ENERGY MODELING DEVELOPMENT AND CALIBRATION FOR A MINI DISTRICT ENERGY LOOP ASSESSMENT COMPRISED OF A SET OF CAMPUS BUILDINGS

by

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of the requirements for the degree

of

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GLOSSARY or NOMENCLATURE

MSU	Montana State University
LEED	Leadership in Energy and Environmental Design
CBECS	Commercial Building Energy Consumption Survey
EUI	Energy Use Intensity
DH	District Heating
TMY	Typical meteorological year
AMY	Actual meteorological year

ABSTRACT

District energy loops are comprised of a network of buildings connected in a water-source loop with utilization of heat pumps to allow for buildings to share thermal energy. To assess the feasibility of creating a district energy loop, the heat sharing capabilities of the proposed interconnected buildings needs to be analyzed. This paper develops a method to assess a mini-district energy loop from historical utility data. Energy modeling was used to create a simple building model from building construction specifications and given inputs from the University Services Engineers on Montana State University's campus.

With the energy model developed, the historical utility data was compared to the hourly heat demand and electricity consumption for the building on an outdoor temperature basis. Calibration techniques for heat demand were comprised of increasing or decreasing the outdoor air ventilation requirement and the base heat demand. Electricity consumption was calibrated by altering the equipment plug load in the spaces.

The simulated data was validated with metered hourly heat demand data for a high-energy use laboratory building on MSU's campus. This simple energy model was reconfigured to represent another building at MSU by altering building envelope dimensions, and then re-applying calibration techniques to generate hourly heating and cooling data. Converting the model to be heat-pump compatible allowed for internal thermal energy sharing within the building to occur. Hourly heat demand and hourly heat availability were determined for external thermal energy sharing for a high-energy use laboratory building. After which, heat sources, heat sinks, and thermal energy storage tanks were assessed to determine the feasibility of a district energy loop.

INTRODUCTION

Energy Standards

All except seven states in the United States have adopted a minimum requirement for commercial buildings energy codes based on ASHRAE Standard 90.1 – Energy Standard for Buildings Except Low-Rise Residential Buildings. [1]

Beyond mandated energy standards for commercial buildings, all state owned, or publicly funded buildings have more stringent requirements. State owned buildings can consist of office buildings, public schools, colleges and universities, and numerous other facilities. These facilities can equate to as much as 10% of the government's annual operating budget [2]. Mandatory energy savings targets are put in place for new construction, as well as existing buildings in order to not only reduce energy consumption and energy bills, but also to promote energy efficient buildings and retrofit projects.

Montana State University (MSU)

Montana has passed legislation that requires all state-owned and state-leased buildings to exceed the most recent International Energy Conservation Code by 20% [3]. Montana has specifically passed the Montana High Performance Building Standard Goals, that requires all state projects with a budget larger than $5 million to achieve a minimum LEED Certification level of Silver [4]. On MSU's campus, there are currently eight LEED certified buildings. The MSU buildings and its corresponding level of LEED rating can be seen in Table 1.

Table 1. LEED Rating Level for MSU Buildings.

MSU Building	LEED Certification Level
Gaines Hall	Silver
Miller Dining Hall	Silver
Rendezvous Dining Hall	Silver
Cooley Labs	Gold
Jabs Hall	Gold
Gallatin Hall	Gold
Yellowstone Hall	Gold
Norm Asbjornson Hall	Platinum

LEED stands for Leadership in Energy and Environmental Design. MSU is committed to achieving a minimum LEED Certification rating of Silver for all new buildings and major renovations. MSU is promoting energy savings through efficient design and is committing to designing a campus based on factors like human comfort, sustainable practices, water and energy efficiency, while considering the longevity of the building itself.

MSU owns and operates campus buildings for their lifetime. Responsible energy decisions are important because these buildings will serve future students in their quest for higher education for decades and maybe even centuries to come. MSU has a program called the Smart Building Initiative; where an annual investment of $250,000 is provided to increase energy efficiency and save on long-term costs [5].

Beyond practicing efficient design at a singular building level, campuses should focus on efficient design for campus wide applications. Designing an energy loop that allows buildings to share heat with each other promotes an efficient campus through an innovative solution. Looking at the campus holistically is important into discovering these innovative ways to increase efficiency for a campus.

Table 2 shows MSU's campus annual electricity, steam, and water consumption, as well as energy use intensity (EUI) for the campus from 2014-2017. EUI is a measure of total energy consumption of a building in kBtu per usable square footage of building space per year.

Table 2. MSU energy consumption data.

Energy use	2014	2015	2016	2017	Average
Electricity (million kWh)	21.5	20.7	21.0	21.9	21.275
Steam (MMBTU)	143,289	132,463	132,708	135,647	136,027
Water (Million Gallons)	64.63	62.32	62.03	64.30	63.32
EUI (kBtu/ft^2-year)	77.7	72.5	77.0	82.1	77.33

The Commercial Building Energy Consumption Survey (CBECS) publishes energy usage data for a sample size of over 7,000 buildings. From data published in 2012, Electricity consumption (kWh) by end use was analyzed. From the results, an education building has a cooling load of approximately 20% of the total electricity consumption. A commercial building in climate zone 1, very cold/cold, has a cooling load of 9.1%, and a commercial building in the mountain region has a cooling load of 13.4% [6]. From these results, it can be inferred that 9-20% of the total electricity load for MSU is used for cooling.

If it is estimated that 20% of the electricity consumption for MSU's entire campus is indeed cooling, then an estimated 4,255,000 kWh, or equivalently 14,518 MMBTU of electricity is used for cooling per year. Along with the cooling demands on campus, the heating load is 136,027 MMBTU. This shows the need to analyze MSU's campus for a district energy loop that is capable of sharing energy from building to building.

District Heating

A heat producing facility produces heat, in this case in the form of water, to an end consumer of buildings [7]. A steam plant is a heat producing facility that is used to boil water and supply steam to hydronic fin tube radiators, or heat exchangers within buildings. On MSU's campus, district heating is accomplished using a central steam plant and significant piping infrastructure to distribute steam to a majority of campus buildings. This method does not allow MSU to share energy between buildings. Buildings connected in a loop need to use water to exchange energy instead of using steam as the single heat source.

Heat Pumps

Heat pumps allow for heat to be utilized from various heat sources and heat sinks that would be wasted in a normal district heating application [8]. Applying heat pumps on a building by building basis on MSU's campus would allow for a building in cooling mode to reject its excess heat and act as a heat source for another building that is in heating mode. The utilization of heat pumps connected to a district loop allows for buildings to transfer energy directly with one another.

Another benefit to using heat pumps as the main heat source allows for integration of renewable energy into the heating systems due to a change of fossil fuels from natural gas to electricity. Heat pumps are deemed as a viable option for integration into a district heating loop depending on multiple factors [8]. Kontu points out that these factors depend largely on electricity and fossil fuel prices. In Montana, electricity prices are relatively low and it seems feasible to integrate heat pumps into a district heating (DH) system. Out of all

DH system sizes, small systems were found to have the largest potential for heat pump integration [8].

Background

Cooling Tower

On MSU's campus, various buildings have a form of cooling that is a building level chilled water-loop integrated with cooling towers. A cooling tower is a piece of equipment that is responsible for rejecting heat from a water-loop. In building operation, chilled water is supplied to the spaces that need cooling and warmer water is returned to the cooling tower. The cooling tower is responsible for rejecting some of the heat added to reduce the temperature of the water. This water is then sent to the chiller to be cooled further to be supplied to rooms within the building. The schematic of how an open loop cooling tower works can be seen in Figure 1.

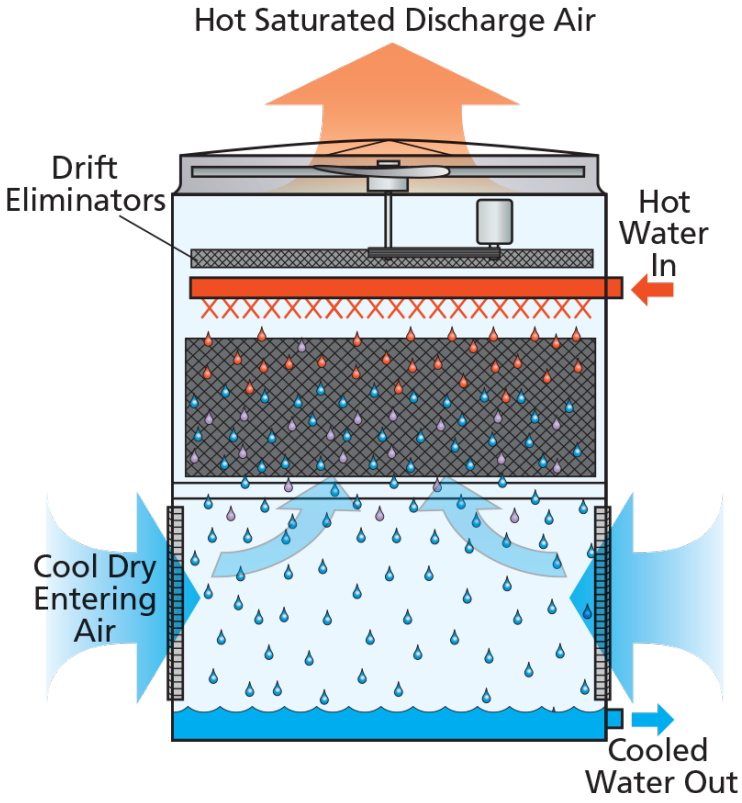


Figure 1. Basic Operation of Open Loop Cooling Tower [9].

Two types of cooling towers exist on MSU's campus: open circuit and closed-circuit cooling towers. Closed circuit cooling towers are used for glycol-water mixture water source loops so that the glycol is not evaporated into the air potentially causing health issues. Open circuit cooling towers are primarily used for chilled water loop containing only water. This also requires make-up water to be supplied to the cooling tower to account for the water evaporated off the chilled water stream.

For a campus set of buildings, different buildings are going to be in cooling mode and heating mode simultaneously. Instead of rejecting heat via the cooling tower, a building in heating mode can exchange heat and utilize this rejected heat from the cooling tower due to integration of heat pump technology.

Refrigeration Cycle

A heat pump uses the refrigeration cycle to provide either heating or cooling to a space. If a heat pump is in cooling mode, the air stream flows over the evaporator, thus providing cooling the the form of cool air. This in turn requires heat to be rejected off the condenser. A basic schematic of how a refrigeration cycle works can be seen in Figure 2.

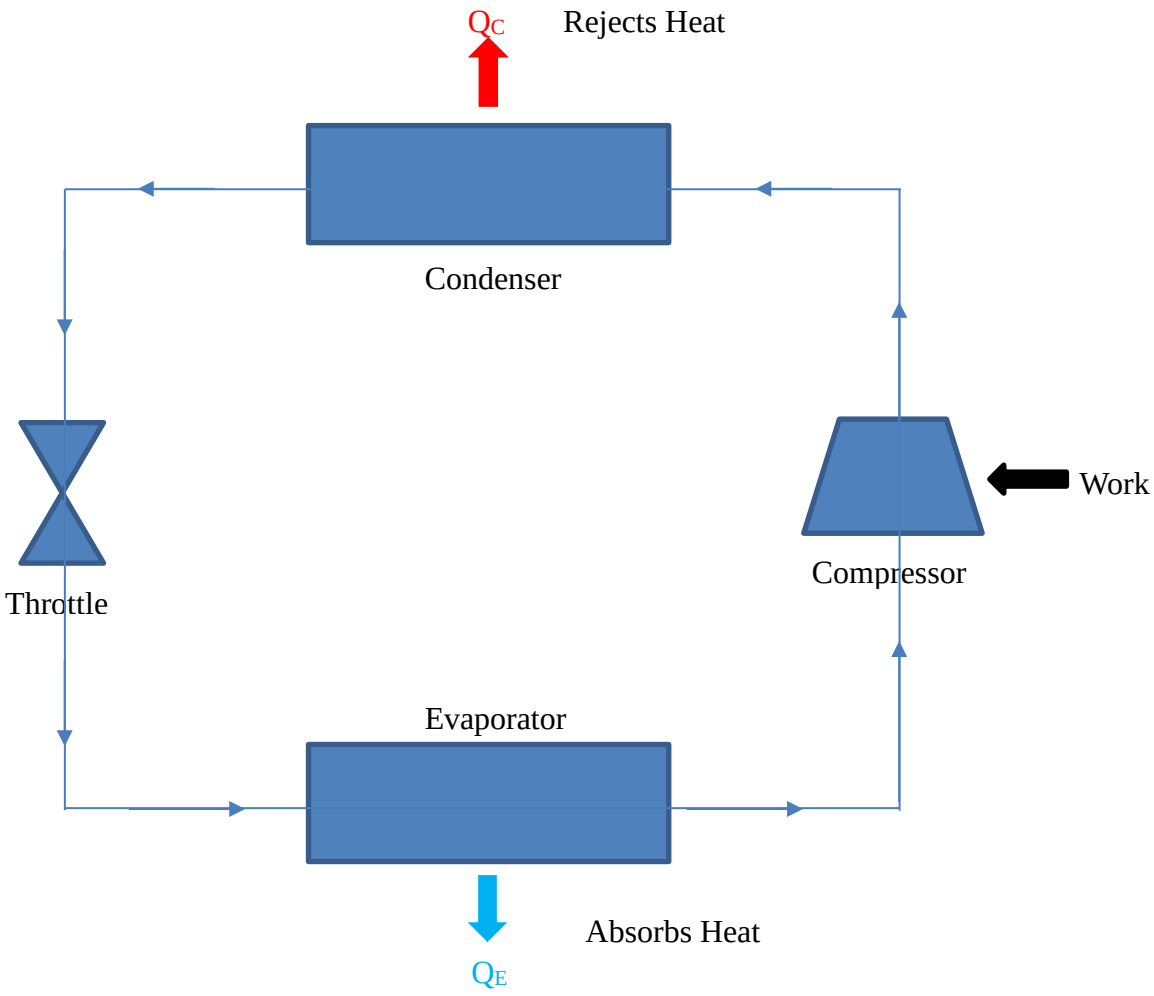


Figure 2. Refrigeration cycle.

Mini-District Energy Loop

District heating is the distribution of heat to various buildings connected in a piping network from a centralized heat source or various heat producing facilities or entities. In Finland, roughly half the population live in district-heated buildings [10].

District heating has gone through three main generations and types of district networks. The first generation started in the United States around the 1880s using steam as the main source for heat distribution. Due to high heat loss with the utilization of steam within ducting led to the second generation. The second generation supplies pressurized water at very high temperatures, usually over 212^{o}F, rather than steam. This generation thrived from around 1930 to 1970 due to the utilization of combined heat and power (CHP) plants. The third and newest generation supplies pressurized water similar to the second generation, but at temperatures below 212^{o}F [11].

There has been a lot of recent research on low temperature district heating. [12] points out that lower temperatures lead to less heat loss in distribution piping, and allows for easier integration with renewable energy sources.

In one research paper, a control mechanism was developed to optimize the set point temperature of the district energy loop by controling the integration of arbitrary sources and consumers [13]. This conrol mechanism was implemented in two different cases, one in California and one in Germany. These two cases led to 58% and 84% primary energy consumption reduction from gas-fired district heating to bidirectional low temperature district energy systems with this agent-based control [13]. Also this research shows a 13%

reduction in electricity when there is a temperature set point control for low temperature networks when compared to a free-floating temperature.

Optimal design for low temperature bidirectional district energy loop in regards to diversity of heating and cooling loads research was performed by [14]. Other research delves into the integration of renewable energy and storage systems into district energy loops [15], [16].

However, none of the research performed shows analysis for buildings that should be connected together in a district energy network for an optimum energy loop, nor how to develop a process to identify these buildings and assess the overall thermal profile for every building integrated in the mini-district energy loop.

Any campus consisting of multiple buidlings with the interest of developing a district energy loop must first develop a thermal profile. A thermal profile for campus would be an assessment of the hourly heat demand and hourly heat rejection or heat availability quantities for each building. However, a campus with multiple buildings won't have hourly sub-metering in place for every building to determine the hourly heat demand and heat availability profiles. Most campuses have basic utility data.

A district energy loop is an energy loop that allows for associated buildings to be connected together to share thermal energy. A mini-district energy loop is a small subset of buildings within a campus connected together via a water source loop. Buildings within the mini-district energy loop use water source heat pump technology to directly share energy from building to building. A schematic of a basic mini-district energy loop connected to just two buildings can be seen in Figure 3.

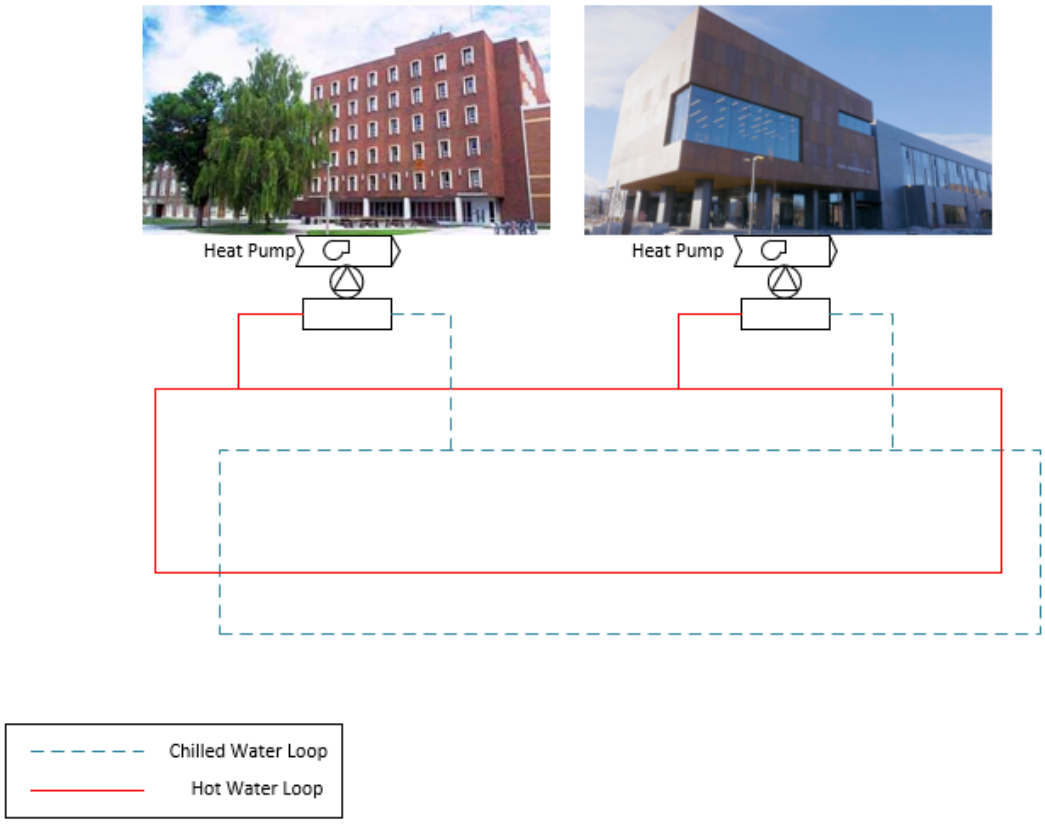


Figure 3. Mini-District Energy Loop Schematic Example.

Purpose

The goal of this research is to develop a model which creates hourly heat demand and heat availability data from documented historical utility data. This hourly heat demand and heat availability data can then be used to assess the feasibilty of connecting various buildings together to form a mini-district energy loop.

Need for research

To analyze a set of buildings on a campus, creating in-depth energy models of every building is one option. The problem with this option is that it can be expensive and time consuming. Even after an energy model is created, there needs to be validation with the heating and cooling loads to have certainty in the results. This expresses need to develop a simple and relatively accurate model of the building. Developing a method that can transform historical utility bill data into an hourly report for building heating and cooling needs will help facilitate the analysis for a district energy loop. There is no need for integration of expensive data logging devices to continually monitor hourly demands for heating and cooling and it will cut down on time and cost of creating energy models from scratch for every single building.

Currently there are no existing models that describe how to develop a mini-district energy loop for a group of buildings on a campus using only historical utility data. The monthly utility data can then be used to calibrate the model to obtain an accurate hourly load profile. This is a vital step for assessing a thermal profile for a building in the analysis of a mini-district energy loop.

DEVELOPMENT OF MODEL

When designing a district energy loop for a campus setting, the main information required for the analysis is hourly heat demand and hourly heat rejection data. The ultimate goal is to determine the buildings that have heat to reject and if it corresponds to an exact time when another building has a heat demand. Hourly heating and cooling data provide information regarding the heat sharing capabilities between buildings. The method of analyzing the thermal energy sharing capabilities between buildings for implementation of a mini-district energy loop can be seen in the following flowchart in Figure 4.

In order to get hourly heating and cooling data, there are two main options: energy modeling or extensive sub-metering of systems.

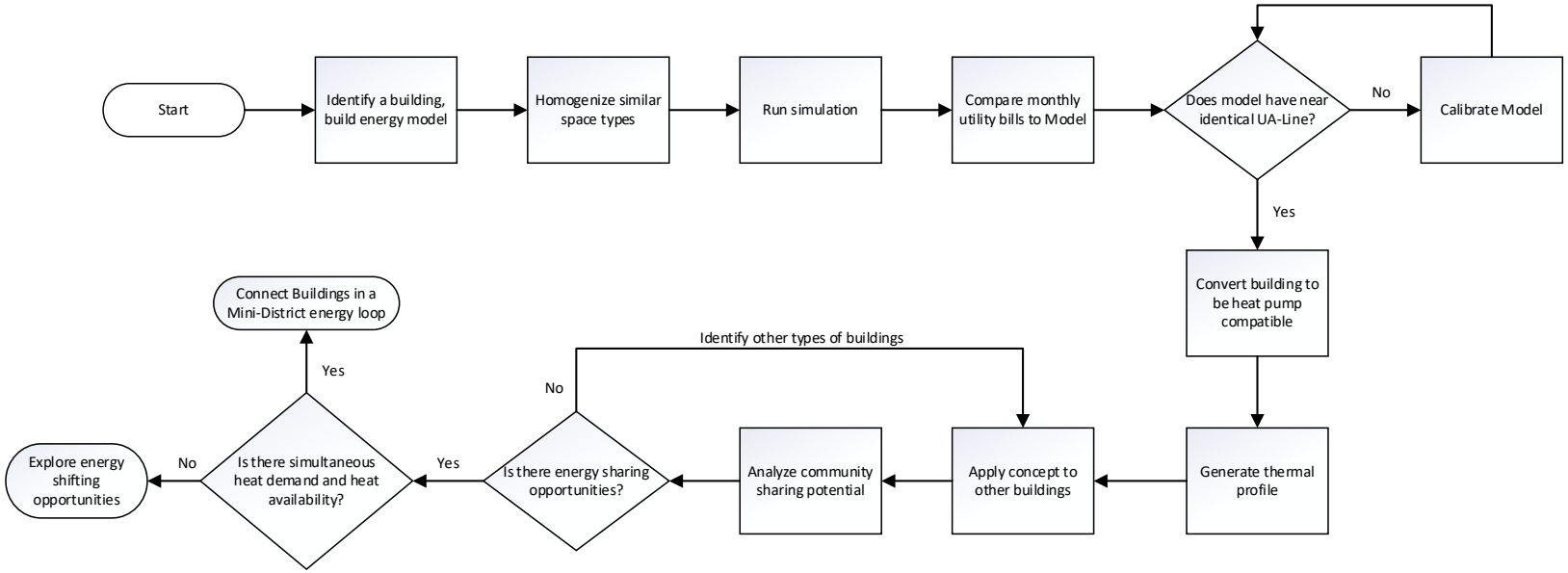


Figure 4. Development of Model Flowchart.

Sub-metering

To get hourly heating and cooling data, metering systems would need to be installed on steam supply lines at building entry, electrical panels, and specifically on the piece of cooling equipment in the building i.e. the cooling tower, condenser unit or the specific equipment is used to reject heat. Metering the steam input into the building on MSU's campus is accomplished by metering the condensate return. This measures the amount of water in gallons, returned to the heating plant. The amount of water pumped back can be correlated to the amount of steam originally serviced to the building. However, this is not the exact heat demand due to heat losses in the piping. This information provides a very close estimate of the heat demand on a whole building level in hourly increments.

Metering the cooling tower is required to obtain information on how much heat is available within the building. This information is vital into creating a thermal profile for the building and assessing the quantities and exact times that a building either has heat to share or has a heat demand. Metering a building can be expensive and takes at least a year to accrue data that is of interest.

Energy Modeling

The other option to sub-metering the entire building, would be to create an energy model. An energy model is a model developed by computer software that inputs specific parameters and calculates heating and cooling loads, and more importantly, hourly heating demand and cooling quantities for a building. Energy modeling could be done at a much faster pace than metering and at a much lower cost. The drawback is obtaining accurate

results. Various inputs into an energy model can drastically affect the results. A very thorough energy model does not necessarily lead to accurate data files.

Plan of attack

The purpose of this research was to develop a model that any campus can use to analyze a set of buildings for a district energy loop given monthly building utility data. Sub-metering the campus and analyzing the data was not deemed as a reasonable method. Instead, an energy model, capable of being calibrated with monthly utility data to obtain accurate results, was chosen as the main source for obtaining relevant information from the building.

For the analysis, an energy model will be created, and then calibrated with real historical utility data from the building. Given this calibrated model, the heat demand and cooling possibilities for a given building on a campus setting can be assessed, and conclusions can be drawn into the development of a district energy loop. The heat being rejected off the cooling tower can lead to the amount of heat available for a given building to share. For the future of this paper, heat availability will refer to the heat being rejected by the cooling tower.

Trane TRACE 700

The energy modeling software chosen for this research was Trane TRACE 700 [17]. This software was chosen for its capabilities of modeling building systems at a high level, as well as its prominent use on MSU's campus. Commercial buildings are typically dominated by internal loads, which means that building energy loads are dictated by

activities and equipment taking place inside the buildings. This means that buildings in a cold climate could be in cooling mode year-round. The goal from the energy model is to get an hourly heating demand, and an hourly heat rejection profile for each given building. There are 8,760 hours in a year, so in the future of this paper, the 8760 files will refer to an hourly energy report.

ASHRAE Standard 140 – *Standard method of Test for the Evaluation of Building Energy Analysis Computer Programs* is a standard that various energy simulation based programs must be in compliance with in order to be validated as an energy simulation program [18]. Trane TRACE 700 was tested in compliance with ASHRAE Standard 140-2014, and is BESTEST (Building Energy Simulation Test and Diagnostic Method) validated for calculation and comparison with similar analysis programs [17].

Cobleigh Hall

Cobleigh Hall is a six-story laboratory and office building on MSU's campus. This building was chosen as the starting point of this research because of its well documented historical utility data, as well as its available hourly condensate return meter data. In order for a model to be developed and be deemed as accurate, good utility data must be in place for calibration of the energy model. Also the current metering of hourly heat demand into the building allows for validation of the energy model and techniques used to develop the model.

Inputs to the model

In order for the energy model to be an accurate representation of the building itself, inputs from the actual building itself were required. The major inputs required for facility services to provide for the energy model are listed as following:

- Building dimensions
- Generic R-values for building envelope
- Window percentages by façade
- Functions of given spaces and layout of interior spaces
- Occupancy, lighting, and equipment schedules
- Thermostat settings and setbacks
- HVAC equipment configuration
- Power rating on fan equipment
- Pump head on chiller (if applicable)
- Plant type or recourses consumed in the building
- Weather file in TMY or similar format.

Lighting occupancy density, equipment plug load density and unspecified R-values were default to ASHRAE Standard 90.1 - 2013 [19]. Also airflow design specifications were default to ASHRAE Standard 62.1 – 2013 [20]. Weather files in a TMY3 format can be downloaded from NREL's site, the National Solar Radiation Data Base [21].

Setting up the initial energy model accurate was crucial to the accuracy of the following analysis performed. One method used to simplify the energy model was to homogenizing the space types within the building. For Cobleigh Hall, offices are located on the perimeter of the building, and the interior space is designated as laboratories. The

first floor of the model was developed using a perimeter and core five-zone model. A graphical representation can be seen in Figure 5.

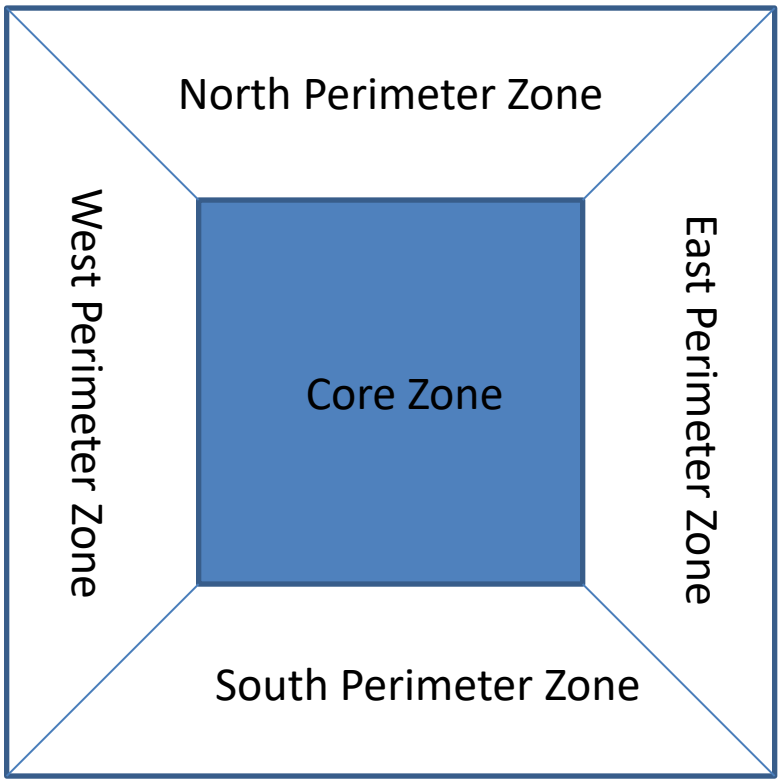


Figure 5. Perimeter and core five-zone model.

This homogenized building model was applied to Cobleigh Hall on a per floor basis. Once the first floor of the model was set up, each additional floor was input into the energy model using the "Copy" function built into TRACE 700. This was done to drastically decrease modeling time and was only able to be done because each floor of the building was similar in space type utilization. The first floor was defined to have slab on grade construction, and the top floor was set up to have a roof, which the other floors did not have.

Once the energy model was created, an hourly energy report of the building was performed. This 8760 had to be compared to the historical utility data for the building, so the monthly consumptions were compared. One issue when comparing the monthly consumptions for both steam input into the buildings, as well as electricity consumption, is the weather file. The bin weather file used does not exactly correspond to any given year of historical utility data. Weather files derived for use of energy model simulations are more comprehensive methods that represent weather data that are closer to a long-term average instead of any one single year. TMY3 weather files were created for cites with a minimum of a 15-year period of consistent weather data; this allows for a statistical character of climate for a given location rather than including extreme temperatures [22]. For this research, instead of just comparing end consumption uses, the monthly consumption defined by an average monthly temperature was compared for the 8760 file to the historical utility data.

For the historical utility data, the monthly average temperature for the respective year was found through Weather Underground [23].

For the 8760 file, the hourly temperature was averaged for each month. The electricity consumptions, as well as the steam consumption for the building was summed over the entire month. The comparison for the historical utility data and the model for the monthly electricity consumption can be seen in Figure 6.

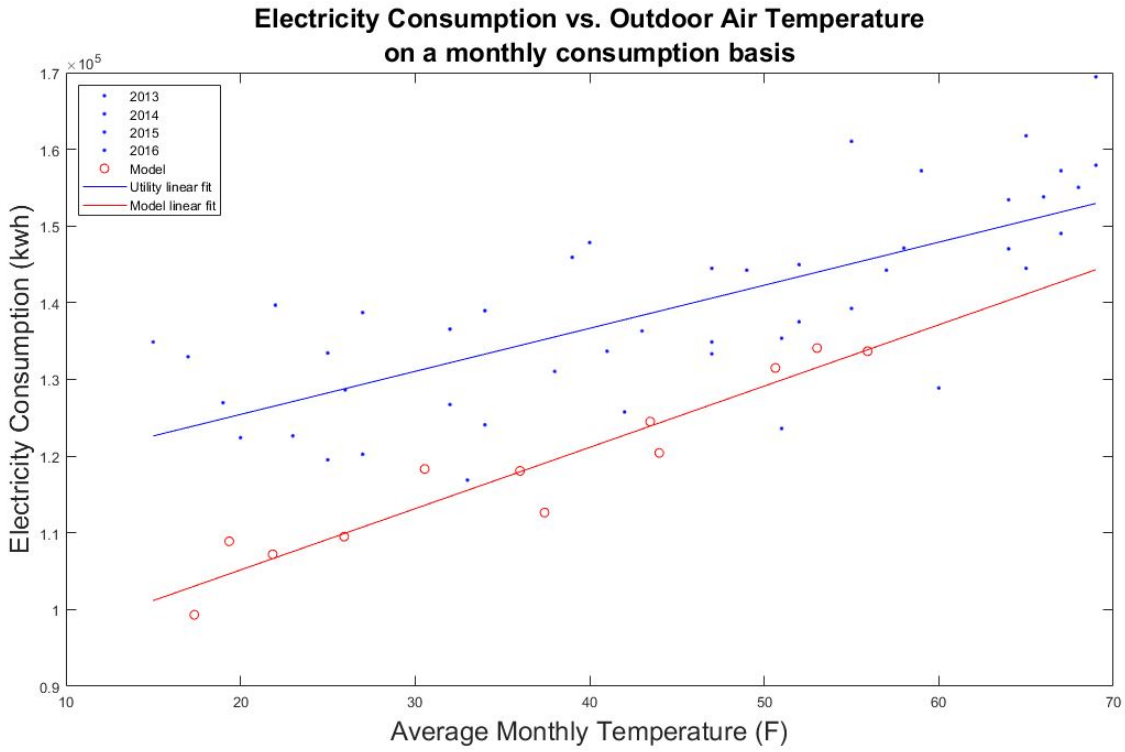


Figure 6. Initial electricity report compared to historical utility data.

The comparison for the historical utility data and the model for the monthly steam consumption can be seen in Figure 7.

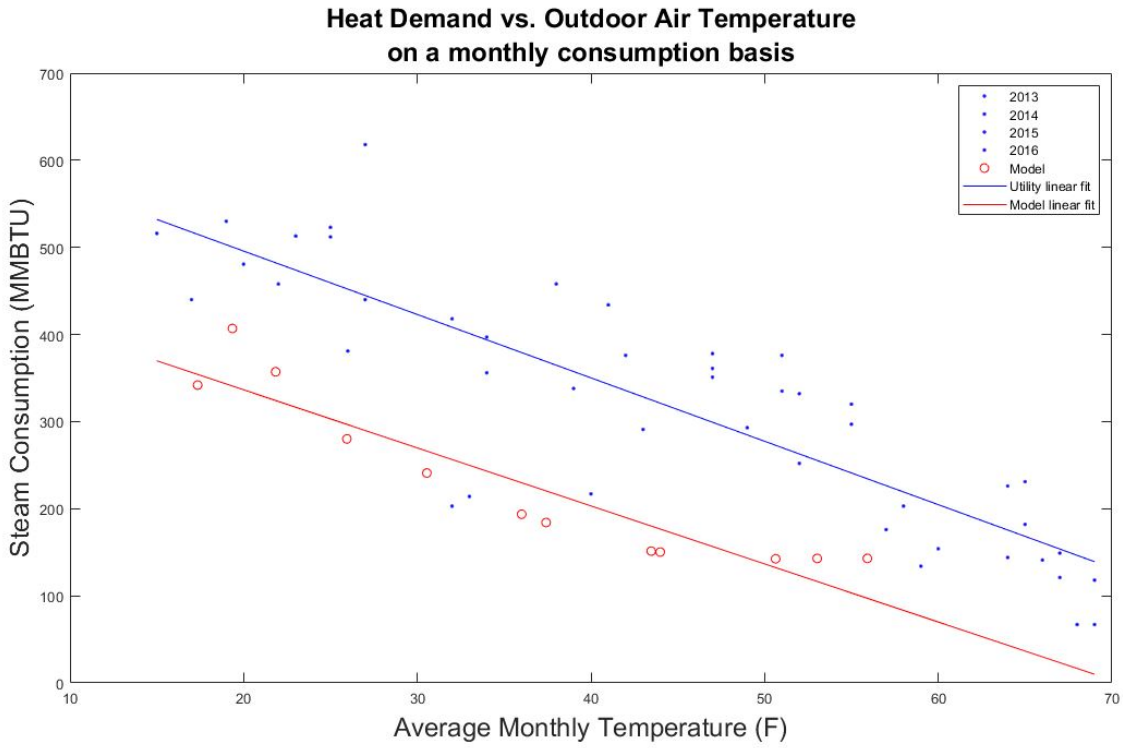


Figure 7. Initial steam report compared to historical utility data.

From Figure 6 and Figure 7, it can be seen that there is a need for calibration of the energy model. The electricity consumption, and heat demand for the building are far from where the building is actually performing. This model is therefore in need of major calibration in order to represent the building being modeled with higher accuracy.

Calibration

From the initial comparison, it can be seen that the historical utility data, and the 8760 file don't exactly match up on either the heat consumption for the building, or the electricity consumption. The energy model therefore must be calibrated on two major sections: the electricity consumption and the heating load.

Electricity Calibration

Calibrating the electricity consumption for the building can be done in a myriad amount of ways: changing the lighting load, equipment load, equipment plug load, scheduling, etc. Given the initial inputs of HVAC equipment sizing, lighting loads, as well as schedule of the building itself, altering these would not lead to accurate results. This leaves changing the equipment plug load of the lab spaces. Knowing the exact equipment load from the various lab spaces is nearly impossible unless already monitored. In the case of this building, or most buildings on any campus setting, not having metered electric loads per laboratory space leads to making estimates on equipment plug load. Thus, the energy model was calibrated by changing the equipment plug load density within the high use laboratory spaces. The calibrated results can be seen in Figure 8.

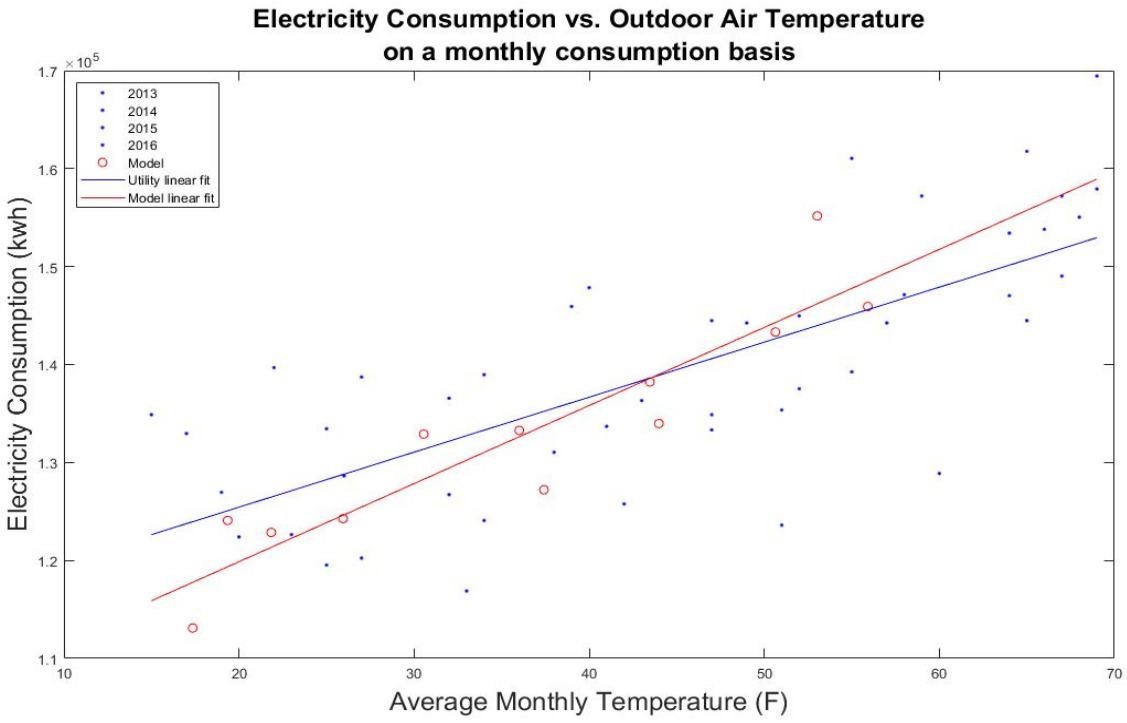


Figure 8. Calibrated electricity report compared to historical utility data for Cobleigh Hall.

Heating Load Calibration

The other major part of calibration for the building was to calibrate the heating load. The heating load could be altered through infiltration rate, façade R-values, outdoor air intake, or any scheduling. Once again, it was verified that the correct schedules were input into the original model, so the main source of calibration had to be one of the other methods. All of the other methods have one thing in common: outdoor air. Altering the infiltration rate, façade R-values and outdoor air intake, all change the outdoor air coming into the building. Infiltration and façade R-values come in as a space load, whereas the outdoor air intake would only be considered an HVAC equipment load.

A space load would correspond to the outside air temperature directly cooling down the space by infiltrating through the walls, doors, and windows, or through heat conduction through the walls. Because the room is changing temperature the supply air temperature is what is heating up or cooling down the space. If the outdoor air only directly goes to the HVAC equipment through increased outdoor air intake, then that outside air temperature never reaches the space, instead it is heated up before it ever enters the space. In the case of Cobleigh Hall, the building is pressurized which means that there is no air infiltration through any surface.

Original R-values given from the construction documents were verified accurate, so the main increase in outdoor air had to increasing outdoor air intake. Due to high exhaust rates in laboratory spaces, the outdoor air intake into the laboratory spaces was increased. The calibrated heat demand for the building can be seen in Figure 9.

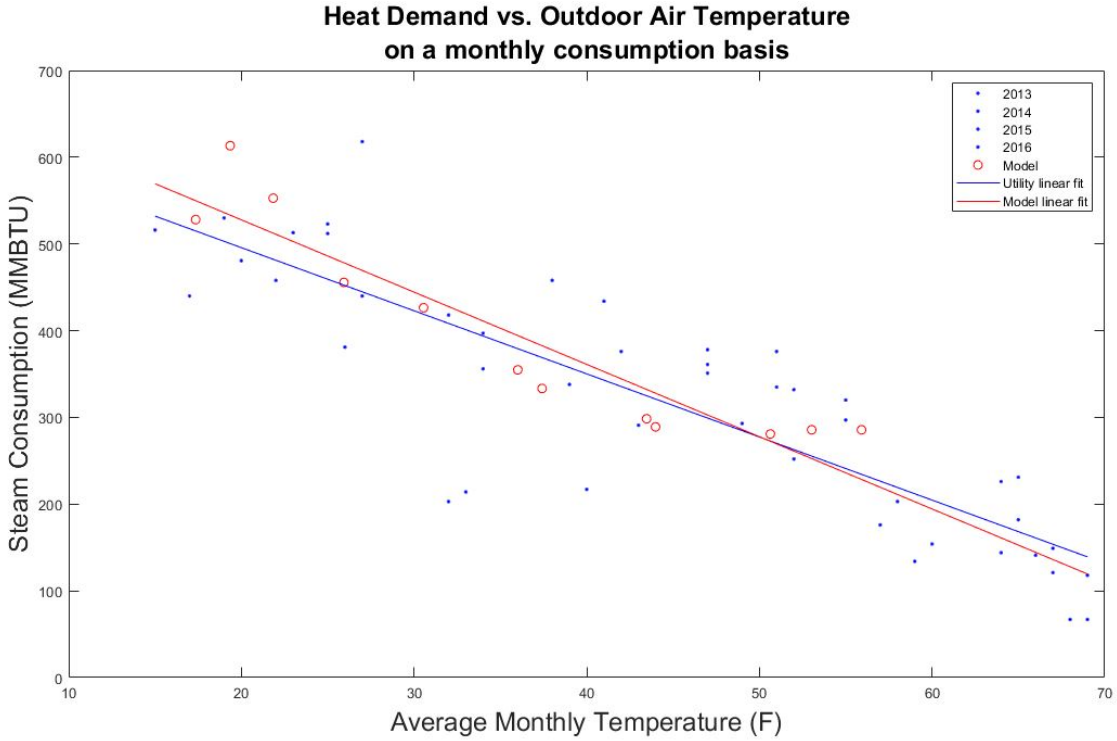


Figure 9. Calibrated Steam report compared to historical utility data for Cobleigh Hall.

This implies the assumption that the increase in outdoor air is valid as a direct HVAC equipment load rather than a space load.

Assumptions in Calibration Method

Infiltration:

$$q_s = \frac{Q * c_p * \Delta T}{v_o}, \qquad where\ Q = \frac{ACH * V}{C_T} \tag{1}$$

Outdoor air intake on unit:

$$q_s = \frac{Q * c_p * \Delta T}{v_o} \qquad where\ Q = CFM_{outdoor\ air} \tag{2}$$

Wall façade R-values:

$$q_s = \mathrm{U} * \mathrm{A} * \Delta T \tag{3}$$

As can be seen from equations 1, 2 and 3, all are a function of ΔT, where $\Delta T = T_i - T_{OA}$. This means that all are directly affected by T_{OA}, the outside air temperature. After calibrations techniques were applied, the energy model resembled a more accurate representation of the actual building itself according to the outdoor air temperatures. The key result of interest within this energy model is the hourly energy report containing hourly heat demand and hourly heat rejection for a given building. This hourly energy report is designated as a building thermal profile. With the energy model calibrated with historical weather and utility data, the model has now gone from utility bills, to hourly data. The thermal profile for Cobleigh Hall can be seen in Figure 10.

Thermal Profile

The thermal profile for Cobleigh Hall can be seen on the following page in Figure 10. It can be seen that there is constant heat available year-round for Cobleigh Hall as well as a constant heat demand for the building year-round. This can be seen by the offset in the heat demand. This constant heat demand and heat availability for Cobleigh Hall shows the ability for the building to share heat internally before analyzing additional buildings and comparing the thermal profiles of multiple buildings. Sharing heat internally within a building is possible if the building mechanical systems are converted to be heat pump compatible. Using heat pumps as the main cooling source will allow for direct sharing of excessive heat due to cooling requirements. This heat pump would serve in lieu of the cooling tower during times of the year when there is heat demand at the same time as heat availability. The cooling tower would only be necessary when there is no more heat demand.

Heat Pump Conversion

A thermal profile can show all the heat sharing capabilities of a campus in a general sense. One method for these buildings to transfer heat with one another is via a heat pump. A heat pump will also allow for the building to share energy internally before being shared with other buildings.

Modeling the building as heat pump compatible requires knowledge of how much heat is available, as well as COP profiles for specific heat pumps. Converting a building to heat pumps will increase the direct electric load on the building due to the constant load on

the compressors in the heat pump but will drastically decrease the steam heat load input into the building. Enough heat has to be available to share internally for the cost to outweigh the increase in the electric load.

For this model, the heat pump conversion was achieved through modeling in TRACE700. This was done due to ease of operation and functionality through the TRACE program itself. The new 8760 file can be seen in Figure 11.

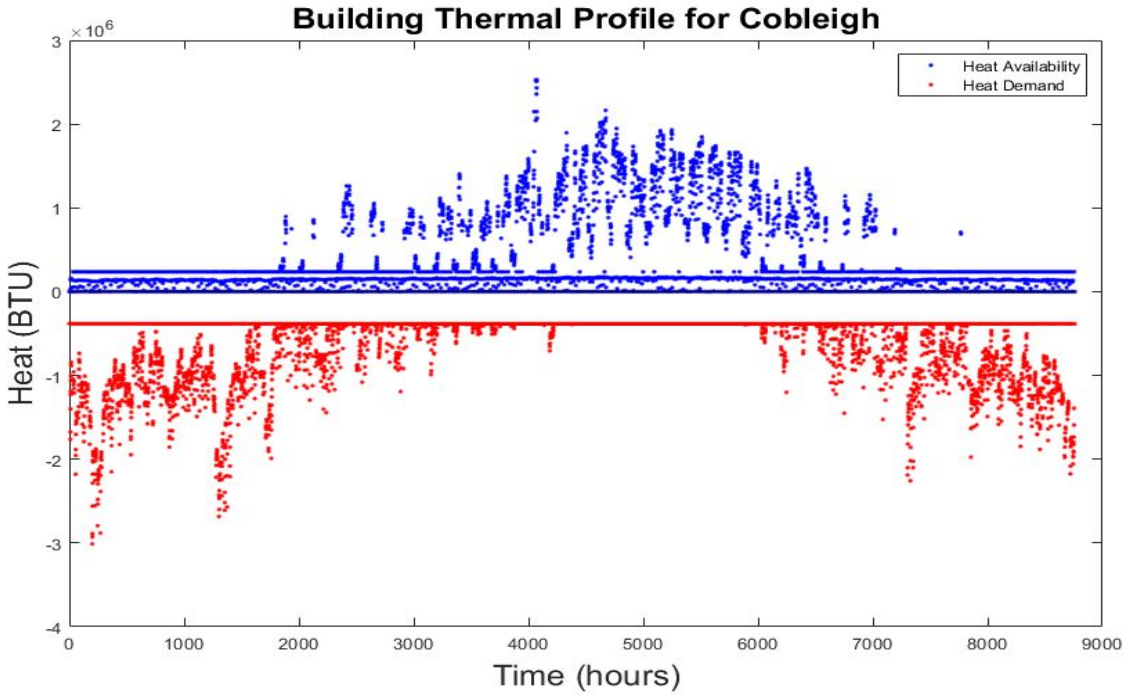


Figure 10. Cobleigh Hall thermal profile showing heat demand and heat availability as an hourly report.

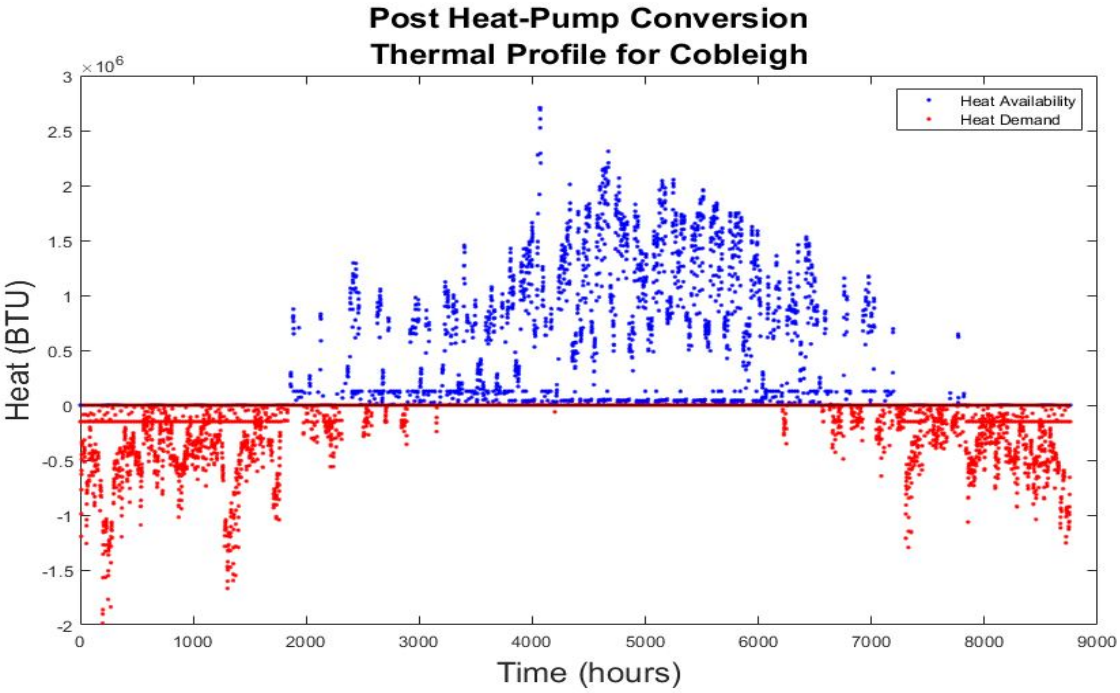


Figure 11. Cobleigh Hall thermal profile Post-Heat pump conversion showing heat demand and heat availability as an hourly report.

The thermal profile for Cobleigh Hall after the heat pump conversion no longer has constant heat availability during the winter months, and there is no heat demand for the summer months. After this conversion, the building does not have any simultaneous heat demand and heat rejection, instead, the building is able to share energy internally. There are now two main periods for this building, the period of heat rejection during the summertime, and the period of heat demand in the wintertime. There is however, a period during the off-season months where there is excess heat some weeks, and then heat demand on other weeks. This would indicate that there is some possibility for shifting energy around with the use of thermal energy storage. The use of thermal energy storage will be discussed in the next chapter. The comparison of Cobleigh Hall for the original model, and post-heat pump conversion can be seen in Table 3.

Table 3. Comparison of energy consumption before, and after heat pump conversion for Cobleigh Hall.

Energy Source	Cobleigh Hall Pre Heat Pump Conversion	Post-Heat Pump Conversion	Percent Change (%)
Steam Consumption (MMBTU)	4,705.5	858.4	-81.8%
Electricity Consumption (kWh)	1,594,323	1,706,970	+7.1%
Maximum Electric Demand (kW)	427	502	+17.6%
Building Site Energy (kBtu/ft^2-year)	127.9	84.3	-34.1%
Source Energy (kBtu/ft^2-year)	268.2	231.7	-13.6%
C0$_2$ Emissions (Metric tons) [24]	1376	1252.5	-9.0%

From the conversion, it can be seen that the steam consumption is decreased drastically by 81.8%. However, the electricity consumption and maximum peak electric demand increase by 17.6 % and 7.1% respectively. In order for the heat pump conversion to be realistic, the overall utility cost after a heat-pump conversion in the building must be lower. Building site energy, is the total amount of energy consumed by the building. Whereas source energy incorporates the process of how the energy was originally produced and serviced to the building. Electricity generation incurs substantial losses, and associating the total energy required to produce that given electricity and associate all of the losses in production and transmission is important to analyze the buildings overall impact. In this case, the most important result for the decrease in total energy is the decrease of 13.6% in the source energy for the building. Another metric to discuss is the decrease in CO_2 emissions from this decrease in overall energy consumption. For this paper, only a preliminary analysis using an EPA estimator was used [24]. From this estimator, the CO_2 emissions was reduced by approximately 9%.

For a brief cost comparison, the utility rates at MSU will be examined to confirm a lower annual utility cost. At MSU's campus, 1 MMBTU of steam costs roughly $10. The electricity consumption rate is around $0.10/kWh, and the electric demand charge is around $10/kW. The annual utility costs can be seen in Table 4 for reference.

Table 4. Comparison of energy consumption before, and after heat pump conversion for Cobleigh Hall.

Energy Source	Cobleigh Hall Pre Heat Pump Conversion	Cobleigh Hall Post-Heat Pump Conversion	Change
Steam Charge	$47,055	$8,584	-$38,471
Electricity Consumption Cost	$159,432.30	$170,697	+$11,264.70
Electric Demand Cost	$4,270	$5,020	+$750
Total annual utility cost	$210,748.30	$184,301	-$26,447.30

From the results, it can be seen that the annual utility cost for a post heat pump conversion is $26,447.30 lower than that of the original system layout. The post heat pump conversion is at a lower annual utility cost because it is able to utilize waste heat produced during simultaneous cooling and heating loads. The total heat load saved internally in the building was 3,847 MMBTU or $38,471, however, the cost to move that energy was $11,264.70 due to the increase in electricity consumption from the compressors running on the heat pump.

Applying Concept to Other Buildings

The process described above for Cobleigh Hall can be applied to other campus buildings. This process includes homogenizing the building into specific space types using the core and perimeter 5-zone model, then starting the development of the model. Exterior wall dimensions, space sizes, and window percentages by façade are first set up, then the floors are copied and pasted until the energy model physically represents the actual

building. Once this is achieved, building HVAC equipment sizes are altered, then results are generated. After the results are generated, the same calibration techniques are performed in order to get historical utility data to match up with the model results compared to outside air temperature. Once the model is calibrated, the 8760 file is generated, and a post heat pump conversion for the building is applied. The inputs into the energy model for Barnard Hall can be found in Appendix B.

The calibrated model for electricity consumption and heat demand compared to historical utility data for Barnard Hall can be seen in Figure 12 and Figure 13.

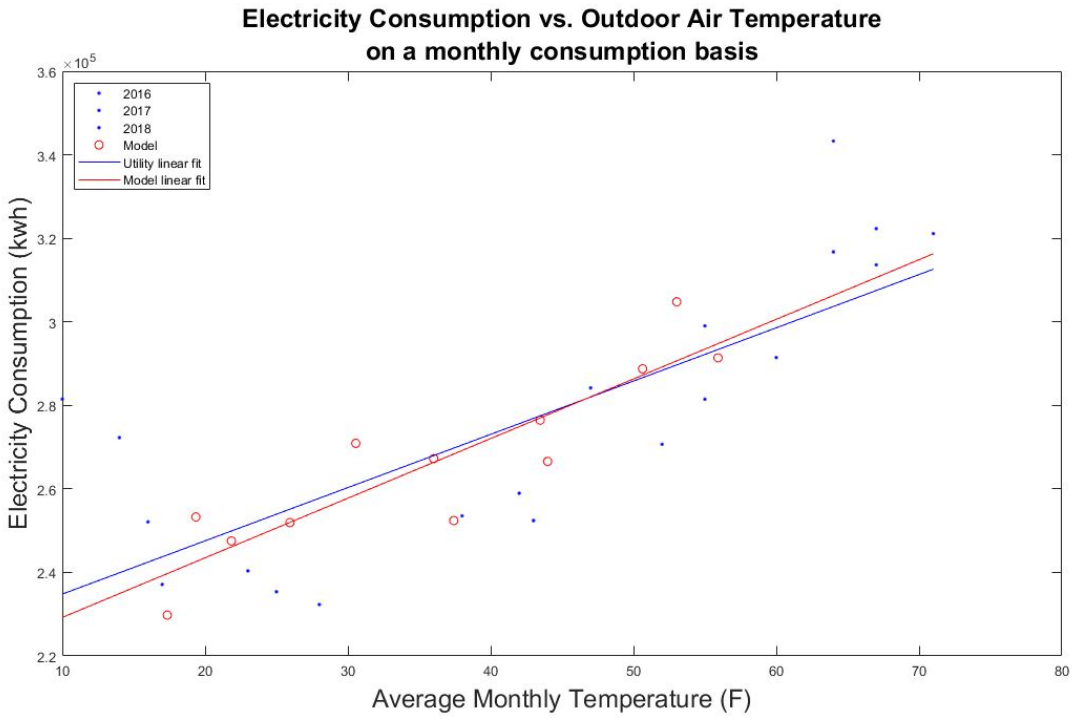


Figure 12. Calibrated electricity report compared to historical utility data for Barnard Hall.

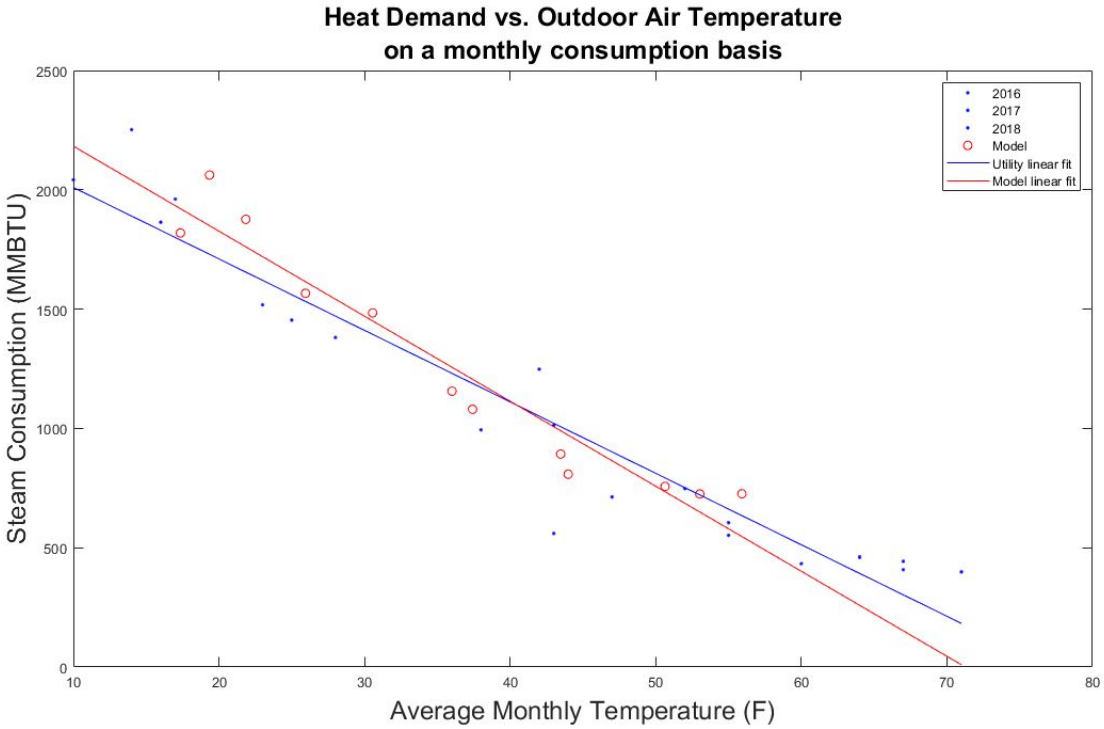


Figure 13. Calibrated Steam report compared to historical utility data for Barnard Hall.

The thermal profile for Barnard Hall for the original design, and the post heat pump conversion can be seen in Figure 14 and Figure 15.

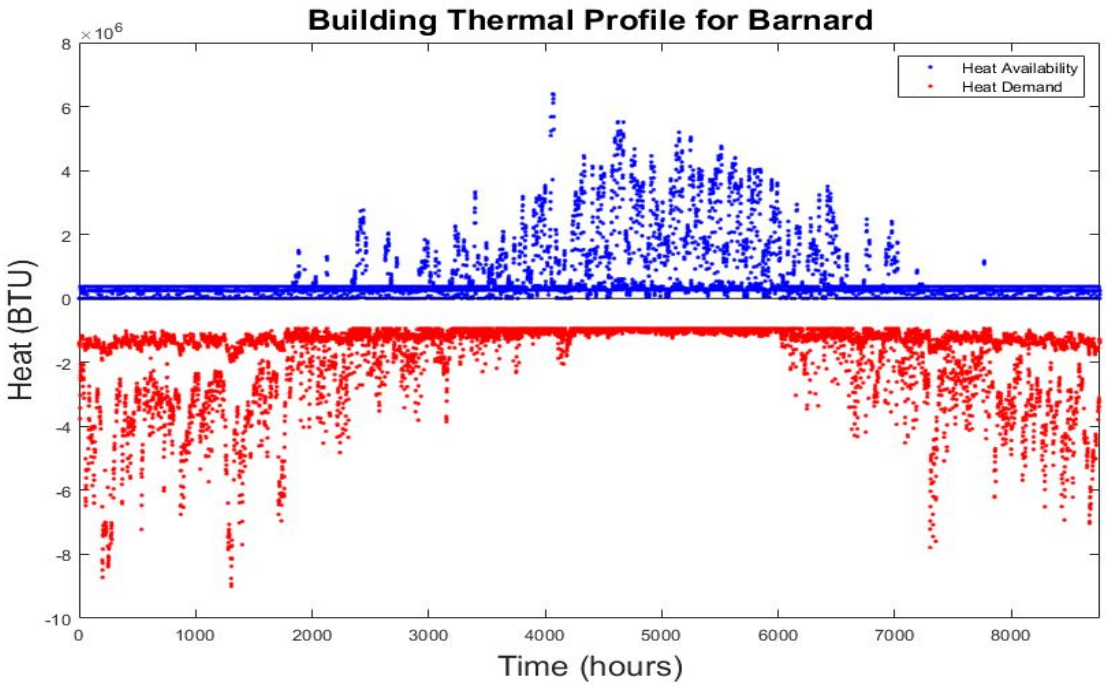


Figure 14. Barnard Hall thermal profile showing heat demand and heat availability as an hourly report.

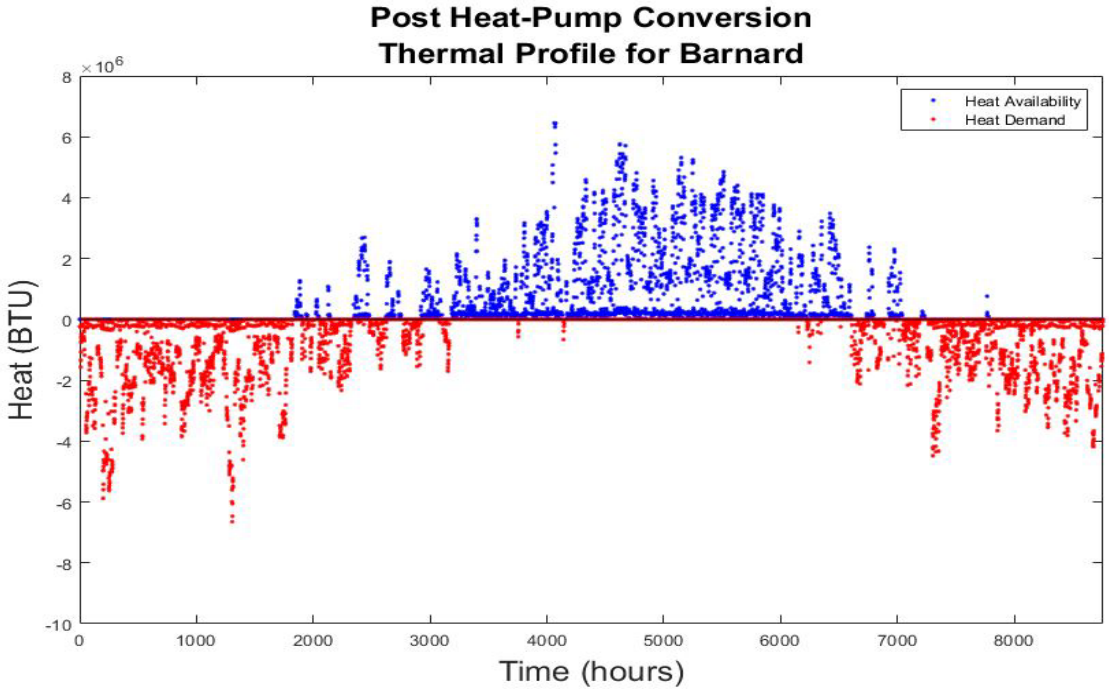


Figure 15. Barnard Hall thermal profile Post-Heat pump conversion showing heat demand and heat availability as an hourly report.

The conversion from the already defined model for Cobleigh Hall was easily altered to represent Barnard Hall. From the energy model, it can be seen that Cobleigh Hall and Barnard Hall have very similar heat rejection and heat demand profiles. This is what was expected due to the fact that the buildings have the same function and are very similar in layout. The magnitude of the heat demand and heat rejection are however different. This is due to the different size of the buildings, and their respective usable square footages of various spaces.

Validation

Throughout the development of this model, hourly heat demand and heat rejection for a given building has been produced from historical utility data. Knowing the exact time that a given heat demand and heat availability for a given building is important in the development of a mini-district energy loop. Heat sharing capabilities between buildings must happen instantaneously, which means that the 8760 file generated from this model must be accurate. In order to validate the results presented, the heat demand within Cobleigh Hall will be compared to an hourly report from the building itself.

In order to compare the model to the actual building itself, the configuration of the metered data must be reviewed. For Cobleigh Hall, steam is supplied to the building and runs through fin-tubbed radiators on the exterior of all of the offices. Reheat coils in the laboratory spaces also use steam to supply hot air to each space as well. The metered data for heat demand is set up as metering the condensate return line. All steam supplied is assumed to return as condensate and is pumped back to the heating plant. Due to some losses in the system, this will not be 100% accurate, but will be very close to the actual

supply. There is roughly a 1000-gallon tank in the mechanical room in Cobleigh Hall. When this tank completely fills up, the return pump turns on and cycles the water (condensed steam) back to the heating plant. Because of this setup, heat demand is only assessed in intervals due to a number of cycles from the pump turning on per hour.

The data we want to validate is high steam use during the winter months, as well as a low steam use during the summer months. This would allow us to validate the base heat loss which can be assessed in the summer months, as well as the hourly loads seen in the winter. The metered data obtained from University Services for this project had a few gaps in it. The gaps in the hourly metered data were from the meter being stuck, and reporting the same value for several days. This happened a few times in the data. Because of this, only two months were compared for the hourly metered data and the 8760 file generated from the model. The two months chosen for comparison were February and August. These months were chosen because they resembled a winter and summer month, as well as there was consistent, accurate data given from the metered report and no such gaps in data existed.

February

The condensate return data for Cobleigh Hall provided was from February 2018. This data was compared to the heat demand for Cobleigh Hall for the original model before the heat pump conversion. The data was directly compared to heat demand in BTUs vs. hour in February. Figure 26 and Figure 27 in Appendix D show the comparison on a month basis and week basis in order to get a good feel for the similarities and differences between the data. The biggest notable difference between the model and the metered data is that the

metered data is plotted on very straight lines and discrete intervals. This is due to the way that the condensate return pump only turns on when the tank if full. It can also be seen that on the day scale, Figure 16, the model is a little bit lower in heat demand than the metered data. This shows the need to compare the results on a temperature basis, especially since the model was calibrated due to outside air temperature.

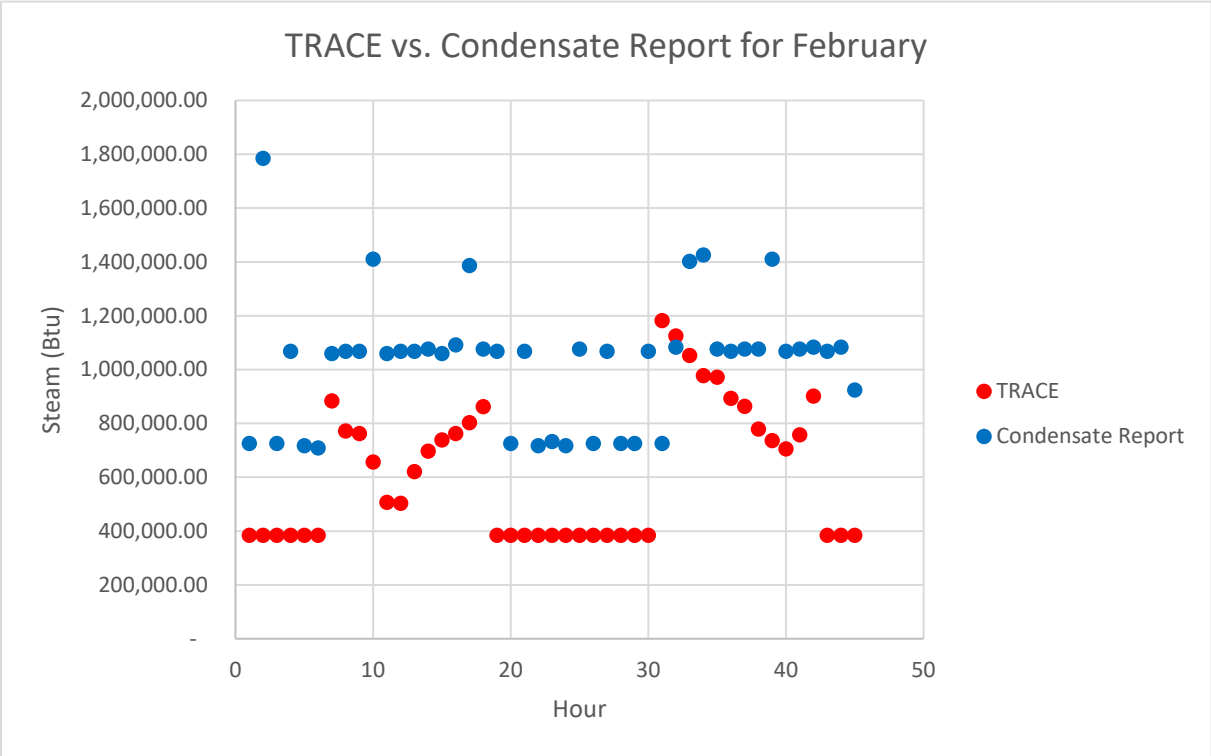


Figure 16. Cobleigh Hall Validation of hourly heating load. Comparison between metered data and model data in steam usage in BTU for February on a day scale.

Figure 17 shows the heat demand comparison on an outside air temperature basis. This data is hard to draw conclusions from, especially since the metered data is on such an interval basis. There is no reasonable way to correlate slopes the data like previously done in the calibration method section for heat demand and outdoor air temperature. Also the model shows that February contains much lower temperatures than the actual historical

data given for February 2018. The weather comparison for the model and real historical weather on an hourly basis for February 2018 can be seen in Figure 30 in Appendix D.

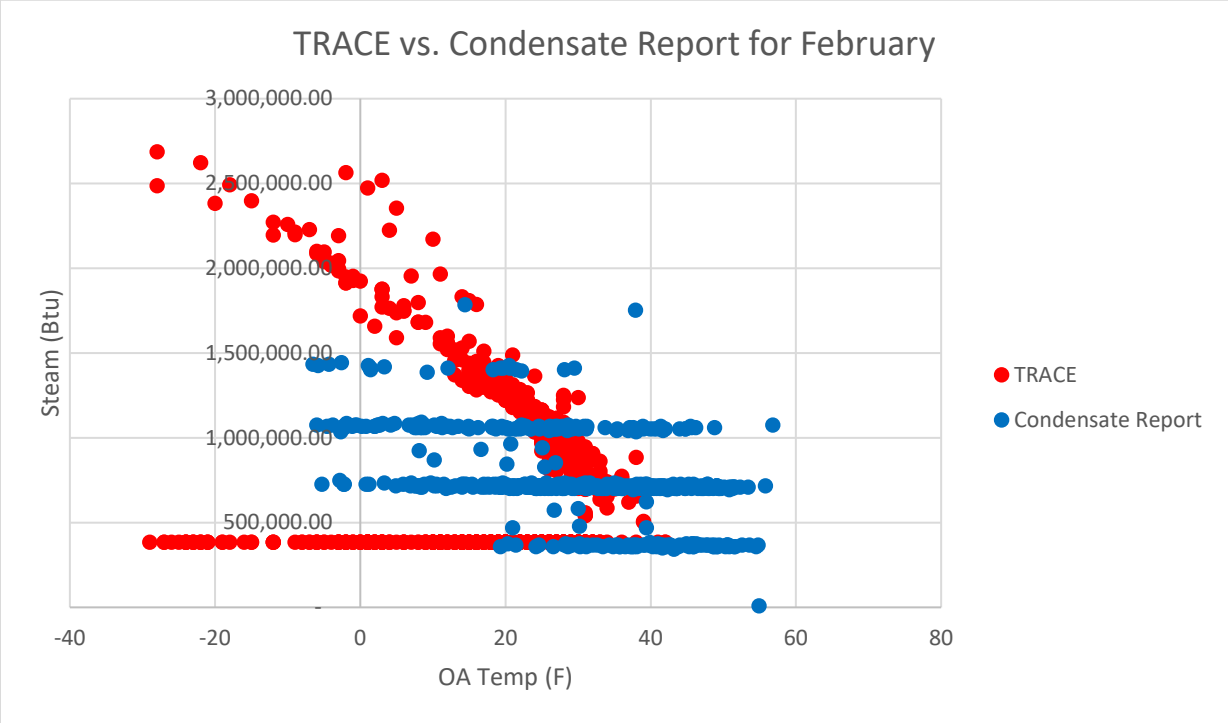


Figure 17. Cobleigh Hall Validation of hourly heating load. Comparison between metered data and model data in steam usage in BTU vs. Outdoor Air Temperature for February on a month scale.

In order to compare the data on a more relevant scale, the heat demand for the building in BTU's was divided by the temperature difference between the outside air temperature minus the inside air temperature given by $\frac{BTU}{T_{OA}-T_{IA}}$. The inside air temperature for Cobleigh Hall was estimated to be an average 70 degrees F. The heat demand for the building is caused by this exact temperature difference. So the heat demand was plotted on a $\frac{BTU}{T_{OA}-T_{IA}}$ basis. Figure 28 and Figure 29 in Appendix D show the results on a month and a week basis. Figure 18 below shows the results on a day basis. From this comparison, it can

be seen that the hourly heat demand for the model is very similar to that of the metered data for the building itself. This shows that the model does accurately represent the actual building being modeled, and that the hourly heat demand modeled for the building happens at the exact time and magnitude that it should.

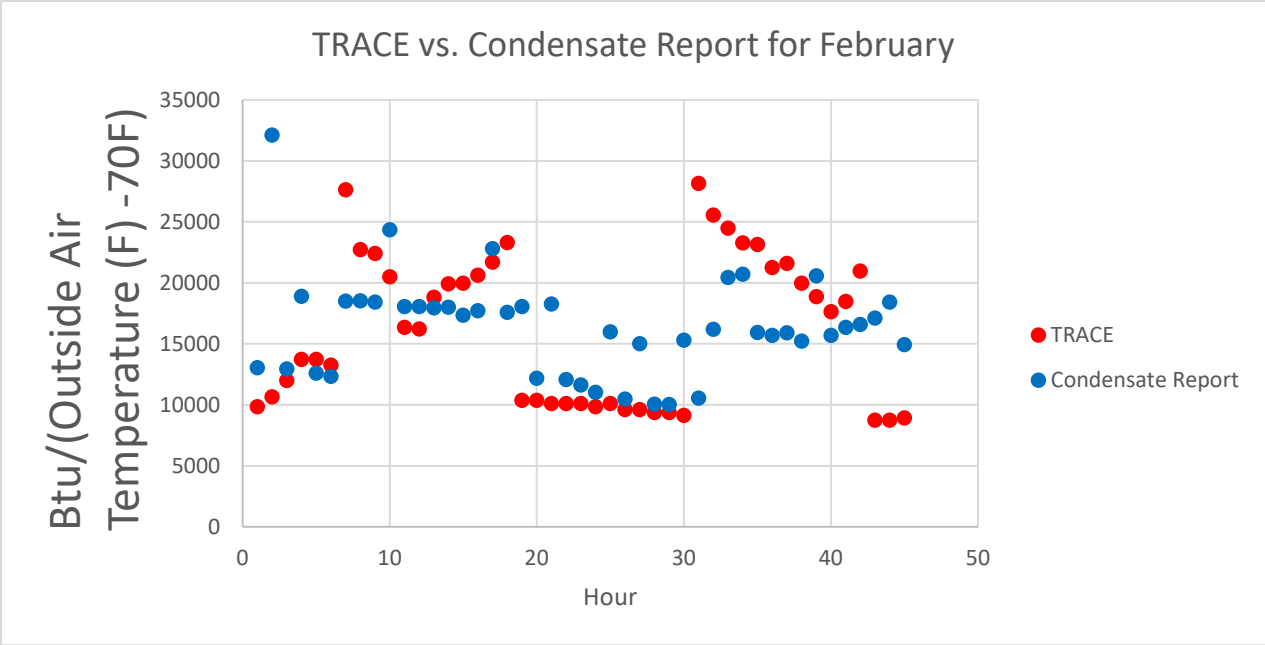


Figure 18. Cobleigh Hall Validation of hourly heating load. Comparison between metered data and model data in steam usage in BTUs divided by the temperature difference between 70 degrees F and the Outdoor Air Temperature for February on a month scale.

August

For a summer month, the heating loads in a high energy use laboratory space would not be temperature dependent. There would be a heating load for the reheat coils located in the laboratory spaces due to the high volume of air coming into the space, and some sort of heat losses associated with the steam piping throughout the building. The comparison for the model and the metered data for Cobleigh Hall were only compared on an hourly basis, and not a temperature basis. The results can be seen in Figure 19. From the

comparisons, it can be seen that the metered data should be an average between 0 Btu and the interval located around 450,000 Btu. This would be due to the condensate return tank only filling up once every two hours. The model is therefore very close to the actual average heat demand in the summer months for the building.

From the comparisons given in the model and the metered data from the building itself, it can be determined that the model is indeed accurate, and that the heat demand for the model directly correlates to the metered data, or the building itself.

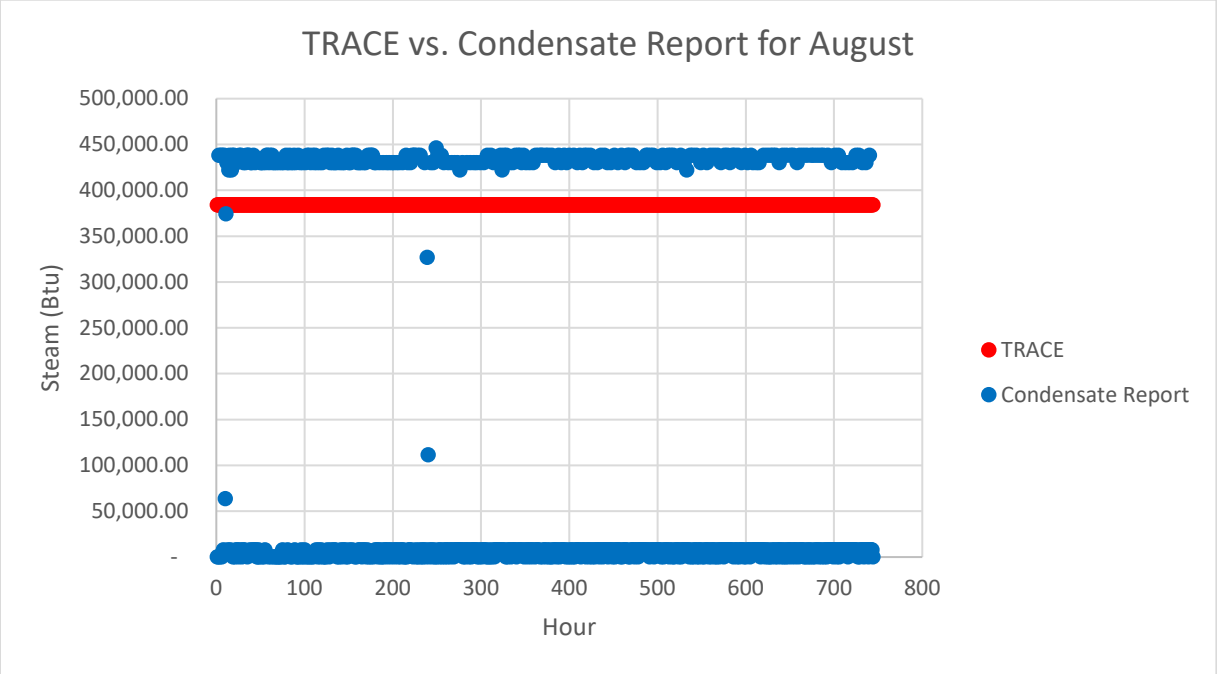


Figure 19. Cobleigh Hall Validation of hourly heating load. Comparison between metered data and model data in steam usage in BTU for February on a month scale.

Validation of Hourly Heat Rejection

Now that the hourly heat demand for the building is deemed as accurate, the next part to validate is the hourly heat rejection data or the cooling loads for the building. In order to validate this, the cooling methodology used in the energy model must be validated. There are eight different types of cooling methods to choose from in Trane TRACE 700. Those eight are:

- TETD – TA1
- CLTD – CLF
- TETD – TA2
- TETD – PO
- CEC – DOE2
- RP359
- RTS (ASHRAE Tables)
- RTS (Heat Balance)

There seems to be no widely accepted method in the energy modeling community as to which method is the best or provides the most accurate results. All these cooling loads were first developed to calculate the overall cooling load by hand. For the development of this model, cooling loads were not calculated by hand. The purpose of the model was to obtain accurate results but also to develop a model that can be replicated quickly and with ease. This shows the need to validate the energy modeling techniques used to derive heat rejection or heat availability data for any given building. As for the cooling load methodology chosen in this analysis, the TETD-TA1 method was chosen with use of

TRACE 700. This method was selected due to its simplicity of algorithm, as well as its prominent use in industry. There is no widely accepted cooling method that should be chosen above any of the others.

Energy Modeling Compliance

Compliance with Appendix G - *Performance Rating Method* in ASHRAE Standard 90.1 [19] is a requirement for energy modeling simulations for LEED compliance. In Appendix G, section G3.1.2.3 Unmet Loads, the unmet loads for the building shall not exceed 300 hours out of the 8760 hours simulated. Development of this model must comply with these compliance standards in order to be deemed as an accurate model. For Cobleigh Hall, the unmet load hours for heating and cooling are 13 and 74 respectively. This is identical to the heat-pump compatible model as well.

ASHRAE 209 – *Energy Simulation Aided Design for Buildings Except Low-Rise Residential Buildings* [25] is a new standard that describes methodology for applying energy modeling to the design process of a building. In the case of this model development, certain sections of the standard are more applicable than others. In section 5.3 Climate and Site Analysis, a typical meteorological year (TMY) file defined for Gallatin Field, Bozeman, MT was selected. This complies with section 5.3 and the informative Appendix A. The TMY weather format was used instead of an actual meteorological year (AMY), due to difficulties in obtaining all relevant weather data in an AMY. Due to inabilities to obtain an AMY, comparisons were not made to the TMY due to exception 1 in section 8.1.3.2.

Section 8.2.3.4 in ASHRAE 209 states that a scatter in which the independent variable is the average outdoor air temperature, and the dependent variable is the normalized total energy use must be plotted. For the analysis of this paper, the calibration method complies with section 8.2.3.4 due to the scatter plots created when comparing the simulated model results and the historical utility bill data.

For compliance on major renovation projects, it is recommended that ASHRAE 209 be used as a guideline and compliance procedure for development of a mini-district energy loop integrating new construction projects, and major renovation projects.

RESULTS

With a model developed to obtain hourly heat demand and heat availability quantities for a given building, the results need to be processed for implementation in a district energy loop. Important information with regards to developing a district energy loop is to assess the viability of connecting various buildings together and determined how, when and where heat needs to be shared.

Quantities and Summaries

To assess a building's ability to transfer heat to other buildings, it is first important to know the total quantity of energy that can be shared. In Table 5, the total heat demand and availability can be seen for Cobleigh Hall in the current configuration and the post-heat pump conversion configuration.

Table 5. Heat demand and heat availability of Cobleigh Models.

Heat Type	Current Configuration	Post-Heat Pump Conversion
Total Heat Demand (MMBTU)	4,704	858
Total Heat Availability (MMBTU)	2,712	1,657

Community Sharing

Analyzing a mini-district energy loop requires the ability to connect multiple buildings together or be able to analyze the differences in thermal profiles between various buildings. For this research, the Cobleigh Hall and Barnard thermal profiles for post-heat pump conversion were combined together. The combined thermal profile would be the

thermal profile for a district loop just containing those two buildings. From this analysis, the overlay of thermal profiles can be seen in Figure 20.

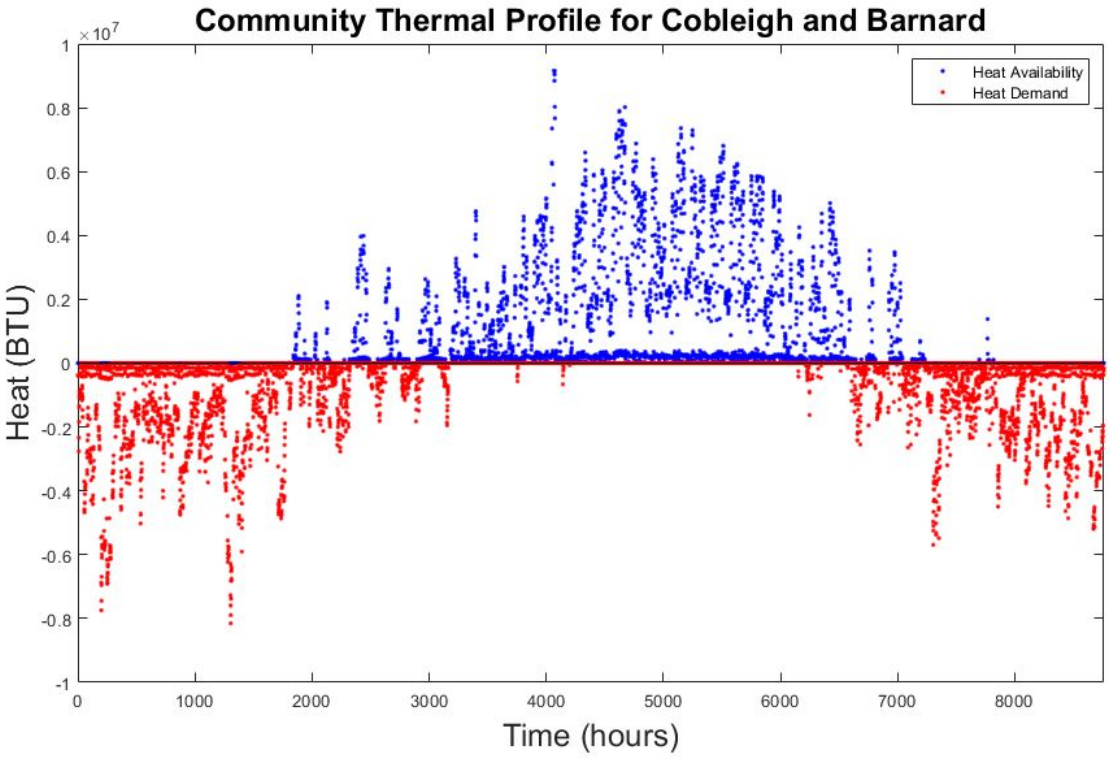


Figure 20. Cobleigh Hall and Barnard Hall thermal profile Post-Heat pump conversion showing heat demand and heat availability as an hourly report.

From the combination of the two thermal profiles post-heat pump conversion show that there is little overlap in heat demand and heat availability. This is due to both thermal profiles looking very similar and the buildings ultimately having identical schedules. The total heat savings by connecting the two buildings together would be 10.193 MMBTU. This would be equivalent to around $101.93 savings in annual energy.

Community sharing is a vital aspect in assessing the differences in thermal profiles between possible buildings to connect in a mini district energy loop. This assessment can

be as easy as overlapping the multiple thermal profiles for different buildings to determine simultaneous heat demand and heat availability quantities for a set of connected buildings.

From this analysis, it was determined that connecting two high energy use laboratory buildings together in a mini-district energy loop would not give much or any energy savings. Both buildings have the same schedules and same function of spaces resulting in similar thermal profiles.

Buildings that could be compatible with sharing thermal energy with a high-energy use laboratory space would be a heat producing facility, as wells as a building that has high domestic hot water loads or a geothermal borefield for potential heat sinks. Cobleigh Hall would require being connected to a viable heat source for the winter months, and a heat sink for the summer months for an effective mini-district energy loop.

Thermal Energy Storage

Another aspect to analyzing a mini-district energy loop is assessing any viable options for saving energy between buildings or for a given building itself. It was determined to analyze the possiblity of utilizing thermal energy storage to shift energy in the shoulder seasons months during the spring and fall. From the post-heat pump conversion thermal profile, it can be seen that there are multipe times during the year where heat demand and heat availablilty look like they are happening simultaneously, or at least alternating frequently. This would be due to the shoulder seasons where some days would require heating, while some days would require cooling due to the changing of the seasons. The shoulder season months can be seen within the highlighted circle seen below in Figure 21.

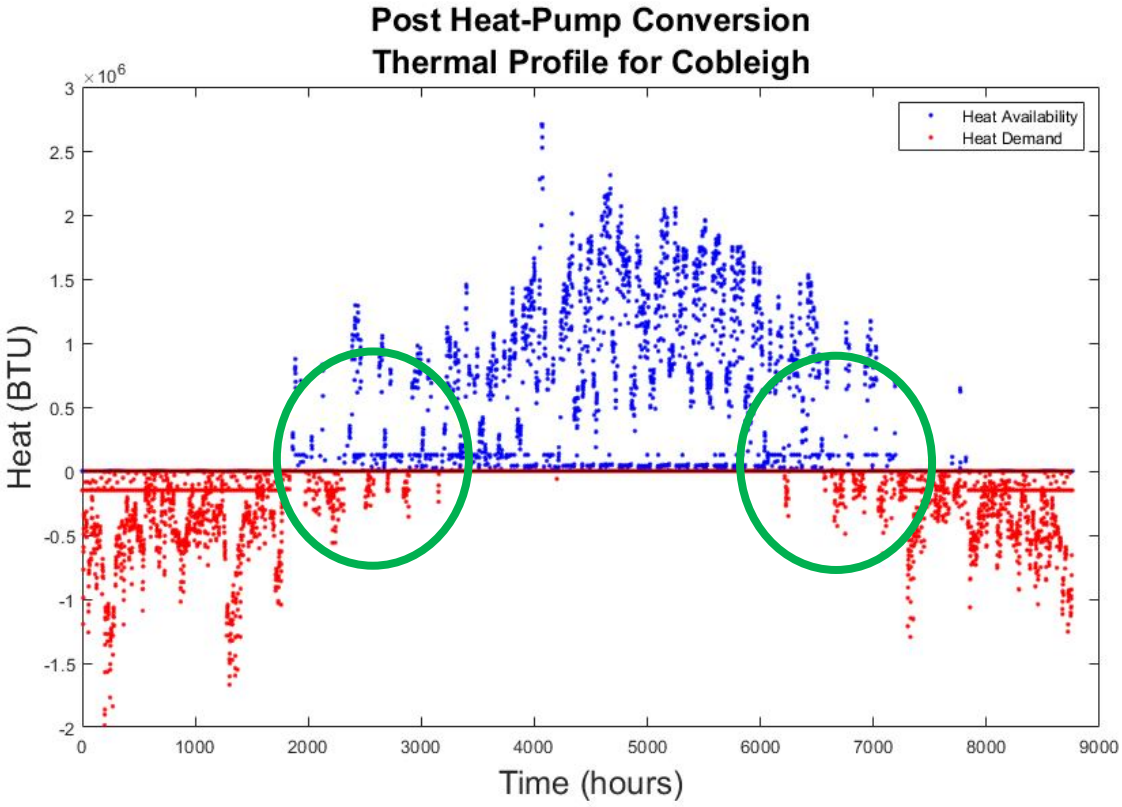


Figure 21. Cobleigh Hall thermal profile Post-Heat pump conversion showing heat demand and heat availability as an hourly report.

This thermal profile shows alternating between heat demand and heat availability for these shoulder seasons. In order to determine the fine details of the above figures, Figure 22 and Figure 23 show a zoomed in portion of the two highlighted circles shown above.

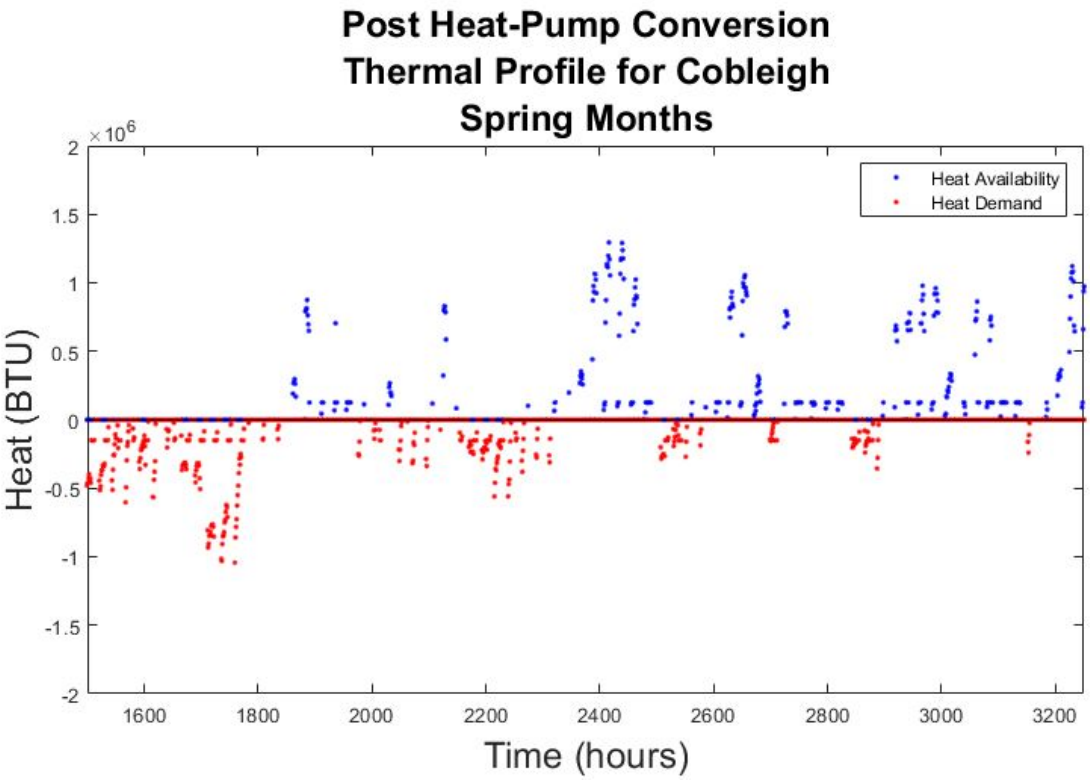


Figure 22. Cobleigh Hall thermal profile Post-Heat pump conversion showing heat demand and heat availability as an hourly report zoomed in on the spring months.

Figure 22 shows the zoomed in portion of the thermal profile for the spring months. For reference, hour 1600 in the year signifies March 8th, and hour 3200 represents May 14th. This figure shows two months of data for heat demand and heat availability and shows that the heat demand and heat availability is indeed alternating and not happening at simultaneous times. Thermal energy storage would allow for the heat availability to be stored in the form of water in order to shift this energy to weeks of need.

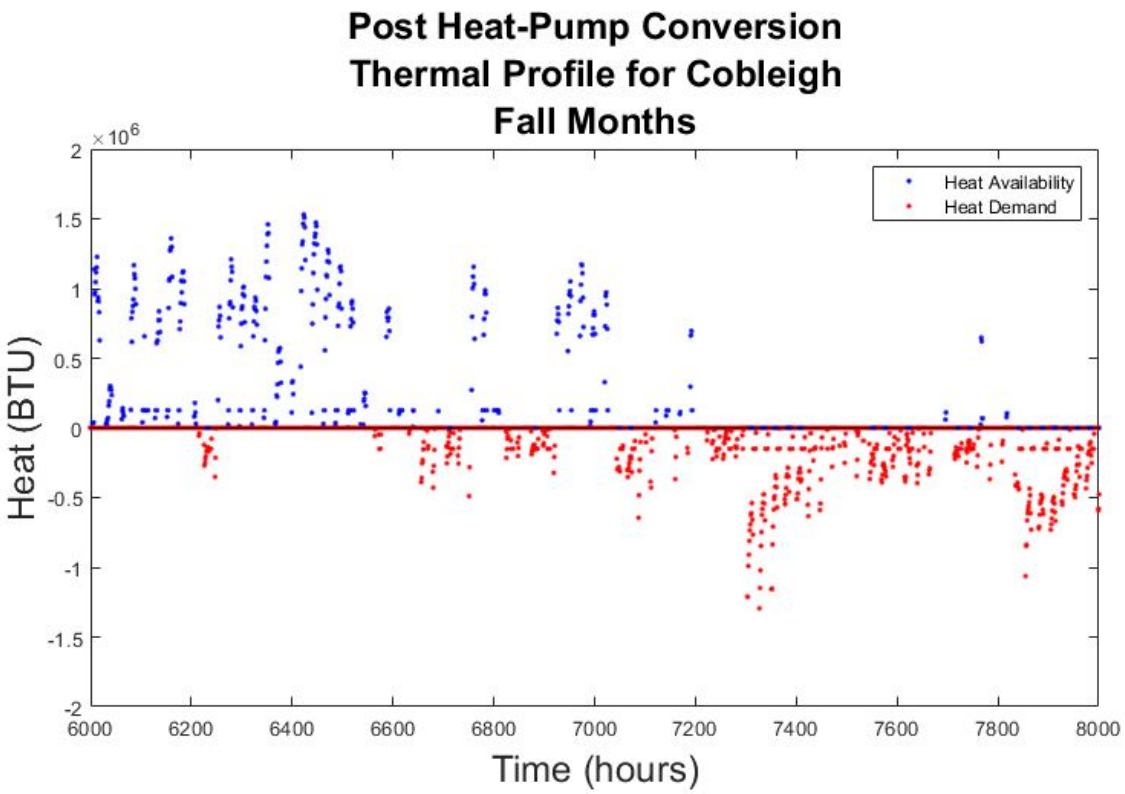


Figure 23. Cobleigh Hall thermal profile Post-Heat pump conversion showing heat demand and heat availability as an hourly report zoomed in on the fall months.

Figure 23 shows the zoomed in portion of the thermal profile for the fall months. For reference, hour 6000 in the year signifies September 8th, and hour 8000 represents November 30th. For this section of the year, any stored heat from the summer months could be shifted to the start of the colder days where heat demand is needed.

With the use of thermal energy storage, these alternating days and weeks of heat demand and heat availability would be diminished. Ideally there would be only two seasons of the thermal profile, that of heat demand, and that of heat availability. Determining the quantity of energy during these alternating heat demand and heat availability periods is important in determining if there is actually enough energy worth shifting around.

Table 6. Heat demand and heat availability assessed during the shoulder seasons for Cobleigh Hall.

Energy Source	Heat Demand (MMBTU)	Heat Availability (MMBTU)
March 8th to May 14th	138.72	197.58
September 8th to November 30th	74.56	114.17
Total heat	213.28	311.75
Heat worth	$2,132.80	$3117.50

From the results in Table 6, it can be seen that there is roughly a 213 MMBTU heat demand, and a higher equivalent heat availability during the same time. Not all of this heat will be able to be shifted though due to limits on the temperature within the thermal energy storage tank. Since Cobleigh Hall is in the post-heat pump conversion, a storage tank will only be useful from 60^{o}F to 90^{o}F [26]. Any temperature above 90^{o}F, then the heat pump can't effectively reject any more heat to the storage tank. Below 60^{o}F, then there is no more heat available to extract. The main goal of a thermal energy storage tank is to diminish the alternating heat demand and heat availability, and effectively shift this energy from one week to another. The thermal energy storage tank analysis can be seen in full in Appendix C.

One BTU is defined as the amount of energy required to raise one pound of water, one-degree Fahrenheit. In order for a thermal energy storage tank to be useful in shifting energy during the shoulder season, the tank must be large enough to handle an entire week of heat demand.

Different tank sizes were analyzed until a configuration that allowed for the smallest tank size with the most energy saved within this shoulder season was determined. The heat savings implemented as a function of the thermal energy storage tank size can be

seen in Table 7, along with the simple payback period. With the utilization of thermal energy storage, the design should be able to completely shift all of the energy within these shoulder periods. From the analysis, it was determined that a thermal energy storage tank of 20,000 gallons of water completely shifted all of this energy. Any tank size above 20,000 gallons was starting to shift energy from the fall months into the start of the winter months. With this design, a 20,000-gallon tank was the maximum tank size necessary. The 20,000-gallon thermal energy storage tank allowed for a simple payback period of 54.1 years with a construction cost of $2.00/gal for an energy storage tank.

Table 7. Assessment of Thermal Energy Storage tank size compared to total heat savings in MMBTUs and simple payback period in years.

Thermal Energy Storage Tank Size (Gallons)	Heat Savings (MMBTU)	Simple Payback (Years)
5,000	43.89	22.8
10,000	46.68	42.8
15,000	57.50	52.2
20,000	65.18	61.4
25,000	68.16	73.4
30,000	67.96	88.3
35,000	72.13	97.0
40,000	71.79	111.4

The thermal profile of Cobleigh Hall after utilization of a thermal energy storage tank can be seen in Figure 24.

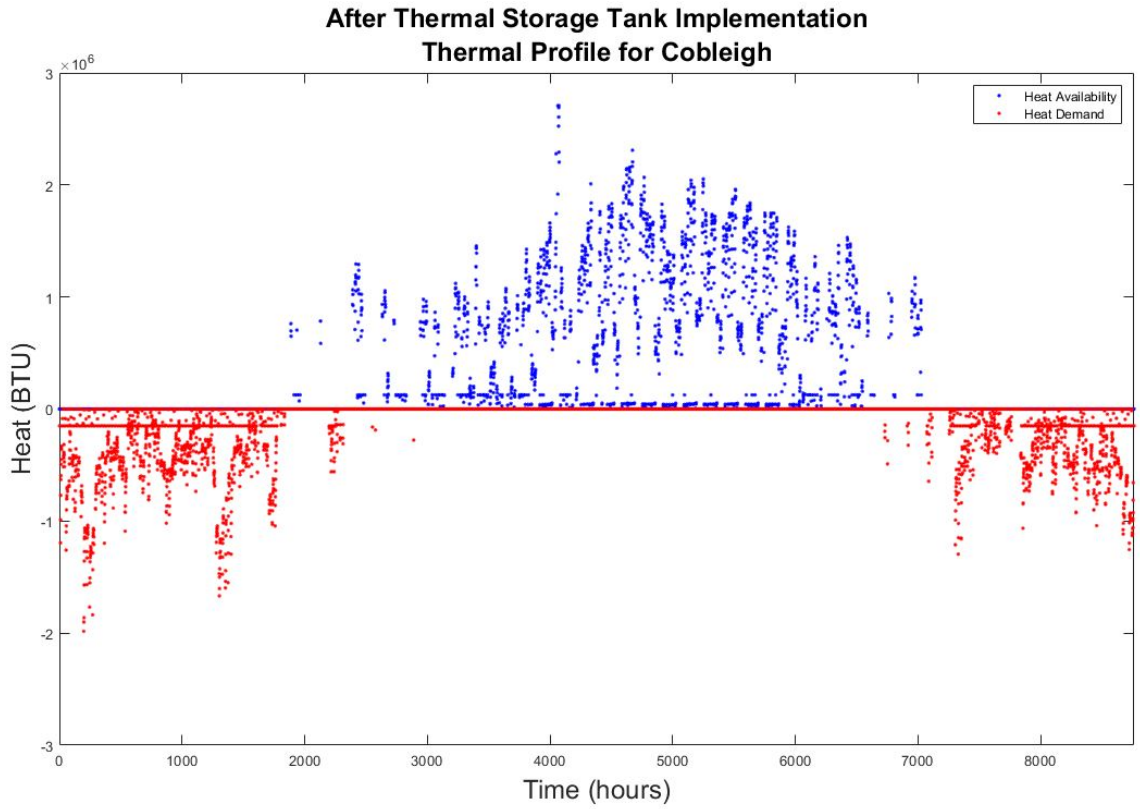


Figure 24. Cobleigh Hall thermal profile after implementation of thermal energy storage..

The new thermal profile shows that there is no longer shoulder seasons where there is alternating heat demand and heat availability.

Thermal energy storage was designed for only one building in this case. If multiple buildings are configured in a mini-district energy loop, then a thermal energy storage tank could be analyzed for the set of buildings.

Thermal energy storage is important for this analysis because it allows a method for expanding the sharable energy within a given building. If multiple buildings are configured together in an energy loop where simultaneous heating and cooling loads do not exist, thermal energy storage would provide a method for these buildings to still be able to share energy.

The thermal energy storage tank temperature profile can be seen in Figure 25. From the figure, it can be seen that the storage tank is only utilized for short periods during the year.

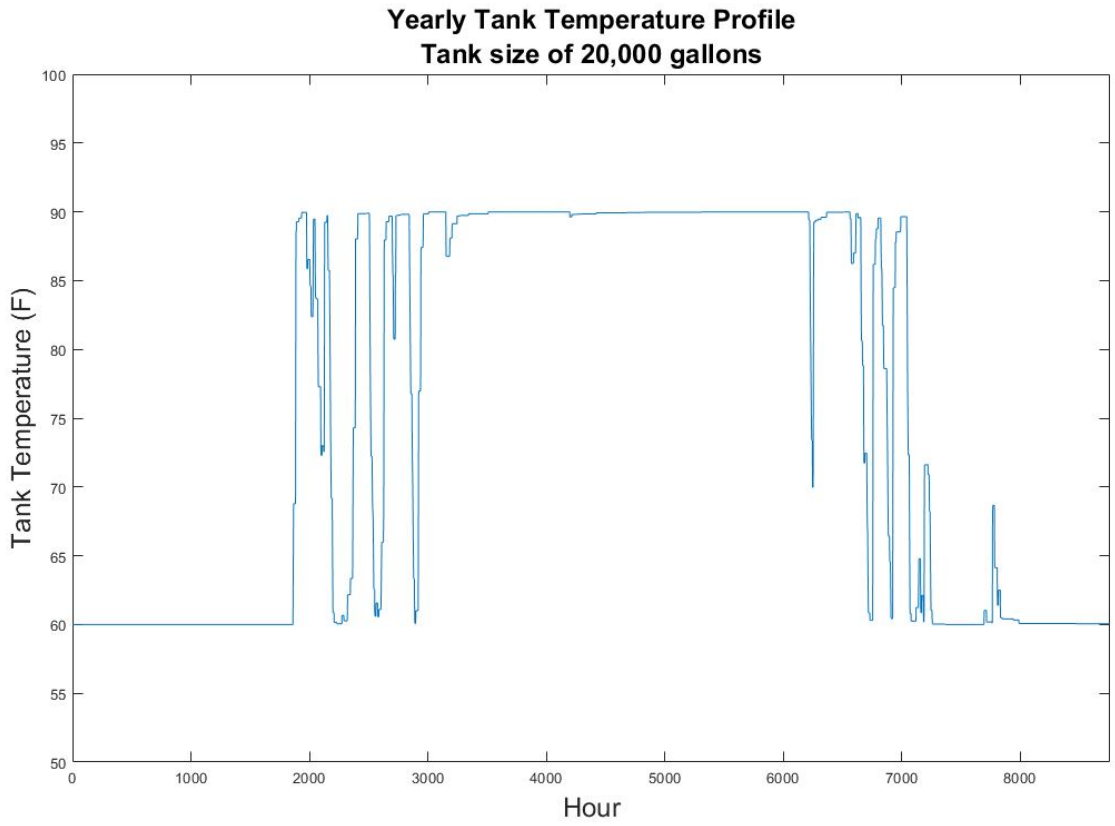


Figure 25. Thermal energy storage annual tank temperature profile.

During the peak summer months, the thermal energy storage tank could be used for peak load shedding by creating cold water during the middle of the night, then using this cold water for cooling during the day. This configuration would be ideal for locations where there is tier electricity rates scheduled. This would mean that electricity is more expensive during the day, and cheaper during the night. This would also help decrease the peak electric demand cost. However, in Montana, there is not time of day rate schedules, so analysis of cost saving measures were not applied.

Heat Sources

Identifying heat sources is key to development of a mini-district energy loop. Heat sources are buildings that have a constant cooling load, or more importantly, constant heat availability. Finding buildings, or given functions that constantly give off heat, especially during the winter will allow for maximum use of a mini-district energy loop.

Identifying high electricity users on a campus can lead to finding constant heat availability. One type of building with a constant cooling requirement would be a data center. College campuses with heavy research-based applications have data centers that are used for processing and distributing large amounts of data which are compiled of a network of computers. The vast quantity of computers and equipment located in data centers radiate heat which requires a constant cooling load so that the equipment doesn't overheat. This constant cooling load shows a viable option for a year-round heat source to be connected in a mini-district energy loop.

Combined heat and power (CHP) plants are another application of constant heat availability year-round. Many campuses have CHP plants to act as the main source of electricity which provide reliable and resiliency energy generation. This allows campuses to operate independently of the grid so that they aren't affected by blackouts caused by natural disasters [27]. These facilities have a very high thermal energy output and serve as a constant heat source year-round.

Heat Sinks

Heat sinks are buildings or entities that have a constant heat load, even during the summer months. Cobleigh Hall has 1,657 MMBTUs of heat available during the summer months. The goal of a mini-district energy loop is to find somewhere where this heat availability can be used or rejected without sending it to the cooling tower and condenser chiller.

Identifying entities that constantly need heat on a campus setting could include the heat requirement of a swimming pool. Another source of a heat sink on a campus setting includes domestic hot water loads. Domestic hot water loads are scheduled at very specific times, especially when considering dormitory showering use. On a college campus setting, students are only briefly on campus during the summer when there are scheduled orientation visits. Another source of a domestic hot water load is the use of food preparation within the dining halls; this is also scheduled at very specific times.

A geothermal ground loop provides an opportunity for a constant heat rejection application during the summertime by utilizing the constant earth temperature. This is done by using geothermal borefields integrated with a water source loop. Given assessments of the ground thermal conductivity and number of borefields, the heat rejected by the ground can be determined. A geothermal ground source loop provides a very viable option into essentially “free” cooling and means to locate somewhere to reject heat.

Equipment Plug Load Analysis

A previous graduate student at MSU analyzed the current district energy loop configuration on campus, and used modeling software to predict the average heat load and heat availability for each building connected to this mini-district energy loop [28]. From the analysis, lighting and motion occupancy sensors were installed in each laboratory space. Also direct metering of the electrical panel serving single laboratory spaces was also set up. These sensors and metering devices were installed to validate the occupancy schedule, as well as the equipment load in the laboratory spaces.

From the occupancy sensors, it was determined that there was no great method to installing these occupancy sensors to generate a valid schedule for a laboratory space. The motion sensors were typically not ideally placed to capture all movement inside the laboratory space, so motion in and out of the spaces weren't fully recognized. The lighting sensors installed also posed a problem: in spaces that were adequately day lit without the use of overhead lighting, lights that were turned off couldn't be directly correlated to a period of occupancy.

Also, in the research performed by Joshua Talbert, metering devices were implemented to determine the overall equipment load on a W/ft^2 basis for a laboratory space. Two laboratory spaces were measured, and it was determined that an average of 6.74 and 4.91 W/ft^2 were identified in the two spaces. This shows a fairly large variation between different space types, and in order to develop a better average for an entire building, more measurement devices would need to be installed.

For the research performed in the paper, it was determined that calibrating an energy model's electricity use in the laboratory spaces by increasing or decreasing the equipment plug load was deemed as valid. From Joshua Talbert's research, it can be shown that various laboratory spaces are going to have a wide range of equipment plug load densities. Instead of validating every single laboratory space, an average equipment plug load density for the laboratory spaces will yield a close enough heat demand and heat availability profile on an entire building load basis. This means that no electricity sensors need to be installed for every single laboratory space, instead an average equipment plug load density can be assumed, and more importantly determined from a monthly utility bill.

As for occupancy sensors, an entire building wide occupancy was deemed as a valid approach for setting up the energy model. When the model is first set up, accurate schedules, and space functions given by the facility engineers and construction drawings were determined to represent the building on an accurate basis. Interviews with building staff, as well as laboratory users would yield a more wholesome approach to the modeling setup, but the hourly load profile for the building modeled, Cobleigh Hall, was determined to represent the hourly load profile for the entire building.

CONCLUSION

Model

The model derived in this research can be explicitly laid out in the following sections.

Inputs

The major necessary inputs into the energy model that need to be obtained from construction drawings or the building owner are:

- Building dimensions
- Generic R-values for building envelope
- Window percentages by façade
- Functions of given spaces and layout of interior spaces
- Occupancy schedules
- HVAC equipment configuration
- Power rating on fan equipment
- Pump head on chiller (if applicable)
- Plant type or recourses consumed in the building
- Weather file in TMY or similar format.

Lighting occupancy density, equipment plug load density and unspecified R-values were default to ASHRAE Standard 90.1 - 2013 [19]. Also if airflow design specifications were default to ASHRAE Standard 62.1 – 2013 [20].

The model was defined as a perimeter and core five zone energy model on a per floor basis. This allowed for easy implementation of multiple floors for the model.

8760 Generation

Once the model was accurately configured, the hourly energy results were generated. The 8760 file was split up into two major components: the heating load, and the rest of the electricity load.

The 8760 file now had to be compared to historical utility data. For this, the outside air-dry bulb temperature was averaged for each month, and the consumption of the heating source and total electricity load was also recorded for each month. This allows for "utility bills" to be generated from the 8760 file. This was compared to the past four years of historical utility data. Linear lines were plotted along with the data for comparison.

Calibration

After initial comparisons between the model and historical utility data were observed, calibration efforts were applied to represent a more accurate model with respect to the outdoor air temperature.

Heating Calibration. Two aspects to the heating calibration need attention. The slope of the line is directly affected by the outdoor air intake into the building. This was altered only in the laboratory spaces and represented as changing the direct outdoor air intake into the laboratory spaces. Increasing the outdoor air consumption will cause the slope of the heat demand line to increase or get steeper, whereas decreasing the outdoor air consumption will cause the slope of the heat demand line to decrease or flatten out.

The other aspect to the heat demand for the building is base heat load. Changing the base heat load causes the linear line in the model to either move up or down. This is because in the summer months when the temperature is warmer, there is still some kind of base heat load required either due to domestic hot water loads, or outdoor air pre-heat for the laboratory spaces. Increasing the base heat load causes the heat demand line to move up vertically.

Electric Calibration. Another aspect to calibrating the model is to calibrate the electricity consumption in the building to account for the right amount of heat generation within rooms due to electric loads. For the model development in this research, it was deemed accurate to alter the electric plug load in the laboratory spaces. Increasing this plug load causes the electric consumption line in the model to move up vertically.

After all calibration techniques were applied, the corresponding model should be within a few percent of the historical utility data on an outdoor air temperature basis.

Final 8760 for Thermal Profile

Once calibration techniques were applied, the thermal profile of the building was identified. The thermal profile of the building can be used for assessing the heat demand, and total heat availability for each building on a campus setting on an hourly basis. This information would inform how much heat is available to be shared within a campus set of buildings.

Convert Building to be Heat-Pump Compatible

A conversion of the building to be heat pump compatible allows for direct energy sharing of heat within the building, as well as to other buildings if available. Converting

the building to utilize water-source heat pumps is one method to exchanging energy internally and externally. In order to do this a conversion, the plant type in the energy model changed to a heat pump needs to take place. After modifying the model to be heat pump compatible, a new thermal profile is developed. This new thermal profile shows only the excess heat available, and direct heat demand for the building after the building has shared heat internally. This new thermal profile would be used for assessing the heat sharing capabilities with other buildings only.

Apply Concepts to Other Buildings

The purpose of this model was to develop a simple modeling method for analyzing the hourly heat demand and heat availability for a building based on historical monthly utility data and basic building inputs. For development of a district energy loop on a campus setting, there can be multiple buildings of the same type and function. This shows the ability to use the same model as long as the type of building and function is similar. In this research, the development of a high-energy use laboratory, Cobleigh Hall, should be easily applied to another high-energy use laboratory.

To apply the Cobleigh methodology to another building, the only thing that needs to remain is the first floor of the energy model. With only one floor of the model defined, exterior wall lengths, window percentages, space sizes, and HVAC equipment type and size need to be altered. Since the new building has the same functions, schedules, lighting loads, and space type setups are already defined, the next step is to just copy and paste rooms until the entire building is defined.

After the physical model is defined, the calibration techniques are applied until the model corresponds to historical utility data on an outside air temperature basis. This entire process can be achieved in a fraction of the time as the original model. This process allows for an easy and fast way to develop a model for any kind buildings.

Community Sharing Capabilities

With multiple building models defined, external energy sharing is analyzed. Energy sharing between multiple buildings is possible when there is heat availability at the same exact time as a heat demand in another building on an hourly basis.

Thermal Energy Storage

Thermal energy storage in the form of a tank is analyzed to assess the possibility of shifting energy between buildings when there are alternating periods of heat demand and heat availability within a building. These periods usually occur in the shoulder seasons when there are alternating periods of warmer weeks and then colder weeks.

Heat Sources

Assessing the viability of a district energy loop requires there to be heat sources year-round, or particularly in the colder months where most buildings have a heat need. Analyzing the total heat demand for the winter months for a building will help contribute to the magnitude of a heat source needed to offset this heat demand. An ideal district energy loop would have a perfect balance of heat demand and heat availability for all buildings interconnected. This is usually not the case, so assessing the heat sources available during

the winter months will help in determined the viability of implementing a district energy loop.

Heat Sinks

Along with assessing heat sources for the colder winter months, finding heat sources during the warmer months where most buildings have heat available is important in assessing a district energy loop. Heat sinks are areas of portions of buildings that are going to have a constant heat demand, even during the summer months.

Intended use for Model

The purpose of this research was to develop a method for which any campus with multiple buildings could effectively analyze the heat demand, and heat availability within their set of buildings to assess the potential for a district energy loop. This method utilizes historical monthly utility bill data to generate a thermal profile for a given building. This model could be used for generating a thermal profile for an entire campus to assess the total heat demand and heat availability between various buildings.

This research also shows that for a given building, using a calibration method for the heat demand in the building by increasing or decreasing the outdoor air intake is an adequate way to analyze the heat demand on a building level. This method could also lead to the result that the construction type doesn't play a huge factor in this method for analyzing the hourly load profile for a high energy use laboratory. Since Cobleigh Hall is so internally load dominated, it wouldn't matter if the building is constructed with thermal mass, steel stud construction, hay bale wall construction, or any other type. As long as the

calibration techniques discussed in this paper are used in coordination with historical utility data for the building, the model will generate accurate hourly heat demand and heat availability for the building. For other building types, i.e. a classroom building, a dormitory, or an office building without much internal heat gain, the construction type would play a much larger role in determining the heating load as well as the cooling load requirements.

This research was performed for buildings located in Bozeman, Montana, which is located in region 6B on the ASHRAE climate zone map [19]. Climate 6B is designated as cold and dry and doesn't usually require dehumidification or humidification processes.

For this model to be intended to use for campus buildings in any climate though, latent energy must be analyzed. For a set of buildings located in a warm humid climate especially, the sensible cooling load would be identical to the development of the model presented, however, the latent load in the summer and winter would be important to discuss. Due to the outside being humid, this requires buildings with high outdoor air consumption to dehumidify this air. One application for integration into a mini-district loop to account for latent loads would be a desiccant wheel. A desiccant wheel requires heat to be applied to remove the bond of water to the desiccant media. This application shows promising procedures to utilize heat availability from other cooling processes. However, this process still requires the air to be cooled down to be supplied to different spaces in a building. Applications of dehumidification processes should be analyzed to allow for integration into a mini-district energy loop in a warmer climate. Energy efficient dehumidification processes are being studied with integrating different renewable energy into the systems.

One application is a desiccant dehumidification process integrated with solar hot water heating and radiant cooling [29].

Identifying heat sinks would also be the key analysis in determining the viability of a district energy loop in warmer climates. Thermal energy storage for utilization of cooling loads integrated in the district energy loop would be a very important analysis on energy savings, as well as utilization of time of day electric rates and decreasing the maximum Electric Peak load in a warm climate. Along with a thermal energy storage tank, ground-coupled heat pumps integrated with geothermal bore fields should be analyzed as a possible heat sink.

Recommendations

From the analysis, it was determined that connecting two high energy use laboratory buildings is not feasible for a mini-district energy loop because their thermal profiles are so similar. This could imply that connecting similar buildings of any type would not be feasible for connection of a mini-district energy loop. This is all after post-heat pump conversion, and internal energy sharing within the building takes place.

High-energy use laboratories have large potential internal energy savings, and it is recommended that these types of buildings be converted to be heat-pump compatible to maximize the energy sharing capabilities within the building to share energy internally. Also, the use of energy recovery devices on the building exhaust and the outdoor air pre-heat would increase energy savings within the building.

Major renovation projects also pose an easy opportunity for connection and integration for a mini-district energy loop. At MSU, two buildings that have potential due

to renovation projects are the Marga Hosaeus Fitness Center, and Romney Hall. The fitness center renovation would allow for integration of the swimming pool and large gymnasiums. If cooling were to be installed in the gymnasiums, then this could act as a heat source for the swimming pool. Romney Hall is forgoing a major renovation in the near future, due to a complete change of the building function, integrating Romney Hall into a mini-district energy loop would be advantageous.

Including major heat sources, as well as heat sinks into a mini-district energy loop are crucial to the analysis. A major heat source on campus would be the steam plant building. Installing cooling into this building would provide a constant heat source year-round. A major heat sink on campus is the geothermal borefield wells located adjacent to the Norm Asbjornson Hall. At MSU, the infrastructure is already in place with the construction of the steam tunnels. Buildings already connected to the steam tunnels should be analyzed first, as well as buildings that are in close proximity to major heat sources and heat sinks.

Future Work

In a college campus setting, there are five main types of buildings. These include a high-energy use laboratory, classroom, dormitory, dining hall, and a recreational facility. This model development has shown that a model for one high-energy use laboratory can be easily altered to represent another building of similar type and function.

Future work should include four more models to be developed. These include models for a dormitory, a dining hall, recreational facility, and a classroom building. With the development of all five models making up a college campus, a thermal profile for the

entire campus can be mapped out. This would allow for a mini-district energy loop to be fully analyzed given parameters of heat demand, heat availability, and distance between buildings.

Mixed-use space models can be represented as different floors of different respective core and perimeter 5-zone models. This would indicate that only five models must be developed to accurately represent an entire college campus. For different campus settings, i.e. hospitals, engineering facility campuses, or any other campus, the process will be similar. Models can be developed from historical utility data, and then thermal profiles for the campus can be created. Once models are developed for all types of buildings on the campus setting, then a mini-district energy loop can be analyzed.

Other future work would be to compile strategies to effectively compare the analysis of a single energy station with heat pumps located in each and every building.

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APPENDICES

APPENDIX A

APPENDIX A: Inputs into Energy Model for Cobleigh Hall

Table 8. Input to Cobleigh Hall energy model for Office Space, North Perimeter room.

Specified Input in TRACE	Value
Walls	
Length	108 Feet
Width	13 Feet
Floor to Floor Height	12 Feet
Plenum	2 Feet
Wall Construction	12” Concrete, 4” Insulation (Int)
Wall Direction	0 Degrees
Wall U-Factor	0.0645 Btu/hr-ft^2-^{o}F
Window Type	Single Pane, ¼”, Clear
Window U-Factor	0.95 Btu/hr-ft^2-^{o}F
Window SHGC value	0.95
Window area (By Percentage)	6.17 %
Window Shading	Vertical Shading
Internal Loads	
Plug Load	1 W/ft^2
Light Heat gain	1 W/ft^2
Workstations per person	1
Activity	General Office Space
People Density	143 ft^2/person
Sensible Heat gain per person	250 ft^2/person
Latent Heat gain per person	200 Btu/hr
Airflow	
Method	ASHRAE 62.1
Airflow – People	5 cfm/person
Airflow – Area	0.06 cfm/ft^2
Infiltration Rate	0 ACH
Room Exhaust Rate	0 ACH

Table 9. Input to Cobleigh Hall energy model for Office Space, South Perimeter room.

Specified Input in TRACE	Value
Walls	
Length	108 Feet
Width	13 Feet
Floor to Floor Height	12 Feet
Plenum	2 Feet
Wall Construction	12” Concrete, 4” Insulation (Int)
Wall Direction	180 Degrees
Wall U-Factor	0.0645 Btu/hr-ft^2-^{o}F
Window Type	Single Pane, ¼”, Clear
Window U-Factor	0.95 Btu/hr-ft^2-^{o}F
Window SHGC value	0.95
Window area (By Percentage)	6.17 %
Window Shading	Vertical Shading
Internal Loads	
Plug Load	1 W/ft^2
Light Heat gain	1 W/ft^2
Workstations per person	1
Activity	General Office Space
People Density	143 ft^2/person
Sensible Heat gain per person	250 ft^2/person
Latent Heat gain per person	200 Btu/hr
Airflow	
Method	ASHRAE 62.1
Airflow – People	5 cfm/person
Airflow – Area	0.06 cfm/ft^2
Infiltration Rate	0 ACH
Room Exhaust Rate	0 ACH

Table 10. Input to Cobleigh Hall energy model for Office Space, East Perimeter room.

Specified Input in TRACE	Value
Walls	
Length	129 Feet
Width	13 Feet
Floor to Floor Height	12 Feet
Plenum	2 Feet
Wall Construction	12” Concrete, 4” Insulation (Int)
Wall Direction	90 Degrees
Wall U-Factor	0.0645 Btu/hr-ft^2-^{o}F
Window Type	Single Pane, ¼”, Clear
Window U-Factor	0.95 Btu/hr-ft^2-^{o}F
Window SHGC value	0.95
Window area (By Percentage)	6.17 %
Window Shading	Vertical Shading
Internal Loads	
Plug Load	1 W/ft^2
Light Heat gain	1 W/ft^2
Workstations per person	1
Activity	General Office Space
People Density	143 ft^2/person
Sensible Heat gain per person	250 ft^2/person
Latent Heat gain per person	200 Btu/hr
Airflow	
Method	ASHRAE 62.1
Airflow – People	5 cfm/person
Airflow – Area	0.06 cfm/ft^2
Infiltration Rate	0 ACH
Room Exhaust Rate	0 ACH

Table 11. Input to Cobleigh Hall energy model for Office Space, West Perimeter room.

Specified Input in TRACE	Value
Walls	
Length	129 Feet
Width	13 Feet
Floor to Floor Height	12 Feet
Plenum	2 Feet
Wall Construction	12” Concrete, 4” Insulation (Int)
Wall Direction	270 Degrees
Wall U-Factor	0.0645 Btu/hr-ft^2-^{o}F
Window Type	Single Pane, ¼”, Clear
Window U-Factor	0.95 Btu/hr-ft^2-^{o}F
Window SHGC value	0.95
Window area (By Percentage)	6.17 %
Window Shading	Vertical Shading
Internal Loads	
Plug Load	1 W/ft^2
Light Heat gain	1 W/ft^2
Workstations per person	1
Activity	General Office Space
People Density	143 ft^2/person
Sensible Heat gain per person	250 ft^2/person
Latent Heat gain per person	200 Btu/hr
Airflow	
Method	ASHRAE 62.1
Airflow – People	5 cfm/person
Airflow – Area	0.06 cfm/ft^2
Infiltration Rate	0 ACH
Room Exhaust Rate	0 ACH

Table 12. Input to Cobleigh Hall energy model for Lab Spaces in core zone.

Specified Input in TRACE	Value
Walls	
Length	91.5 Feet
Width	63 Feet
Floor to Floor Height	12 Feet
Plenum	2 Feet
Wall Construction	N/A
Wall Direction	N/A
Wall U-Factor	N/A
Window Type	N/A
Window U-Factor	N/A
Window SHGC value	N/A
Window area (By Percentage)	N/A
Window Shading	N/A
Internal Loads	
Plug Load	2.5 W/ft^2
Light Heat gain	1 W/ft^2
Workstations per person	0
Activity	Laboratory
People Density	33.3 ft^2/person
Sensible Heat gain per person	250 ft^2/person
Latent Heat gain per person	200 Btu/hr
Airflow	
Method	Sum of Outdoor Air
Cooling Airflow	4 ACH
Heating Airflow	4 ACH
Infiltration Rate	0 ACH
Room Exhaust Rate	4 ACH

Table 13. Input to Cobleigh Hall energy model for Cold Chambers.

Specified Input in TRACE	Value
Walls	
Wall 1	
Length	108 Feet
Width	13 Feet
Wall Direction	0 Degrees
Wall 2	
Length	129 Feet
Width	13 Feet
Wall Direction	90 Degrees
Wall 3	
Length	108 Feet
Width	13 Feet
Wall Direction	180 Degrees
Wall 4	
Length	129 Feet
Width	13 Feet
Wall Direction	270 Degrees
Wall factors (Same for every wall)	
Wall Construction	12” Concrete, 4” Insulation (Int)
Wall U-Factor	0.0645 Btu/hr-ft^2-^{o}F
Window Type	Single Pane, ¼”, Clear
Window U-Factor	0.95 Btu/hr-ft^2-^{o}F
Window SHGC value	0.95
Window area (By Percentage)	6.17 %
Window Shading	Vertical Shading
Floor to Floor Height	12 Feet
Plenum	2 Feet
Internal Loads	
Plug Load	1 W/ft^2
Light Heat gain	1 W/ft^2
Workstations per person	1
Activity	General Office Space
People Density	143 ft^2/person
Sensible Heat gain per person	250 ft^2/person
Latent Heat gain per person	200 Btu/hr

Table 14. Input to Cobleigh Hall energy model for Current Configuration.

Specified Input in TRACE	Value
System Selection	Variable Volume Double Duct VAV
Heat Plant Configuration	Boiler
Cooling Plant Configuration	Water-Cooled Chiller
Fan Type	FC Centrifugal Variable Frequency Drive
Fan Static Pressure	6.33 in w.g.
Full Load Energy Rate	60 Hp
System Exhaust Fan	0.000321 kW/Cfm-in-wg
Room Exhaust Fan	0.000321 kW/Cfm-in-wg
Pump Head	153 ft
Boiler Efficiency	83.3 %
Base heat load	320 MBtu/hr

Table 15. Input to Cobleigh Hall energy model for Post-Heat Pump Configuration.

Specified Input in TRACE	Value
System Selection	Variable Volume Double Duct VAV
Heat Plant Configuration	Boiler
Cooling Plant Configuration	Water-Source Heat Pump
Fan Type	FC Centrifugal Variable Frequency Drive
Fan Static Pressure	6.33 in w.g.
Full Load Energy Rate	60 Hp
System Exhaust Fan	0.000321 kW/Cfm-in-wg
Room Exhaust Fan	0.000321 kW/Cfm-in-wg
Pump Head	105 ft
Boiler Efficiency	83.3 %
Base heat load	160 MBtu/hr

Table 16. Lighting Schedule, Cobleigh Office.

Lighting Schedule		
Start Time	**End Time**	**Percentage**
12:00 AM	6:00 AM	20
6:00 AM	6:00 PM	100
6:00 PM	10:00 PM	50
10:00 PM	12:00 AM	30

Table 17. Equipment Schedule, Cobleigh Office.

Equipment Schedule		
Start Time	**End Time**	**Percentage**
12:00 AM	6:00 AM	0
6:00 AM	6:00 PM	100
6:00 PM	12:00 AM	0

Table 18. People Schedule, Cobleigh Office.

People Schedule		
Start Time	**End Time**	**Percentage**
12:00 AM	6:00 AM	0
6:00 AM	6:00 PM	100
6:00 PM	12:00 AM	0

Table 19. Lighting Schedule, Cobleigh Labs.

Lighting Schedule		
Start Time	**End Time**	**Percentage**
12:00 AM	6:00 AM	0
6:00 AM	7:00 AM	10
7:00 AM	8:00 AM	50
8:00 AM	12:00 PM	100
12:00 PM	1:00 PM	30
1:00 PM	4:00 PM	100
4:00 PM	5:00 PM	50
5:00 PM	6:00 PM	10
6:00 PM	12:00 AM	0

Table 20. Equipment Schedule, Cobleigh Labs.

Equipment Schedule		
Start Time	**End Time**	**Percentage**
12:00 AM	6:00 AM	0
6:00 AM	6:00 PM	100
6:00 PM	12:00 AM	0

Table 21. People Schedule, Cobleigh Labs.

People Schedule		
Start Time	**End Time**	**Percentage**
12:00 AM	6:00 AM	20
6:00 AM	6:00 PM	100
6:00 PM	10:00 PM	50
10:00 PM	12:00 AM	30

Table 22. Available 100% Schedule.

Available 100% Schedule		
Start Time	**End Time**	**Percentage**
12:00 AM	12:00 AM	100

APPENDIX B

APPENDIX B: Inputs into Energy Model for Barnard Hall

Table 23. Input to Barnard Hall energy model for Office Space, North Perimeter room.

Specified Input in TRACE	Value
Walls	
Length	150 Feet
Width	13 Feet
Floor to Floor Height	12 Feet
Plenum	2 Feet
Wall Construction	12” Concrete, 4” Insulation (Int)
Wall Direction	0 Degrees
Wall U-Factor	0.0645 Btu/hr-ft^2-^{o}F
Window Type	Single Pane, ¼”, Clear
Window U-Factor	0.95 Btu/hr-ft^2-^{o}F
Window SHGC value	0.95
Window area (By Percentage)	6.17 %
Window Shading	Vertical Shading
Internal Loads	
Plug Load	1 W/ft^2
Light Heat gain	1.5 W/ft^2
Workstations per person	1
Activity	General Office Space
People Density	143 ft^2/person
Sensible Heat gain per person	250 ft^2/person
Latent Heat gain per person	200 Btu/hr
Airflow	
Method	ASHRAE 62.1
Airflow – People	5 cfm/person
Airflow – Area	0.06 cfm/ft^2
Infiltration Rate	0 ACH
Room Exhaust Rate	0 ACH

Table 24. Input to Barnard Hall energy model for Office Space, South Perimeter room.

Specified Input in TRACE	Value
Walls	
Length	150 Feet
Width	13 Feet
Floor to Floor Height	12 Feet
Plenum	2 Feet
Wall Construction	12” Concrete, 4” Insulation (Int)
Wall Direction	180 Degrees
Wall U-Factor	0.0645 Btu/hr-ft^2-^{o}F
Window Type	Single Pane, ¼”, Clear
Window U-Factor	0.95 Btu/hr-ft^2-^{o}F
Window SHGC value	0.95
Window area (By Percentage)	6.17 %
Window Shading	Vertical Shading
Internal Loads	
Plug Load	1 W/ft^2
Light Heat gain	1.5 W/ft^2
Workstations per person	1
Activity	General Office Space
People Density	143 ft^2/person
Sensible Heat gain per person	250 ft^2/person
Latent Heat gain per person	200 Btu/hr
Airflow	
Method	ASHRAE 62.1
Airflow – People	5 cfm/person
Airflow – Area	0.06 cfm/ft^2
Infiltration Rate	0 ACH
Room Exhaust Rate	0 ACH

Table 25. Input to Barnard Hall energy model for Office Space, East Perimeter room.

Specified Input in TRACE	Value
Walls	
Length	300 Feet
Width	13 Feet
Floor to Floor Height	12 Feet
Plenum	2 Feet
Wall Construction	12” Concrete, 4” Insulation (Int)
Wall Direction	90 Degrees
Wall U-Factor	0.0645 Btu/hr-ft^2-^{o}F
Window Type	Single Pane, ¼”, Clear
Window U-Factor	0.95 Btu/hr-ft^2-^{o}F
Window SHGC value	0.95
Window area (By Percentage)	6.17 %
Window Shading	Vertical Shading
Internal Loads	
Plug Load	1 W/ft^2
Light Heat gain	1.5 W/ft^2
Workstations per person	1
Activity	General Office Space
People Density	143 ft^2/person
Sensible Heat gain per person	250 ft^2/person
Latent Heat gain per person	200 Btu/hr
Airflow	
Method	ASHRAE 62.1
Airflow – People	5 cfm/person
Airflow – Area	0.06 cfm/ft^2
Infiltration Rate	0 ACH
Room Exhaust Rate	0 ACH

Table 26. Input to Barnard Hall energy model for Office Space, West Perimeter room.

Specified Input in TRACE	Value
Walls	
Length	300 Feet
Width	13 Feet
Floor to Floor Height	12 Feet
Plenum	2 Feet
Wall Construction	12” Concrete, 4” Insulation (Int)
Wall Direction	270 Degrees
Wall U-Factor	0.0645 Btu/hr-ft^2-^{o}F
Window Type	Single Pane, ¼”, Clear
Window U-Factor	0.95 Btu/hr-ft^2-^{o}F
Window SHGC value	0.95
Window area (By Percentage)	6.17 %
Window Shading	Vertical Shading
Internal Loads	
Plug Load	1 W/ft^2
Light Heat gain	1.5 W/ft^2
Workstations per person	1
Activity	General Office Space
People Density	143 ft^2/person
Sensible Heat gain per person	250 ft^2/person
Latent Heat gain per person	200 Btu/hr
Airflow	
Method	ASHRAE 62.1
Airflow – People	5 cfm/person
Airflow – Area	0.06 cfm/ft^2
Infiltration Rate	0 ACH
Room Exhaust Rate	0 ACH

Table 27. Input to Barnard Hall energy model for Lab Spaces in core zone.

Specified Input in TRACE	Value
Walls	
Length	275 Feet
Width	125 Feet
Floor to Floor Height	12 Feet
Plenum	2 Feet
Wall Construction	N/A
Wall Direction	N/A
Wall U-Factor	N/A
Window Type	N/A
Window U-Factor	N/A
Window SHGC value	N/A
Window area (By Percentage)	N/A
Window Shading	N/A
Internal Loads	
Plug Load	3.0 W/ft^2
Light Heat gain	1.5 W/ft^2
Workstations per person	0
Activity	Laboratory
People Density	33.3 ft^2/person
Sensible Heat gain per person	250 ft^2/person
Latent Heat gain per person	200 Btu/hr
Airflow	
Method	Sum of Outdoor Air
Cooling Airflow	5 ACH
Heating Airflow	5 ACH
Infiltration Rate	0 ACH
Room Exhaust Rate	5 ACH

Table 28. Input to Barnard Hall energy model Cold Chambers.

Specified Input in TRACE	Value
Walls	
Wall 1	
Length	108 Feet
Width	13 Feet
Wall Direction	0 Degrees
Wall 2	
Length	129 Feet
Width	13 Feet
Wall Direction	90 Degrees
Wall 3	
Length	108 Feet
Width	13 Feet
Wall Direction	180 Degrees
Wall 4	
Length	129 Feet
Width	13 Feet
Wall Direction	270 Degrees
Wall factors (Same for every wall)	
Wall Construction	12” Concrete, 4” Insulation (Int)
Wall U-Factor	0.0645 Btu/hr-ft^2-^{o}F
Window Type	Single Pane, ¼”, Clear
Window U-Factor	0.95 Btu/hr-ft^2-^{o}F
Window SHGC value	0.95
Window area (By Percentage)	6.17 %
Window Shading	Vertical Shading
Floor to Floor Height	12 Feet
Plenum	2 Feet
Internal Loads	
Plug Load	1 W/ft^2
Light Heat gain	1 W/ft^2
Workstations per person	1
Activity	General Office Space
People Density	143 ft^2/person
Sensible Heat gain per person	250 ft^2/person
Latent Heat gain per person	200 Btu/hr

Table 29. Input to Barnard Hall energy model Shop.

Specified Input in TRACE	Value
Walls	
Wall 1	
Length	75 Feet
Width	18 Feet
Wall Direction	0 Degrees
Wall 2	
Length	175 Feet
Width	18 Feet
Wall Direction	90 Degrees
Wall 3	
Length	75 Feet
Width	18 Feet
Wall Direction	180 Degrees
Wall 4	
Length	175 Feet
Width	18 Feet
Wall Direction	270 Degrees
Wall factors (Same for every wall)	
Wall Construction	12” Concrete, 4” Insulation (Int)
Wall U-Factor	0.0645 Btu/hr-ft^2-^{o}F
Floor to Floor Height	18 Feet
Plenum	2 Feet
Internal Loads	
Plug Load	4.0 W/ft^2
Light Heat gain	1.5 W/ft^2
Workstations per person	0
Activity	Laboratory
People Density	33.3 ft^2/person
Sensible Heat gain per person	250 ft^2/person
Latent Heat gain per person	250 Btu/hr
Airflow	
Method	Sum of Outdoor Air
Cooling Airflow	5 ACH
Heating Airflow	5 ACH
Infiltration Rate	0 ACH
Room Exhaust Rate	5 ACH

Table 30. Input to Barnard Hall energy model for Current Configuration.

Specified Input in TRACE	Value
System Selection	Variable Volume Double Duct VAV
Heat Plant Configuration	Boiler
Cooling Plant Configuration	Water-Cooled Chiller
Fan Type	FC Centrifugal Variable Frequency Drive
Fan Static Pressure	6.33 in w.g.
Full Load Energy Rate	60 Hp
System Exhaust Fan	0.000321 kW/Cfm-in-wg
Room Exhaust Fan	0.000321 kW/Cfm-in-wg
Pump Head	153 ft
Boiler Efficiency	83.3 %
Base heat load	860 MBtu/hr

Table 31. Input to Barnard Hall energy model for Post-Heat Pump Configuration.

Specified Input in TRACE	Value
System Selection	Variable Volume Double Duct VAV
Heat Plant Configuration	Boiler
Cooling Plant Configuration	Water-Source Heat Pump
Fan Type	FC Centrifugal Variable Frequency Drive
Fan Static Pressure	6.33 in w.g.
Full Load Energy Rate	60 Hp
System Exhaust Fan	0.000321 kW/Cfm-in-wg
Room Exhaust Fan	0.000321 kW/Cfm-in-wg
Pump Head	105 ft
Water Source Heat Pump	50 ft
Boiler Efficiency	83.3 %
Base heat load	100 MBtu/hr

APPENDIX C

APPENDIX C: Thermal Energy Storage Tank Analysis

```
%Thermal Energy Storage Tank
clear;clc;close all

COB1 = xlsread('COB_generic_COB22.xls');
COB2 = xlsread('COB_reject_COB22.xls');

COBh = -COB1(:,19); % in kwh
COBr = 12000*COB2(:,10)/3412; %in kwh

L = length(COB1);
Totalheat = zeros(L,1);
Totalreject = zeros(L,1);
Community = zeros(L,1);

for i = 1:L

    Totalreject(i) = COBr(i);
    Totalheat(i) = COBh(i);
    Community(i) = COBh(i) + COBr(i);
end

TotalheatB = Totalheat*3412;
TotalrejectB = Totalreject*3412;

CommunityBtu = Community*3412; %Btu's

% Storage tank can only operate inbetween 50 and 100 degrees F
Size = 20000; %gallons of water
ww = 8.33; %lbs/gal of water
totalw = Size*ww; %total weight of water in lbs

Tank = zeros(L,1);
deltaT = zeros(L,1);
newTank = zeros(L,1);
%initial tank temeprature (60 F)
Tank(1) = 60;
%tank cannot go below 60, cannot go above 90
newTotalheat = zeros(L,1);

energygain = zeros(L,1);
energyneg = zeros(L,1);
energypos = zeros(L,1);
NewrejectBtu = zeros(L,1);
NewheatBtu = zeros(L,1);

for i = 1:L
    deltaT(i) = CommunityBtu(i)/totalw;
    if Tank(i) + deltaT(i) < 60
        Tank(i+1) = Tank(i);
        energygain(i) = 0;
    elseif Tank(i) + deltaT(i) > 90
        Tank(i+1) = Tank(i);
```

```
        energygain(i) = 0;
    else
        Tank(i+1) = Tank(i) + deltaT(i);
        energygain(i) = deltaT(i)*totalw;
    end
    TankB(i) = Tank(i)*totalw;
    TankBnew(i) = TankB(i) - TankB(1);
    if Totalheat(i) == 0
        Totalheatnew(i) = Totalheat(i);
    else
        Totalheatnew(i) = TotalheatB(i) + TankBnew(i);
    end
    if Totalheatnew(i) > 0
        Totalheatnew(i) = 0;
    end
    %Heat or heat waste that is actually used up
    if energygain(i) < 0
       energyneg(i) = energygain(i);
    elseif energygain(i) > 0
        energypos(i) = energygain(i);
    end
    % New thermal profile after heat is shared thoughout building
    NewrejectBtu(i) = TotalrejectB(i) - energypos(i);
    NewheatBtu(i) = TotalheatB(i) - energyneg(i);
end

energypos(energypos == 0) = NaN;
energyneg(energyneg == 0) = NaN;
zero = zeros(L,1);
heat =  abs(sum(TotalheatB)) - abs(sum(Totalheatnew));
disp(heat)

figure(1);%clf(1)
plot(Tank)
axis([0 8760 50 100])
xlabel('Hour','Fontsize',18)
ylabel('Tank Temperature (F)','Fontsize',18)
title({'Yearly Tank Temperature Profile';'Tank size of 20,000
gallons'},'Fontsize',18)

heat = heat/10^6;

fprintf('Total heat savings = %5.2f MMBTU\n',heat)

figure(4);%clf(4)
plot(TotalrejectB,'b.')
hold on
plot(TotalheatB,'r.')
axis([0 8760 -3*10^6 3*10^6])
xlabel('Time (hours)')
ylabel('Heat (BTU)')
legend('Heat Availability','Heat Demand')
title({'Before Thermal Storage Tank';'Thermal Profile for Cobleigh'})
```

```
figure(5);%clf(5)
plot(NewrejectBtu,'b.')
hold on
plot(NewheatBtu,'r.')
axis([0 8760 -3*10^6 3*10^6])
xlabel('Time (hours)','Fontsize',18)
ylabel('Heat (BTU)','Fontsize',18)
legend('Heat Availability','Heat Demand')
title({'After Thermal Storage Tank Implementation';'Thermal Profile for
Cobleigh'},'Fontsize',18)
```

APPENDIX D

APPENDIX D: Validation Figures

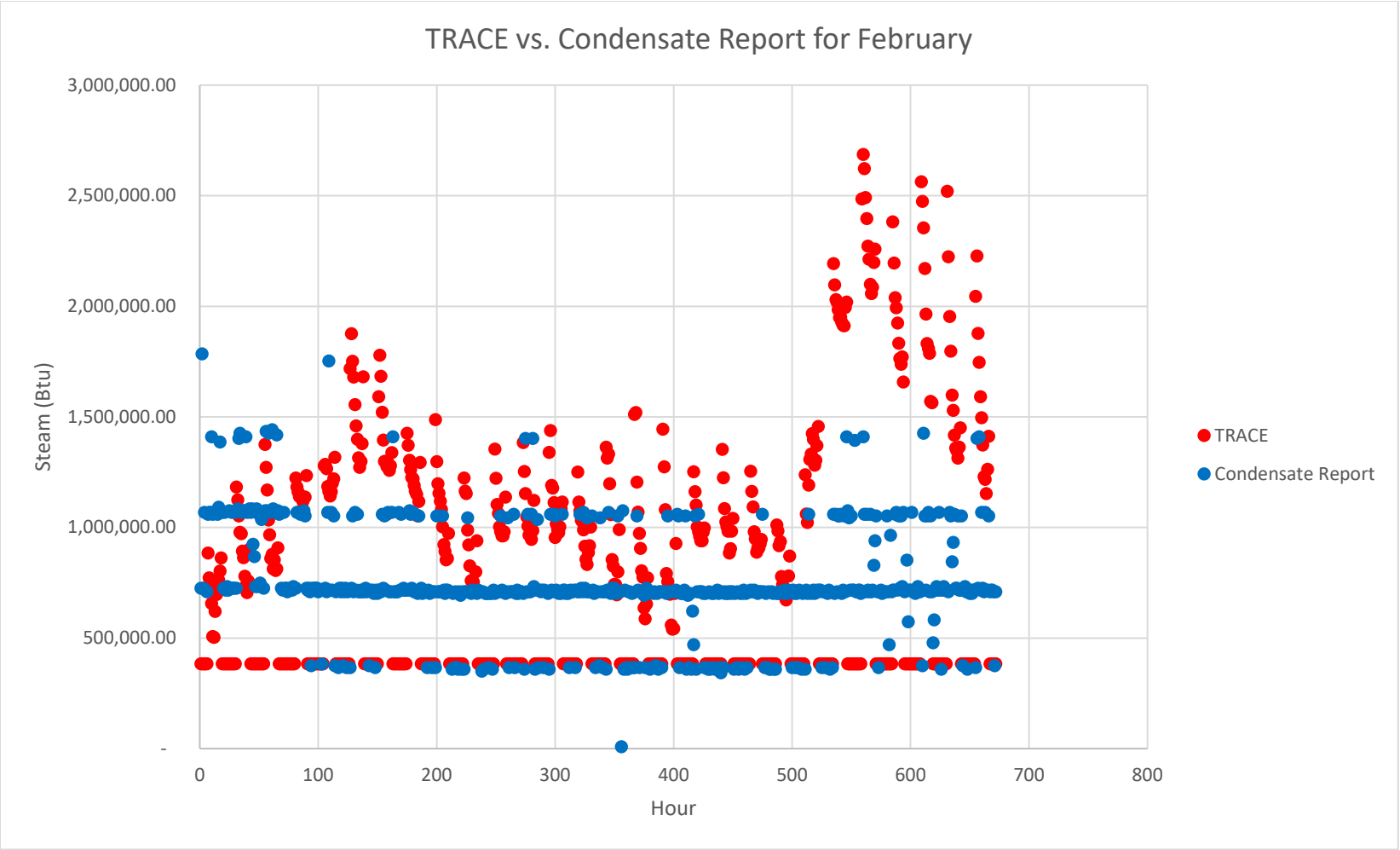


Figure 26. Cobleigh Hall Validation of hourly heating load. Comparison between metered data and model data in steam usage in BTU for February on a month scale.

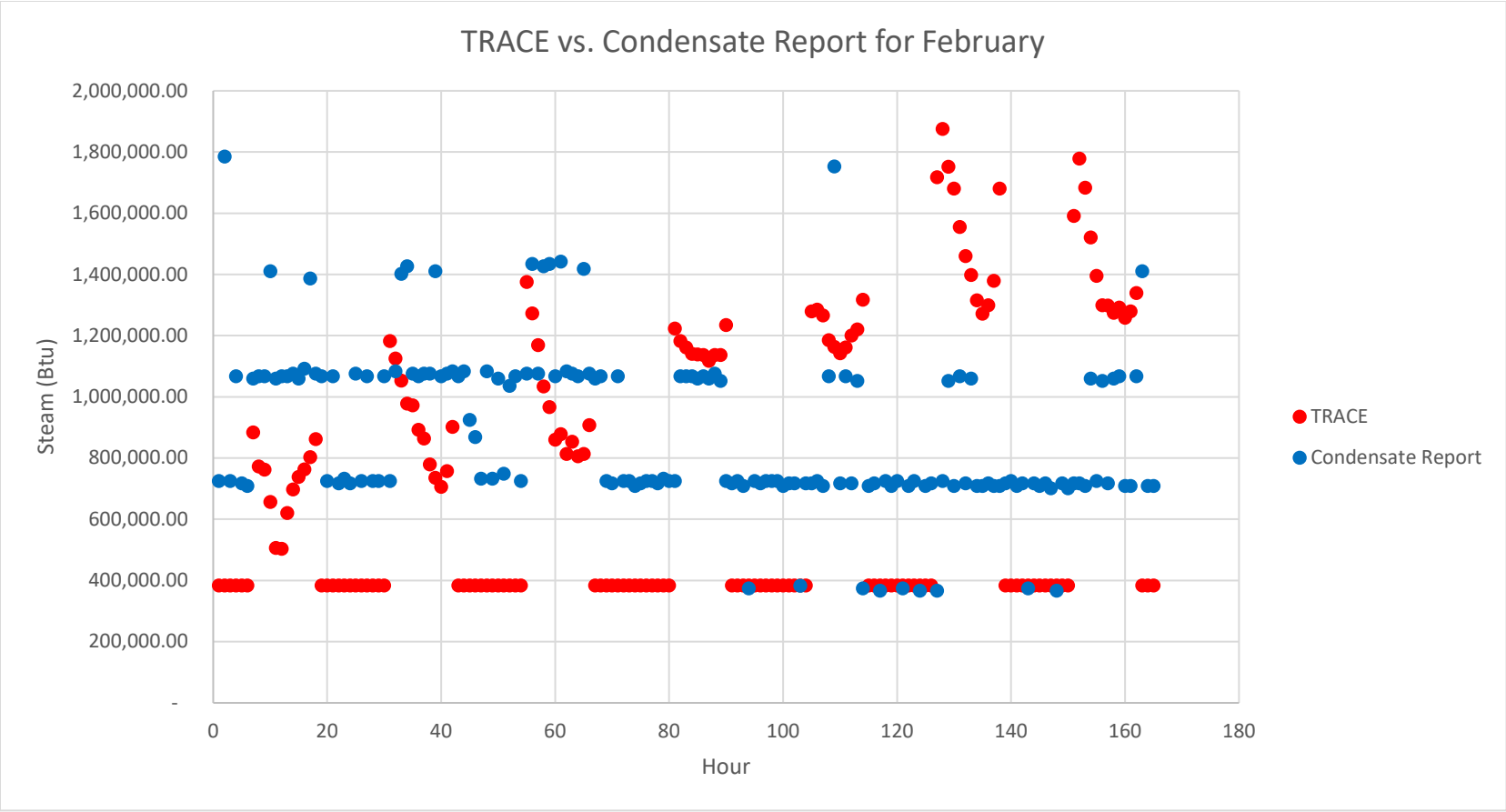


Figure 27. Cobleigh Hall Validation of hourly heating load. Comparison between metered data and model data in steam usage in BTU for February on a week scale.

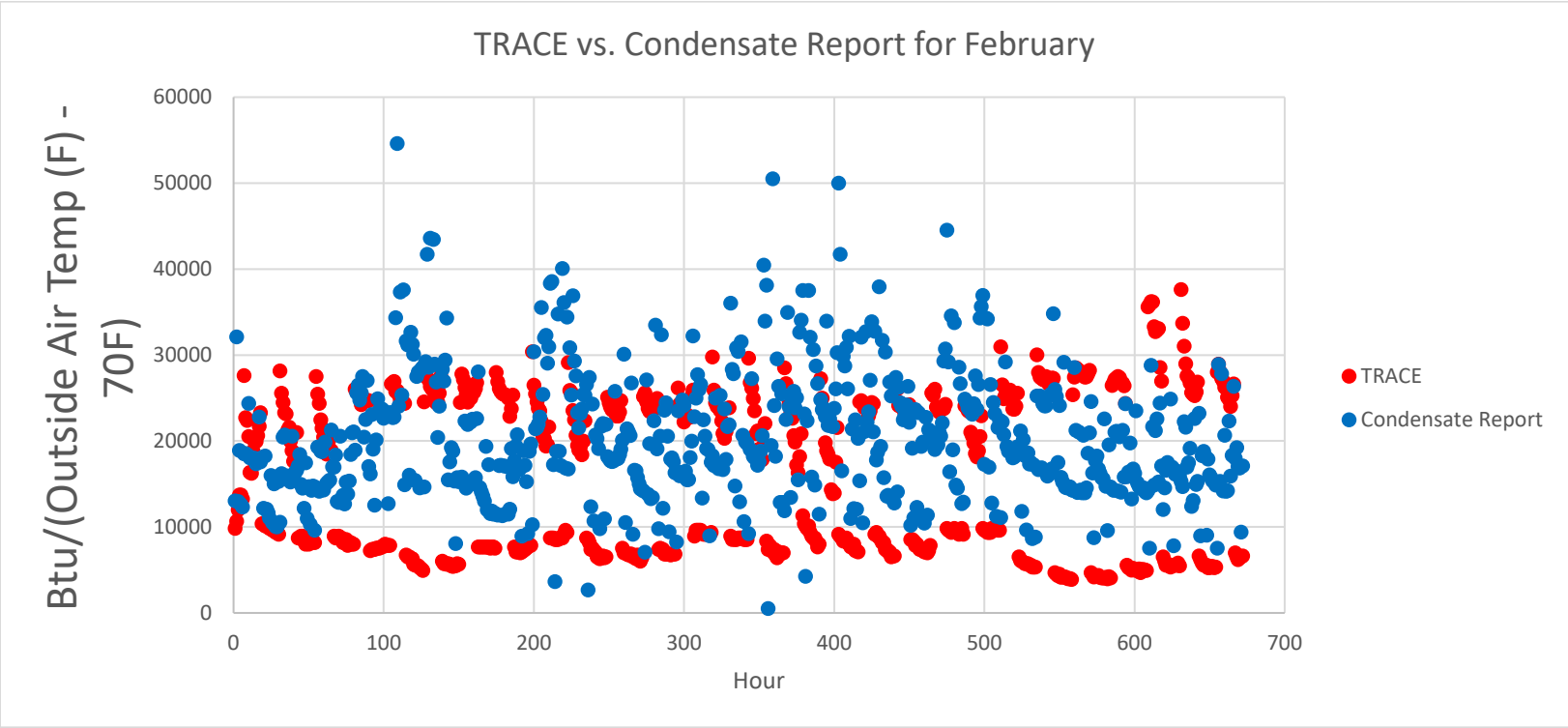


Figure 28. Cobleigh Hall Validation of hourly heating load. Comparison between metered data and model data in steam usage in BTUs divided by the temperature difference between 70 degrees F and the Outdoor Air Temperature for February on a month scale.

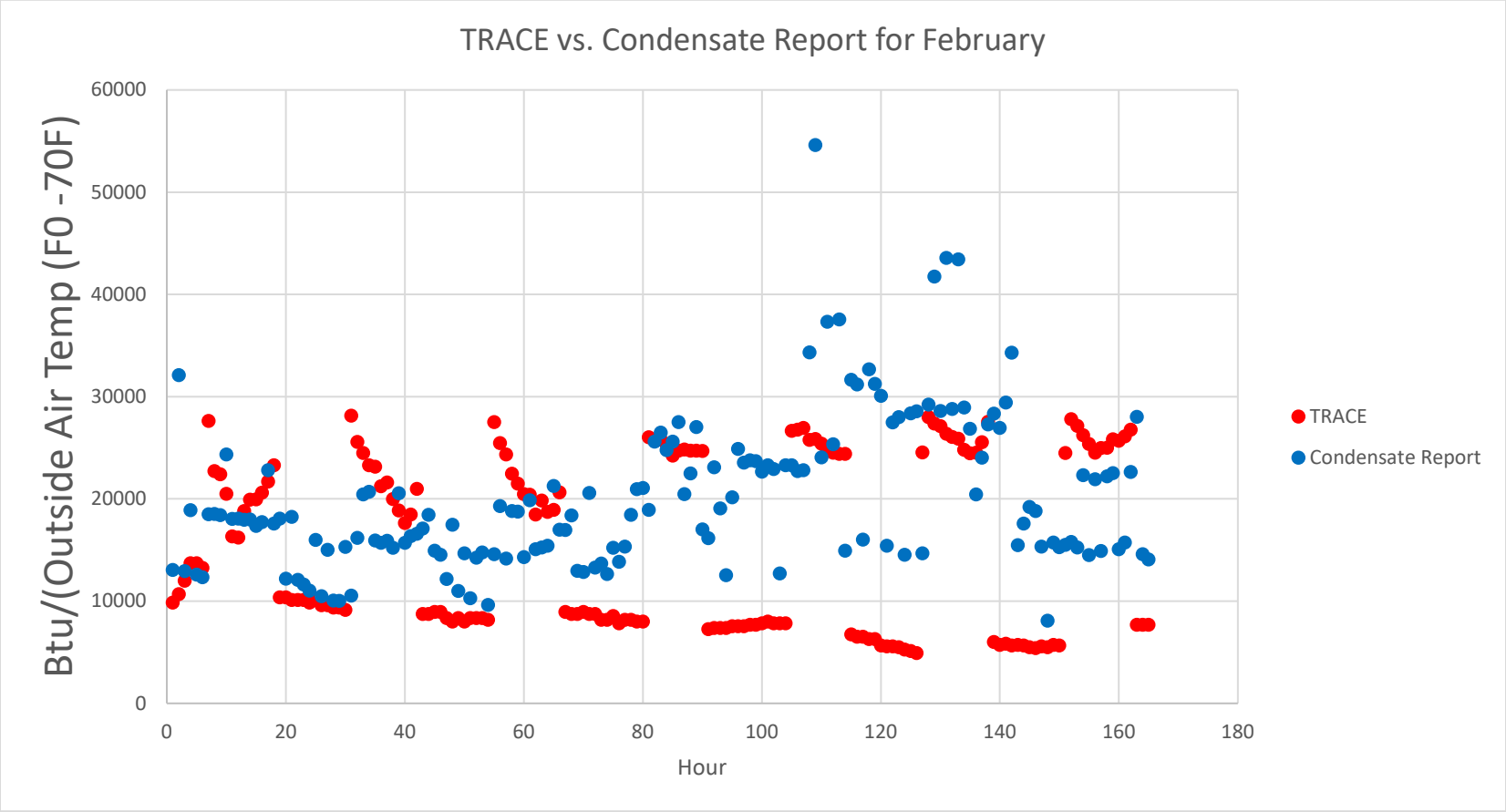


Figure 29. Cobleigh Hall Validation of hourly heating load. Comparison between metered data and model data in steam usage in BTUs divided by the temperature difference between 70 degrees F and the Outdoor Air Temperature for February on a month scale.

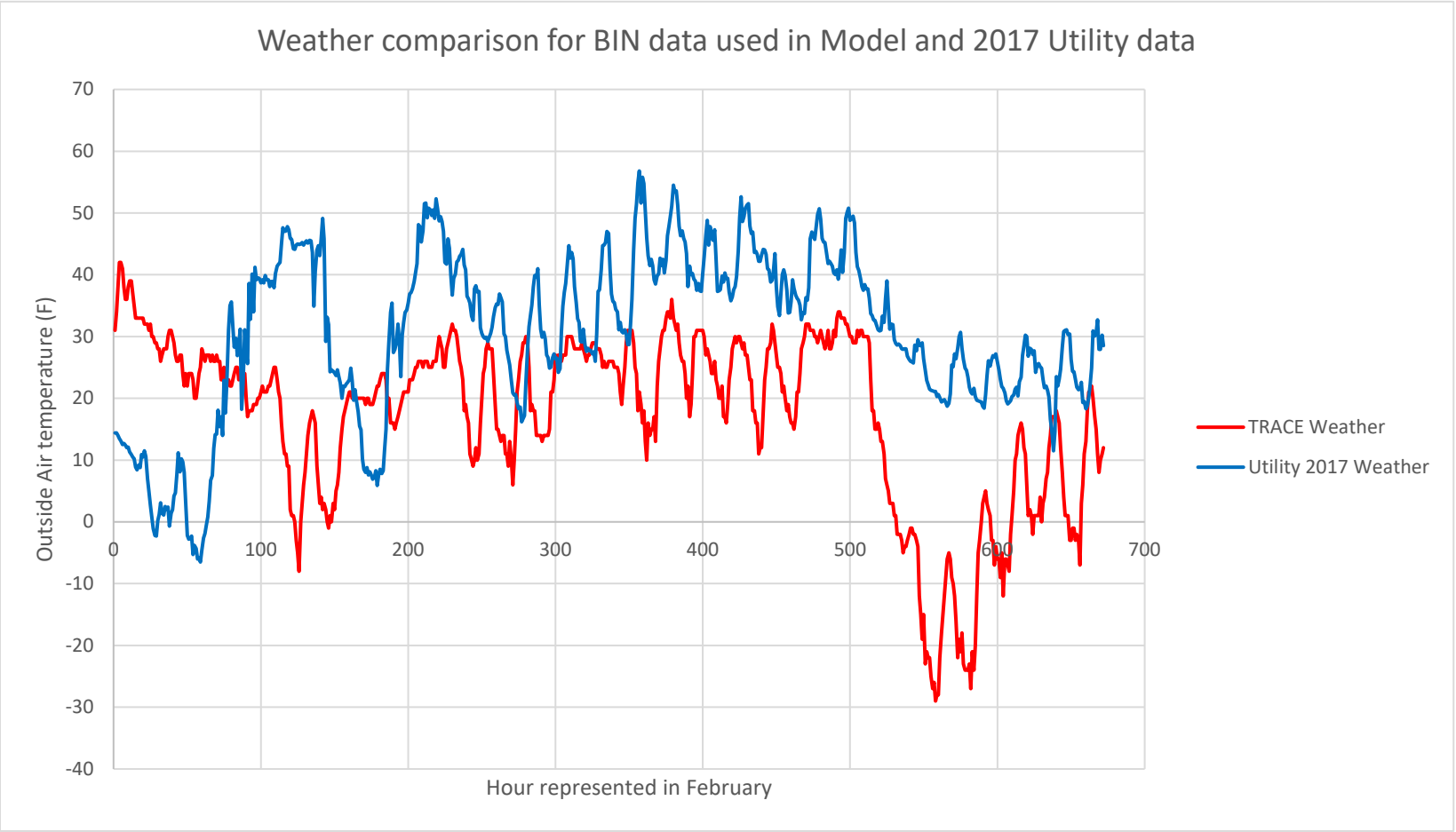


Figure 30. Hourly weather comparison for February 2018 and the model.