.0	12.0	90	312.1	16.74	254.9	110.8	5.5	3.2	314.6	16.01	259.9	102.6	5.8	7.8	315.3	15.79	261.4	99.0	5.8	14.1
75	30.0	2.7	100	275.3	18.62	211.8	118.4	4.3	3.1	277.5	17.81	216.7	111.1	4.6	7.6	278.2	17.57	218.2	107.9	4.6	13.7
75	50.0	6.7	100	294.6	18.63	231.0	119.6	4.6	3.1	296.9	17.82	236.1	111.9	4.9	7.6	297.6	17.58	237.6	108.5	5.0	13.7
75	70.0	12.0	100	303.9	18.64	240.3	120.3	4.8	3.1	306.3	17.83	245.4	112.3	5.0	7.6	307.0	17.59	247.0	108.8	5.1	13.7
75	30.0	2.7	110	267.7	20.76	196.8	127.8	3.8	3.0	269.8	19.86	202.0	120.8	4.0	7.4	270.5	19.59	203.6	117.7	4.0	13.4
75	50.0	6.7	110	286.4	20.78	215.5	129.1	4.0	3.0	288.7	19.87	220.9	121.5	4.3	7.4	289.4	19.60	222.5	118.3	4.3	13.4
75	70.0	12.0	110	295.5	20.79	224.5	129.7	4.2	3.0	297.8	19.89	230.0	121.9	4.4	7.4	298.6	19.61	231.6	118.5	4.5	13.4
75	30.0	2.7	120	259.8	23.19	180.7	137.3	3.3	2.9	261.9	22.18	186.2	130.5	3.5	7.2	262.5	21.88	187.8	127.5	3.5	13.1
75	50.0	6.7	120	278.0	23.21	198.8	138.5	3.5	2.9	280.2	22.20	204.4	131.2	3.7	7.2	280.9	21.89	206.1	128.0	3.8	13.1
75	70.0	12.0	120	286.8	23.22	207.5	139.1	3.6	2.9	289.1	22.21	213.2	131.6	3.8	7.2	289.8	21.91	215.0	128.3	3.9	13.1
85	30.0	2.6	60	346.0	12.64	302.9	83.1	8.0	3.5	348.8	12.09	307.5	74.0	8.5	8.4	349.6	11.92	308.9	70.0	8.6	15.2
85	50.0	6.5	60	370.2	12.64	327.0	84.7	8.6	3.5	373.1	12.09	331.9	74.9	9.0	8.4	374.0	11.93	333.3	70.7	9.2	15.2
85	70.0	11.6	60	381.9	12.65	338.7	85.5	8.8	3.5	385.0	12.10	343.6	75.4	9.3	8.4	385.9	11.94	345.1	71.0	9.5	15.2
85	30.0	2.6	70	336.9	14.00	289.1	92.5	7.1	3.3	339.6	13.39	293.9	83.6	7.4	8.2	340.4	13.21	295.4	79.7	7.6	14.8
85	50.0	6.5	70	360.5	14.01	312.7	94.0	7.5	3.3	363.4	13.40	317.6	84.5	7.9	8.2	364.2	13.21	319.1	80.4	8.1	14.8
85	70.0	11.6	70	371.9	14.02	324.1	94.8	7.8	3.3	374.9	13.41	329.1	85.0	8.2	8.2	375.8	13.22	330.6	80.7	8.3	14.8
85	30.0	2.6	80	327.9	15.49	275.0	101.9	6.2	3.2	330.5	14.82	279.9	93.2	6.5	8.0	331.3	14.61	281.4	89.5	6.6	14.5
85	50.0	6.5	80	350.8	15.50	297.9	103.4	6.6	3.2	353.6	14.82	303.0	94.1	7.0	8.0	354.4	14.62	304.5	90.1	7.1	14.5
85	70.0	11.6	80	361.9	15.51	308.9	104.1	6.8	3.2	364.8	14.84	314.1	94.6	7.2	8.0	365.6	14.63	315.7	90.4	7.3	14.5
85	30.0	2.6	90	318.7	17.15	260.2	111.2	5.4	3.2	321.2	16.40	265.3	102.8	5.7	7.8	322.0	16.18	266.8	99.2	5.8	14.1
85	50.0	6.5	90	341.0	17.16	282.4	112.7	5.8	3.2	343.7	16.41	287.7	103.7	6.1	7.8	344.5	16.19	289.3	99.8	6.2	14.1
85	70.0	11.6	90	351.8	17.17	293.2	113.5	6.0	3.2	354.6	16.42	298.5	104.2	6.3	7.8	355.4	16.20	300.2	100.2	6.4	14.1
85	30.0	2.6	100	309.4	19.01	244.5	120.6	4.8	3.1	311.9	18.18	249.8	112.5	5.0	7.6	312.6	17.93	251.4	108.9	5.1	13.7
85	50.0	6.5	100	331.0	19.02	266.1	122.1	5.1	3.1	333.7	18.19	271.6	113.3	5.4	7.6	334.5	17.94	273.3	109.6	5.5	13.7
85	70.0	11.6	100	341.5	19.03	276.6	122.8	5.3	3.1	344.2	18.20	282.1	113.8	5.5	7.6	345.1	17.95	283.8	109.9	5.6	13.7
85	30.0	2.6	110	299.9	21.10	227.8	130.0	4.2	3.0	302.3	20.19	233.4	122.1	4.4	7.4	303.0	19.91	235.0	118.7	4.5	13.4
85	50.0	6.5	110	320.8	21.12	248.8	131.4	4.5	3.0	323.4	20.20	254.5	122.9	4.7	7.4	324.2	19.92	256.2	119.3	4.8	13.4
85	70.0	11.6	110	331.0	21.13	258.9	132.1	4.6	3.0	333.6	20.21	264.6	123.3	4.8	7.4	334.4	19.93	266.4	119.6	4.9	13.4
85	30.0	2.6	120	290.0	23.48	209.9	139.3	3.6	2.9	292.3	22.45	215.7	131.7	3.8	7.2	293.0	22.15	217.4	128.4	3.9	13.1
85	50.0	6.5	120	310.3	23.49	230.1	140.7	3.9	2.9	312.8	22.47	236.1	132.5	4.1	7.2	313.5	22.16	237.9	129.0	4.1	13.1
85	70.0	11.6	120	320.1	23.51	239.9	141.3	4.0	2.9	322.7	22.48	245.9	132.9	4.2	7.2	323.4	22.17	247.8	129.2	4.3	13.1

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