Center Valley, PA.

Michael Joaquino | Final Report

Advised by Dr. Rim

Penn State Lehigh Valley Campus

Building Information

Architect	Architectural Alliance	Location	Center Valley, PA
Construction Manager	Mortenson Construction	Size (in FT^2 area)	96,274 FT^2
Structural Engineer	Palanisami and Associates, Inc.	Occupancy Type:	Higher Education
Civil Engineer	Liberty Engineering	Building Owner	Penn State
Soil Foundation Engineer	Geostructures, Inc.		
Electrical Design Building	Parsons Electric Company	Cost	$12 Million (Purchase by PSU)
Mechanical Engineer	Beitmen and Huyett, Inc.	Date of Construction:	April 19, 2002—Fall 2003
Fire Protection	Majek Fire Protection, Inc.		

Architecture

- The Penn State Lehigh Valley building is designed to accommodate for primarily higher education use.

- The building suits office space, variety of classrooms/lecture rooms, and common space.

- The building is a total of 3 stories above ground, including a two story atrium lobby.

Structural System

- Overall: The building supports a steel framing system

- Floor system: Each floor supports a metal decking and concrete floor slab

- Roof System: 20ga. Roof metal decking.

Mechanical System

- Ventilation: The building is served by three separate roof top units.

- Among the three roof top units, are 88 VAV fan powered units serving individual zones.

- The server room on the first floor is served by the DX Unit.

- VAV units include electric reheat to accommo-

Lighting/Electrical System

- The main power distribution for this building is supplied by a main line from the utility plant.

- The distribution line leads to the main circuit board which supplies the panel boards throughout the building and the three roof top units.

- The power distribution to light the parking lot is supplied from the building

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Acknowledgements

I would like to thank the Penn State faculty for their guidance and encouragement towards my career path and education. I would also like to thank my friends, my family and my significant other for their support and encouragement.

Without my classmates, my friends I would not have been able to reach my achievements in my education as an Architectural Engineer. Therefore, thank you class of 2017, Architectural Engineering for the moments and hard work spent together.

Lastly, I would like to thank my thesis advisor, Dr. Donghyun Rim and the Office of Physical Plant for their permission to use this building.

Executive Summary

The Penn State Lehigh Valley building is a three-story building intended for primary higher education/University occupancies. This building's mechanical system was analyzed for educational intentions and evaluated in previous technical reports for ASHRAE Standard 62.1 and 90.1 compliances, including an energy model to calculate a block building load. For this thesis, a mechanical system is proposed as an alternative design from the original. This is not intended to discuss flaws of the existing mechanical design but as an educational opportunity to design and propose a mechanical system for an existing building.

The mechanical depth includes the design, calculation and proposal of a geothermal system. Most systems are designed with an energy distribution method, either from a water loop of a chiller/boiler or a simple air-to-air heat pump such as the existing packaged rooftop units of Penn State Lehigh Valley. This alternative design includes a ground source heat pump (GSHP) which exchanges the energy from the geothermal system.

This proposal aims to study the energy consumption and cost effectiveness of the system. The decision to rationale this proposed design, other options are evaluated to compare energy consumption and cost. The goal of this study to find the energy savings difference from a geothermal system to other system designs. Following that study, a cost analysis among different systems to evaluate the optimal distribution system to supplement the geothermal system throughout the building's individual zones.

Additionally, a construction and acoustical study was evaluated for the proposal of the geothermal well installation and the effect of a heat pump as a sound source to a class room respectively. The calculation to determine the optimal location within the building's property was evaluated and the cost of the high initial cost is reasonable for the yearly energy savings.

Building Overview

The Penn State Lehigh Valley Campus was purchased by Penn State in 2009. The building was originally constructed in 2002, and was previously the Lehigh Valley College. The cost of the property, including furnishing, fixtures and equipment was $12 million dollars. The office of Physical Plant did not handle any of the design or construction. It is important to Note that the owner of the building is Penn State, while The Office of Physical Plant handles Penn State's facilities as a construction management and facilities management.

The building is located in Center Valley, Pennsylvania. The building supports about 2000 students among the 3 floors. The building is 96,274 gross square feet, without floor opening. The, chemistry labs, workshops, computer labs, lecture halls building consists of a two-story atrium in the center of the building, and among the 3 floors are multiple styles of classrooms such as music rooms, and offices. There is a café and student lounge in the first floor, on the second floor there is a 2,800-sq. ft. library and the third floor there is a 1000 sq. ft. student lounge. For this building's energy calculations, these zones are broken up among offices, classrooms, and lobby building spaces.

When evaluating the building characteristics, it is important to note that the building does not have a dedicated mechanical space. Relative to this report, the mechanical proposal will address options without the mechanical space. Although this does not constrain the options to expanding the building area due to the lack of surrounding buildings nearby of the school.
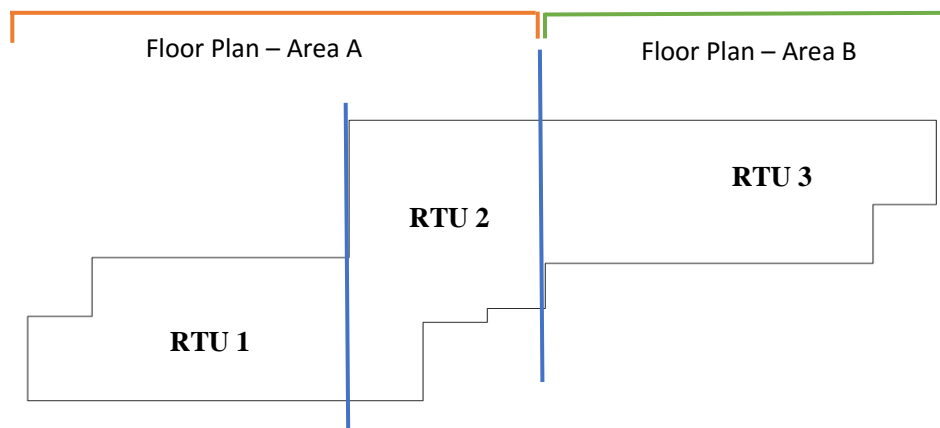
Figure 1: Building Overview

Existing Mechanical Systems Overview

Penn State Lehigh Valley's mechanical system is equipped with three packaged rooftop units, consuming electric and natural gas for DX Cooling and Furnace heating. The supplied air from the rooftop system is supported with VAV units with electric reheat for additional heating the room demands. Table 1 overviews the mechanical system in the building. RTU-1 and RTU-2 serves area A of the building and RTU-3 serves area B. Among each individual zone are served by fan powered VAV units with reheat. The Lehigh Valley building's mechanical system is a primarily air-side system, therefore most of the air is conditioned in the RTU's and the VAV units adjust the temperature and modulates the airflow to satisfy heating loads. The three rooftop units serving the building's mechanical systems are DX Cooled/heated systems and gas fired. The DX unit is packed within the rooftop units and are packaged with the units.

The efficiency of this systems energy consumption based on peak loads will be summarized in this report. The three rooftop units are manufactured by Trane and require 480 V – 3 Phase to power the unit's fan and compressor. Energy saving operations is implemented in this system by running an economizer when the relative humidity outdoor is less than the return air. It is important to note that this building's mechanical unit includes a DX Unit to serve a computer room, while the load is considered in the energy model, the unit itself is not included as a separate system.

Existing Design Heating and Cooling Objectives

Outdoor Design Conditions

Penn State Lehigh Valley building is designed to accommodate heating and cooling peak loads. Table 1 below shows the specifications designed for outdoor design temperatures. In the energy model proposed in technical report two, ASHRAE weather design temperatures was used for outdoor weather conditions at monthly percentile for heating 99.6% and cooling 0.04% loads design. Outdoor winter design temperature was designed for 8.42 F Dry bulb temperature.

Table 1: Outdoor Design Conditions

Outdoor Design Conditions		
Summer Conditions		
Dry bulb and wet bulb	95 DB	78 WB
Winter Conditions		
Dry bulb (Median/Extremes)	(-)	

Indoor Design Conditions

The indoor designed conditions for the Penn State Lehigh Valley building is designed to specifications on the construction drawings shown in table 3 and 4. Rooftop units supply airflow to individual spaces that are then modulated by variable air volume units (VAV Units). Individual spaces are satisfied with exceeded heating loads with electric reheat in the VAV units. The indoor temperature set point is modulated by occupant schedule to save energy usage and utility cost.

Table 2: Indoor Design Conditions

Indoor Design Conditions		
Summer/Winter Conditions		
Indoor Temperature	75 DB	63 WB

Ventilation Requirements

The Penn State Lehigh Valley building is designed with three rooftop units that supply constant airflow throughout the building. These units are designed with a set amount of outdoor air minimum CFM to satisfy the building's outdoor air requirement. This building's mechanical system was deemed compliant to ASHRAE standards 62.1 Ventilation requirements.

Table 3: Ventilation Calculations

AHU Units	Total CFM	O/A Min. CFM	Calculated Total CFM	Calculated O/A CFM
AHU-1	40,740	10,725	21,387	11,547
AHU-2	19,770	4,125	10,016.11	5,718
AHU-3	33,748	14,415	22,785	8,129.1

Block Heating and Cooling Loads

Heating and cooling loads for the Penn State Lehigh Valley building was calculated using IES Virtual Environment Energy modelling program. The second technical report detailed the analysis of the energy model calculations. Although the energy model calculations fall short of the engineer's design, the results were within reasonable range for the cooling coil load. The heating coil load calculated is incorrect, due to missing information to properly calculate the heating coil load.

The engineer designed the rooftop unit to satisfy 105 F supply air temperature coming from the Heating coil. Based on calculations using the psychrometric chart, located in the appendix which shows the correct heating coil load. The rooftop unit conditions the air by a DX cooling system and natural gas heating packaged within the unit.

Table 4: Calculated Energy Model Peak Design Loads

System Sizing	(Peak Value)	AHU CC Total Load (kBTU/h)	AHU HC Total Load (kBTU/h)	Fan Sizes (CFM)	OA Min (CFM)
RTU-1	Coil Sizes	1119.3	609.6	40740	10725
VAV Reheat (DX Cool)					
RTU-2	Coil Sizes	756.03	205.9	19770	4125
VAV Reheat (DX Cool)					
RTU-3	Coil Sizes	1538.41	853.07	33748	14415
VAV Reheat (DX Cool)					

Table 5: Existing Mechanical System

Actual Mechanical Specification	Cooling (kBtu-h)	Heating (kBtu-h)	CFM	O/A Min.
RTU-1	1492	2350.8	40740	10725
RTU-2	751.6	1059.2	19770	4125
RTU-3	1512	2365.4	33748	14415

Table 6: Calculated Coil load with Psychrometric Chart

Unit	Cooling Coil Load [kBTUH]	Heating Coil Load [kBTUH]
RTU-1	1,739.339	2,281.212
RTU-2	1,086.982	786.152
RTU-3	1,664.252	2,388.003

The calculations based from the psychrometric chart shows the heating demand is mostly based to satisfy the 105 F supply air temperature leaving the heating coils. Any heating demand not satisfied by the supply air of the rooftop unit is supplemented by the electric reheat coil of the VAV units. The rooftop unit provides constant outdoor air flow except during unoccupied periods.

Existing Energy Sources and Rates

Annual Energy Use

The Penn State Lehigh Valley building primary source of energy consumption comes from natural gas and electricity. Figure 2 and 3 below breaks down the utility usage throughout the building. The mechanical system consumes electricity for the DX cooling system and electric reheat. Natural gas is consumed primary by the rooftop units to condition air to satisfy the heating load, where the air is heated by natural gas.
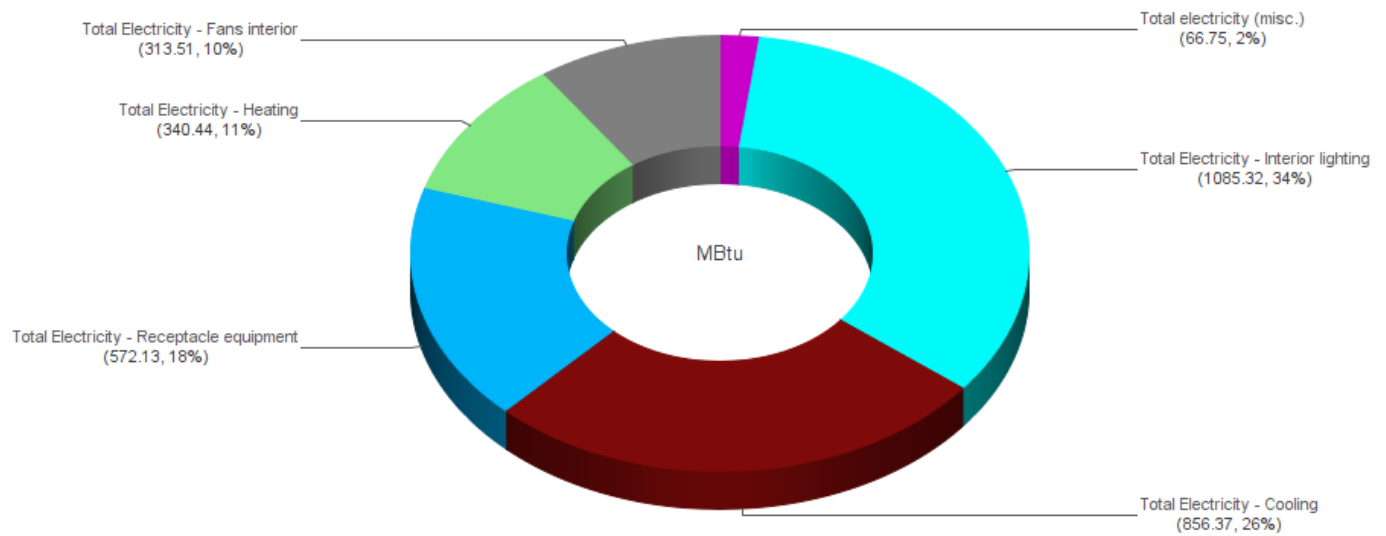
Figure 2: Annual Total Building Electricity Distribution

Table 7: kBTU-KWH – Electricity Building Usage

kbtu to KWH Conversion	kBTU	KWH
Fans Interior	313,510	91,880.71
Heating	340,440	99,773.12
Receptacle	572,130	167,674.8
Misc.	66,750	19,562.49
Interior Lighting	1,085,320	318,075.9
Cooling	856,370	250,977.3
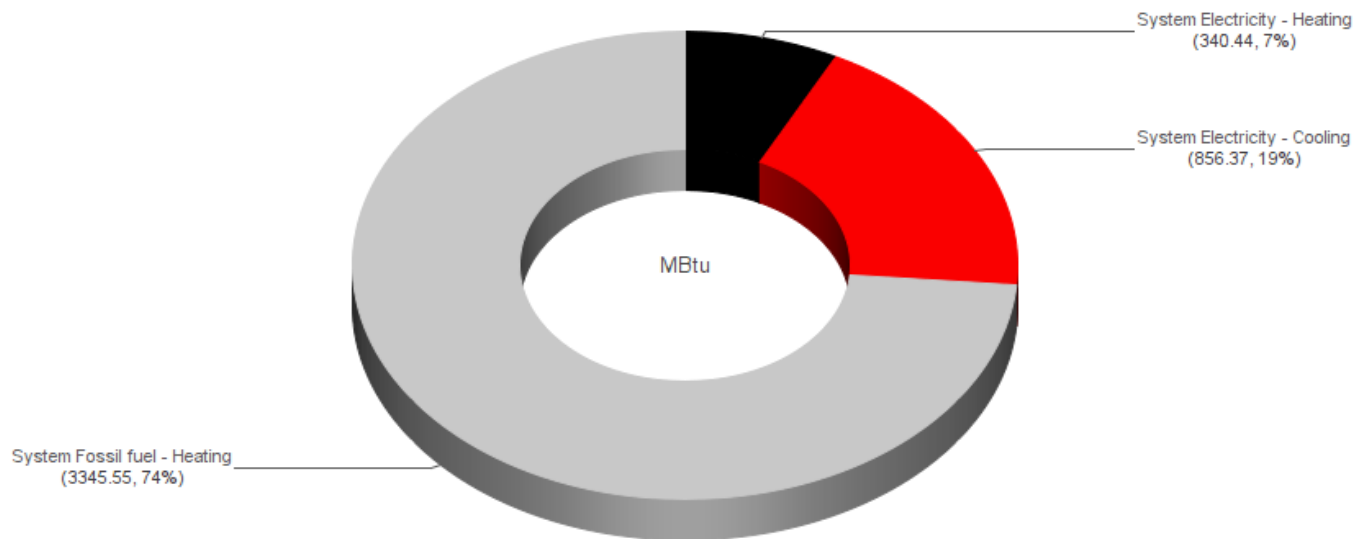
Figure 3: Fossil Fuel Consumption Breakdown

Energy Source and Rates

The entire building's energy consumption is calculated using 2016 cost per unit. The cost of expected energy consumption during the design of this building differs of the cost of consumption today.

USD per Mcf / 1.032 = $ per MBtu.

MMBtu equals 1,000,000 BTUs.

Table 8: Energy Rates

Energy Rates - 2016		
Source	**Rate**	**Unit**
Gas	10.99	USD/Mcf
Electricity	$0.091	Kwh

Annual Operating Cost

The Penn State Lehigh Valley building's annual cost for utility cost is approximated to $125,791. The breakdown by energy type of annual cost is shown in table 9. This building annual energy cost includes the mechanical system and general equipment in the building. The electricity cost is the largest utility bill generated by the Penn State Lehigh Valley building.

Table 9: Building Annual Energy Cost

Annual Energy Cost & Consumption			
Energy Type	**Units**	**Energy Use**	**Cost**
Electricity	kBtu	831,788.48	$ 75,692.75
Gas	MMBtu	4,704.46	$ 50,098.87
Total	kBtu	7,542,642.10	$ 125,791.63

Mechanical Depth Part 1 – Ground Source Heat Pump

The mechanical depth evaluates the alternative mechanical system design for the Penn State Lehigh Valley building. In this mechanical depth, the alternative system to be proposed is the concept of creating a geothermal well as a heat source (in the winter) and sink (in the summer). This system incorporates a ground source heat pump instead of a water-to-water or air-to-air heat pump. The geothermal well transfers stored energy to the mechanical system loop to reduce the energy to condition the supply air.

The design goal is to reduce or replace the energy consumption from a chiller or boiler would produce to satisfy the building's cooling and heating load. Although there is an expected high initial cost for the construction and equipment for a ground source heat pump and geothermal well, the goal is to meet a reasonable payback timeline for savings in energy consumption.

In comparison to the proposed geothermal system are the existing mechanical design and a water-side alternative with DOAS unit. The existing mechanical design are a packaged rooftop units supported with VAV electric reheat boxes, the existing mechanical design is evaluated in more details in the existing mechanical systems section from this report. Throughout this report and calculations, the existing mechanical system is referred to a baseline system for technical comparisons.

Depth Design Objectives

The proposed mechanical system in mind is decided by the ability to meet the cooling and heating demand while creating opportunities for energy savings. The first constraint when selecting a proposed system for the Penn State Lehigh Valley building is the lack of a mechanical room. Traditional mechanical systems designed for commercial buildings include a chiller and boiler loop to condition the supply air, versus conditioning via air-to-air heat pump because of its efficiency difference. By achieving to cool and heat the building without sacrificing a significant area of the building for a mechanical space, a geothermal well will work as an environmental friendly heat source and sink.

Majority of the plumping will be where the geothermal well would exist outside of the building. The first drawback in comparison to a chiller/boiler loop would be the high initial cost due to the construction of the geothermal wells. This difference in savings will be analyzed in the cost comparison of this report. Although this system is expected to consume less energy to operate than a chiller/boiler loop due to the stable ground temperature.

Once the building load is determined through the energy model in IES VE. The borehole length will be calculated and considered for best location based on the soil type surrounding the building. Regarding the borehole length design, the ground temperature will affect the efficiency of the geothermal system. A temperature value far from the deep-ground temperature creates a more efficient geothermal system, resulting to a smaller coil size and heat pump.

Research – Geothermal Systems

Without much initial research, a geothermal system deemed optimal for this building due to large amount of surrounding land. Since space is not a concern, this system alternative has direct advantages:

- Environmental-Friendly Energy saving methods
- Reduce peak building demand
- High Performance Heat Pumps

Due to the design of the geothermal system, it is strongly recommended to design a DOAS unit to meet the building's ventilation rate. This provides the opportunity for greater indoor air quality and reduced coil sizing. A majority of the plumbing will be focused between the geothermal loop and system loop. The ground source heat pump will be controlling the flow rate to efficiently modulate the refrigerant enough to condition the supply temperature.

It is important to note when modelling the geothermal system in IES VE, the program calculates the ground source heat pump capacity assuming the ground temperature is stable to yield the building loads. This does not include soil types and bore field length, a bore field length calculation is explained in the following section.

It is assumed that the length can provide energy to meet the building's demand with the supplemental help of the zone rooms. Realistically this cannot be achieved to meet the building full load capacity, this is when the zone level equipment is designed to supplement additional demand. This mechanical proposal incorporates the geothermal system to be supplemented with an air-cooled condenser heat pump to serve distributed zones.

Design Consideration – Geothermal + Distribution System

Among researching alternative geothermal design, the decision to supplement the geothermal system is evaluated. A geothermal system cannot alone satisfy the building load efficiently. Therefore a distribution system is proposed to pair with the geothermal system. The alternative distribution system includes:

- VAV with Reheat Only
- Air-Cooled Condenser Heat Pump
- Electric Water Chiller and Boiler

The first option is the existing distribution system supplying the individual zones. This won't require additional construction interrupting building occupancy. The second option includes replacing the existing VAV units, albeit a water-less system. The third option is expected to have the highest initial cost and installation. A small sized water chiller and boiler, as well the construction of a mechanical room will be installed to condition a four-pipe VAV box in all individual zones.

Table 10: Cooling GSHP Annual Load

Geothermal + VAV-Reheat		Geothermal+HP		Geothermal+EWC/Boiler	
Date	Load (MBtu)	Date	Load (MBtu)	Date	Load (MBtu)
Jan 01-31	208.809	Jan 01-31	0	Jan 01-31	0
Feb 01-28	199.609	Feb 01-28	0	Feb 01-28	0
Mar 01-31	247.531	Mar 01-31	0.206	Mar 01-31	0.205
Apr 01-30	278.545	Apr 01-30	14.637	Apr 01-30	14.624
May 01-31	332.511	May 01-31	86.659	May 01-31	86.664
Jun 01-30	394.154	Jun 01-30	219.783	Jun 01-30	219.707
Jul 01-31	438.495	Jul 01-31	345.71	Jul 01-31	345.572
Aug 01-31	423.556	Aug 01-31	297.465	Aug 01-31	297.37
Sep 01-30	383.297	Sep 01-30	196.844	Sep 01-30	196.791
Oct 01-31	306.269	Oct 01-31	44.147	Oct 01-31	44.102
Nov 01-30	261.044	Nov 01-30	17.425	Nov 01-30	17.426
Dec 01-31	227.193	Dec 01-31	0	Dec 01-31	0
Summed total	3701.013	Summed total	1222.875	Summed total	1222.462

Table 10 analyze the impact of different distribution systems affect the ground source heat pump load. Based on the annual load necessary to cool, the geothermal system with VAV Reheat only requires a larger demand from the geothermal system. While the two distribution systems supporting individual zones can accommodate the cooling load has the same annual total. The cooling demand required for a distribution system without supplemental cooling is not feasible for an efficient design.

A quick analysis of the electricity consumption, since a geothermal system with VAV Reheat only would require electricity. The energy consumption is far greater than the other two options as shown in table 11. Based on this initial research, only a proposed geothermal system with either an air-cooled condenser heat pump or chiller and boiler. Lastly, all alternative systems will include DOAS Units for equal ventilation requirements.

Table 11: Heating Electricity Energy

Total Electricity - Heating	Total Electricity - Heating (MBtu)	Total Electricity - Heating (MBtu)	Total Electricity - Heating (MBtu)
	Geothermal + VAV-Reheat	Geothermal+HP	Geothermal+EWC/Boiler
Summed total	1512.396	657.49	305.34

Geothermal Bidirectional Cascade System

The geothermal system cannot be optimized for its full energy saving potentials without a proper design and control system. A geothermal system can accommodate the building's cooling and heating demand by two methods, distributed or bidirectional cascade. For this system, a bidirectional cascade design will be selected for this building's design which utilizes a heat recovery chiller to achieve heating and cooling.

A bidirectional cascade designs allows the geothermal system to satisfy the building's heating and cooling loads simultaneously. Figure 5 and 6 illustrates a system operating in cooling or heating mode only. Figure 7 illustrates the distribution system for a bidirectional cascade system, where two chillers supplying a cooling load and heating load. This system can support multiple heat recovery chillers to accommodate a larger demand if necessary.
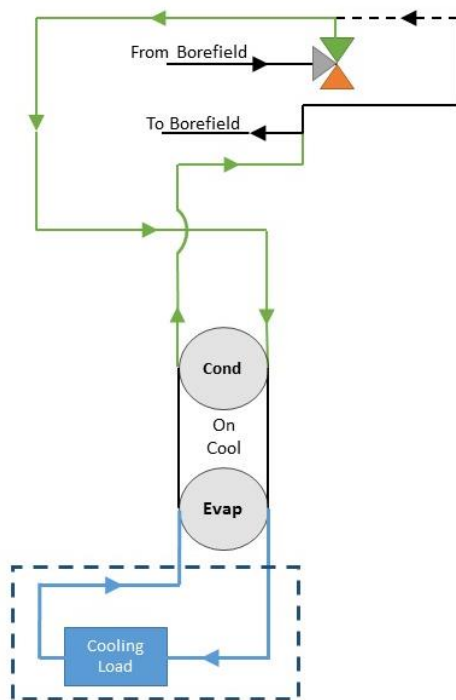
Figure 4: Cooling Only   *Figure 5: Heating Only*
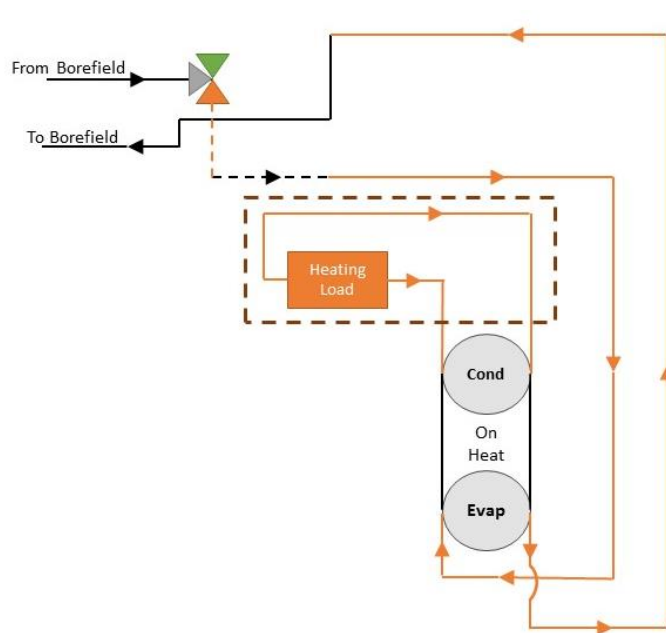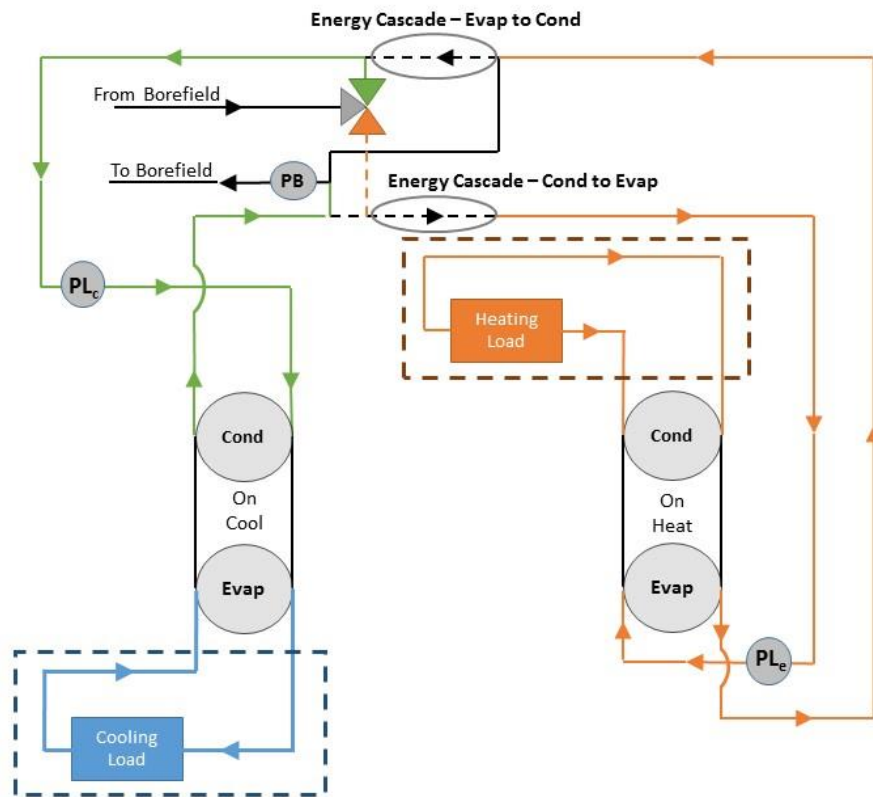
Figure 6: Bidirectional Cascade System ("Central Geothermal System Design and Control" – Trane Commercial.)

The Penn State Lehigh Valley building will require multiple heat recovery chillers to satisfy the coil load, thus creating a larger pumping power for the liquid flow. The design of this system requires the multiple chillers to be connected by the energy cascade direction shown in figure 6. A building with a larger heating load than cooling, the energy cascade from condenser to evaporator will be prioritize.

The Penn State Lehigh Valley building will require a heating dominate system, therefore the bore field energy will transfer to the heating demand first. The colder liquid temperature leaving the evaporator will be utilized to satisfy the cooling demand next. This is system will save the heat pump energy consumption because of the energy recovery from the previous heat pump.
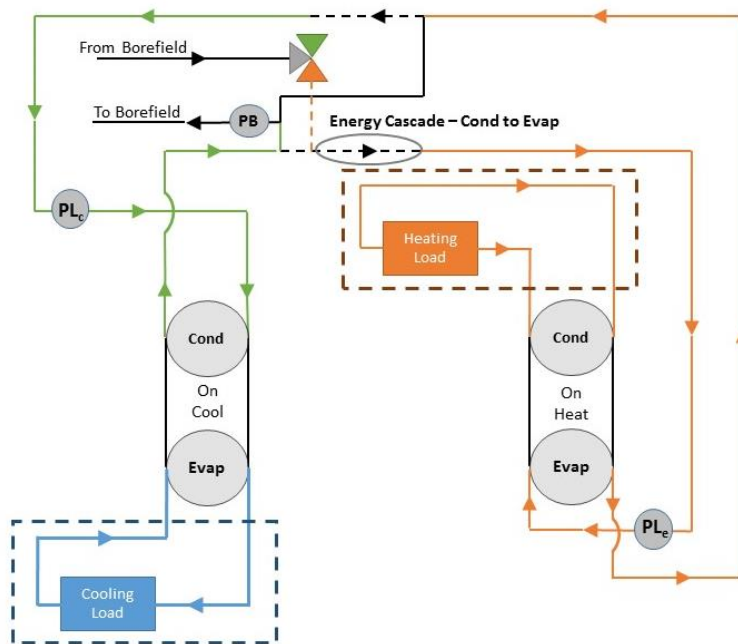
Figure 7: Heating Dominate

Heating Dominate system characteristics;

- Additional energy (BTUs) are called on by the evaporator energy transfer of the heating loop than are rejected from the condenser energy transfer loop.
- The system is considered BTU Deficit
- Evaporator energy transfer loop is cooler than the bore field supply liquid temperature

The system controls are crucial for optimizing energy savings. This system will include a pump control to meet the building's load. PL_c and PL_e loop pump maintains the design heat pump condenser, for cooling or evaporator for heating flow rates. PB is the pump that controls the flow rate entering and leaving the bore field. This controls the efficiency of the bore field energy rejected. The controlled pump is based on the supply temperature from the bore field. Other factors include the building load, number of chillers, operating limits, and seasonal variations. In summary, it is designed to meet the heat rejection requirement of the system without over pumping, which over pumping would create wasted energy.

Borehole Length Calculations

High initial cost is expected when selecting a geothermal system because of the construction of the boreholes. Boreholes need to be drilled 50 to 100ft into the earth ground, the borehole is then filled with the pipe loop and thermal enhancing grout to create a large heat transfer. In order to find the length of the boreholes, 2007 ASHRAE Handbook – HVAC Applications was referenced for calculations:

Required length for cooling:

$$L_C = \frac{q_a R_{ga} + (q_{lc} - 3.41 W_c)\left(R_b + PLF_m R_{gm} + R_{gd} F_{sc}\right)}{t_g - \dfrac{t_{wi} + t_{wo}}{2} - t_p}$$

Required length for heating:

$$L_h = \frac{q_a R_{ga} + (q_{lh} - 3.41 W_h)\left(R_b + PLF_m R_{gm} + R_{gd} F_{sc}\right)}{t_g - \dfrac{t_{wi} + t_{wo}}{2} - t_p}$$

F_{sc} = short-circuit heat loss factor

L_c = required bore length for cooling, ft.

L_h = required bore length for heating, ft.

PLF_m=part-load factor during design month

q_a = net annual average heat transfer to ground, Btu/h.

q_{lc} = building design cooling block load, Btu/h.

q_{lh} =building design heating block load, Btu/h.

R_{ga} = effective thermal resistance of ground (annual pulse), ft-h-$°F$ /Btu.

R_{gd} = effective thermal resistance of ground (peak daily pulse: 1 hr min, 4 – 6 hr recommended), ft-h-$°F$ /Btu.

R_{gm} = effect thermal resistance of ground (monthly pulse), ft-h-$°F$ /Btu.

R_b = thermal resistance of bore, ft-h-$°F$/Btu.

t_g = undisturbed ground temperature, $°F$

t_p = temperature penalty for interference of adjacent bores, $°F$

t_{wi} = liquid temperature at heat pump inlet, $°F$

t_{wo} = liquid temperature at heat pump outlet, $°F$

W_c = system power input at design cooling load, W

W_h = system power input at design heating load, W

Note: Heat transfer rate, building loads and temperature penalties are positive for heating and negative for cooling.

The effective thermal resistance to the ground; R_{ga}, R_{gd}, and R_{gm} are difficult parameters to determine. The Fourier number are related to time of operation, bore diameter, and thermal diffusivity of the ground which will correlate the dimensionless number to a G-Factor in figure 4. The Fourier number equation:

$$F_0 = \frac{4\alpha_g \tau}{d_b^2}$$

α_g = thermal diffusivity of the ground, ft²/day

τ = time of operation, days

d_b^2 = bore diameter, ft

Where τ is calculated by three heat pulses referenced from the 2007 ASHRAE Handbook;

- 10-year pulse of q_a τ_1= 3650 Days

- one month pulse of q_m, τ_2=3650 + 30 = 3680 Days

- 6-hour pulse of q_d. τ_f = 3650 + 30 + 0.25 = 3680.25 Days

Table 5   Thermal Properties of Selected Soils, Rocks, and Bore Grouts/Fills

	Dry Density, lb/ft³	Conductivity, Btu/h·ft·°F	Diffusivity, ft²/day
Soils			
Heavy clay, 15% water	120	0.8 to 1.1	0.45 to 0.65
5% water	120	0.6 to 0.8	0.5 to 0.65
Light clay, 15% water	80	0.4 to 0.6	0.35 to 0.5
5% water	80	0.3 to 0.5	0.35 to 0.6
Heavy sand, 15% water	120	1.6 to 2.2	0.9 to 1.2
5% water	120	1.2 to 1.9	1.0 to 1.5
Light sand, 15% water	80	0.6 to 1.2	0.5 to 1.0
5% water	80	0.5 to 1.1	0.6 to 1.3
Rocks			
Granite	165	1.3 to 2.1	0.9 to 1.4
Limestone	150 to 175	1.4 to 2.2	0.9 to 1.4
Sandstone		1.2 to 2.0	0.7 to 1.2
Shale, wet	160 to 170	0.8 to 1.4	0.7 to 0.9
dry		0.6 to 1.2	0.6 to 0.8
Grouts/Backfills			
Bentonite (20 to 30% solids)		0.42 to 0.43	
Neat cement (not recommended)		0.40 to 0.45	
20% bentonite/80% SiO₂ sand		0.85 to 0.95	
15% bentonite/85% SiO₂ sand		1.00 to 1.10	
10% bentonite/90% SiO₂ sand		1.20 to 1.40	
30% concrete/70% SiO₂ sand, s. plasticizer		1.20 to 1.40	

Source: Kavanaugh and Rafferty (1997).

Figure 8: Thermal Properties of Selected Soils, Rocks, and Bore Grouts/Fills

The thermal diffusivity of the ground, α_g is found in Table 5 (Figure 8) of the 2007 ASHRAE Handbook – HVAC Application. In the existing site features, the site is surrounded by two soil types which are silt loam and limestone. The thermal resistance of the ground calculation was done for both soil types, for α_g the worst-case value was used within the diffusivity range.

The calculations and variables can be found in the Appendix B: Borehole Length Calculation section. The variables found are:

Limestone Thermal Resistance

$$F_1 = 435.6 \quad G_1 = 0.575$$
$$F_2 = 3.6 \quad G_2 = 0.575$$
$$F_f = 52995.6 \quad G_f = 0.575$$

Silt Loam Thermal Resistance

$$F_1 = 290.4 \quad G_1 = 0.515$$
$$F_2 = 2.4 \quad G_2 = 0.18$$
$$F_f = 35330.4 \quad G_f = 0.89$$

These values are then used to find the effective thermal resistance to the ground, using the following equations;

$$R_{ga} = \frac{G_f - G_1}{K_g} \qquad R_{gm} = \frac{G_1 - G_2}{K_g} \qquad R_{gd} = \frac{G_2}{K_g}$$

The resulted value for thermal resistance to the ground completing the unknown variables to calculate the borehole length.

$R_{ga} = 0.201$ $\qquad\qquad$ $R_{ga} = 0.225$

$R_{gm} = 0.225$ $\qquad\qquad$ $R_{ga} = 0.201$

$R_{gd} = 0.120$ $\qquad\qquad$ $R_{ga} = 0.108$

Table 6   Thermal Resistance of Bores R_b for High-Density Polyethylene U-Tube Vertical Ground Heat Exchangers

U-Tube Diameter, in.	Bore Fill Conductivity,* Btu/h·ft·°F					
	4 in. Diameter Bore			6 in. Diameter Bore		
	0.5	1.0	1.5	0.5	1.0	1.5
3/4	0.19	0.09	0.06	0.23	0.11	0.08
1	0.17	0.08	0.06	0.20	0.10	0.07
1 1/4	0.15	0.08	0.05	0.18	0.09	0.06

*Based on DR 11, HDPE tubing with turbulent flow

Corrections for Other Tubes and Flows

DR 9 Tubing	Re = 4000	Re = 1500
+0.02 Btu/h·ft·°F	+0.008 Btu/h·ft·°F	+0.025 Btu/h·ft·°F

Sources: Kavanaugh (2001) and Remund and Paul (2000).

Figure 9: Thermal Resistance of Bores R_b.

| | F_{sc} | |
Bores per Loop	2 gpm/ton	3 gpm/ton
1	1.06	1.04
2	1.03	1.02
3	1.02	1.01

Figure 10: Short Circuit heat loss factor

Limestone

Silt Loam
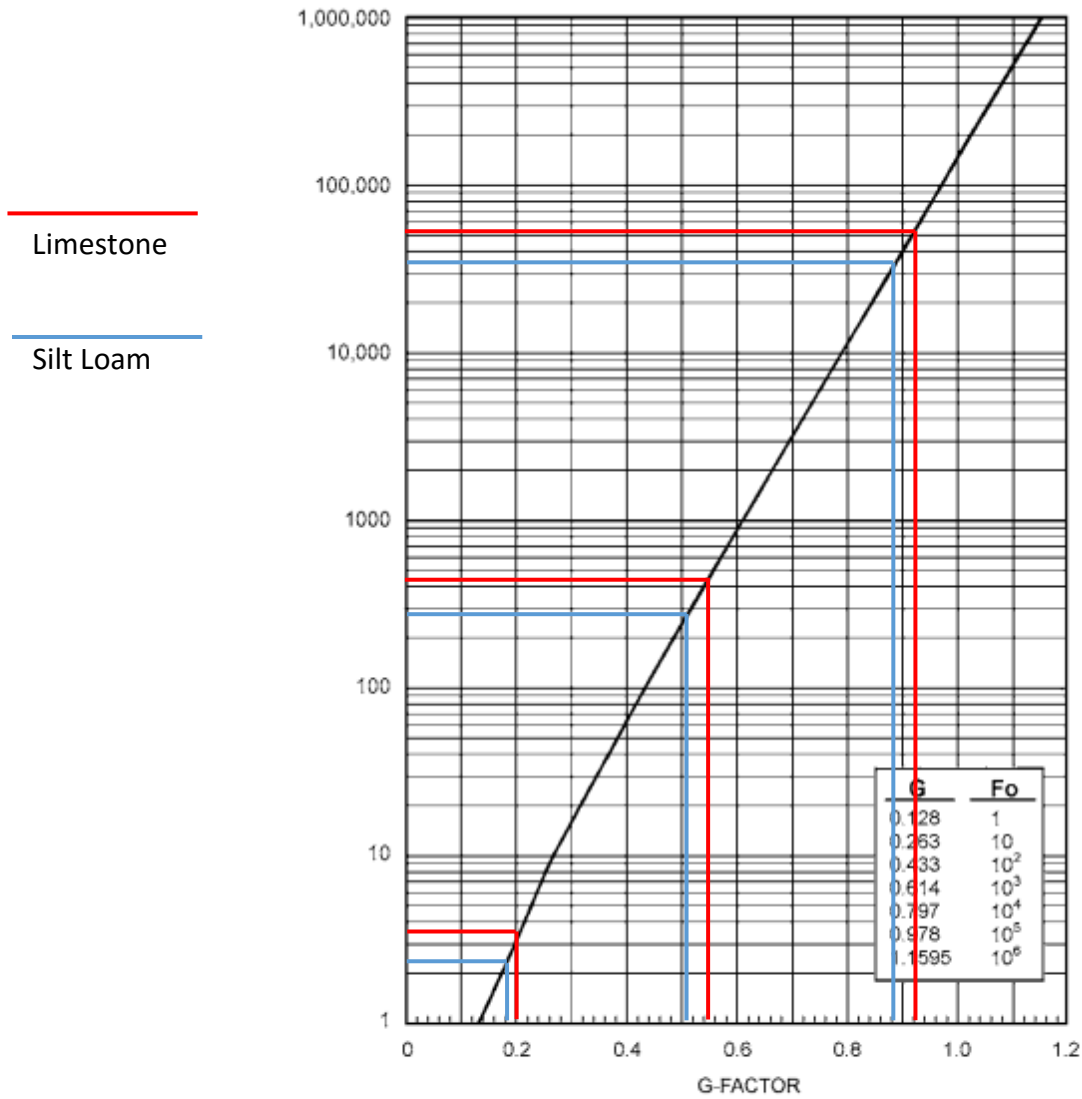
Fig. 15 Fourier/G-Factor Graph for
Ground Thermal Resistance
(Kavanaugh and Rafferty 1997)

Figure 11: Fourier/G-Factor Graph for Ground Thermal Resistance

Figure 12 is referenced to determine the local deep-ground temperature, t_g. The Penn State Lehigh Valley building is located in outside Philadelphia area of Pennsylvania. The local deep-ground temperature is found to be 52°F. This information is also used to determine the liquid temperature at heat pump inlet and outlet, t_{wi} and t_{wo} respectively.

For calculating the borehole length, selecting the temperatures water entering the heat pump is important in the design process. Since actual data is not determined in the energy model calculation, it is assumed the temperature water is 20°F to 30°F higher than t_g in cooling and 10°F to 20°F lower than t_g in heating. This range is a suggested from 2007 ASHRAE Handbook for vertical borehole length calculation for compromising between first cost and efficiency throughout the United States deep-ground temperatures.

Approx. Ground Temperature - 52 °F for Penn State Lehigh Valley Building
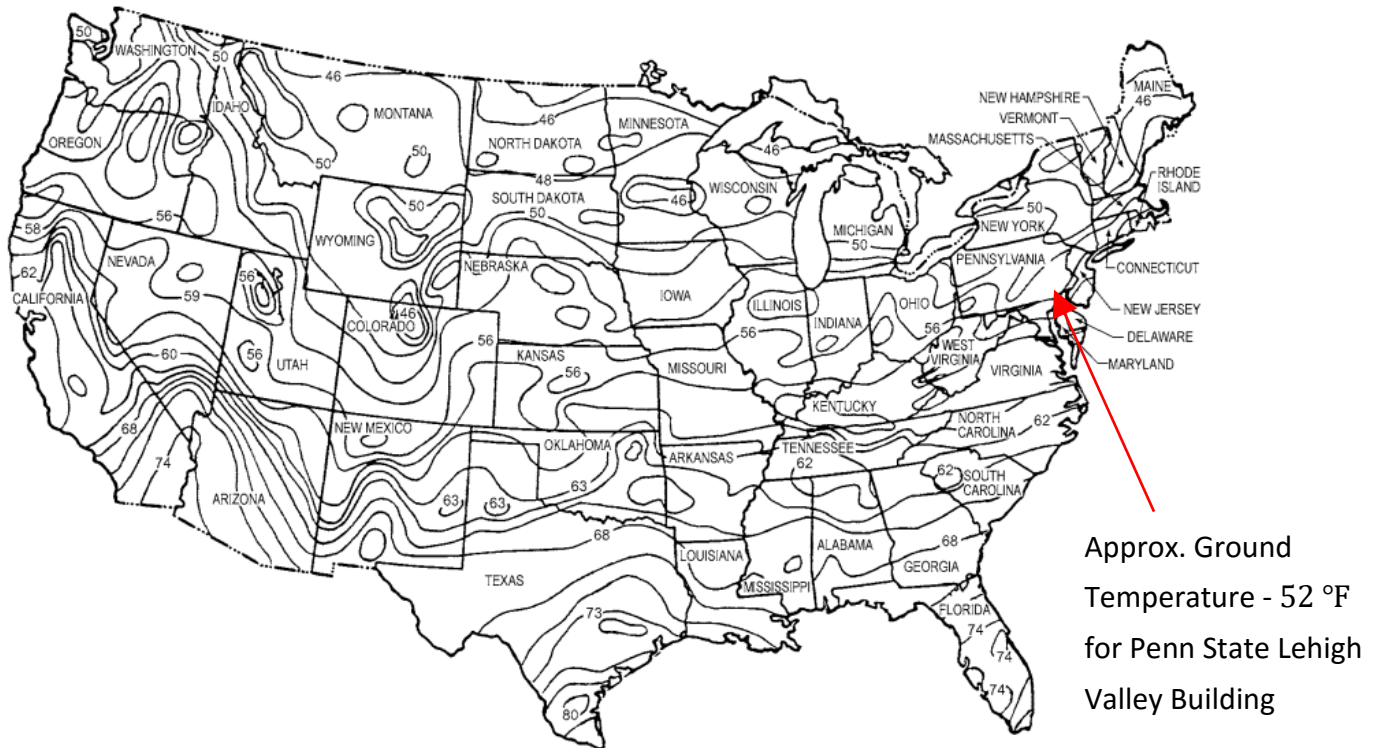
Fig. 17   Approximate Groundwater Temperatures (°F) in the Continental United States

Figure 12: Approximate Ground Water Temperatures (°F)

The borehole length calculation for cooling and heating loads, with a 15% safety factor determined to be;

Table 12: Borehole Length Results

Borehole Length Calculation	Limestone Soil	Silt Loam Soil
Cooling Length [ft]	29300.41	27096.33
Heating Length [ft]	**47211.29**	54370.19

When L_h is larger, the design length for heating should be selected. Therefore during cooling mode, the efficiency benefits of an oversized ground coil should be used to compensate for the higher first cost. For this building's demand load, which is heating dominate the L_h length should be selected.

The borehole length calculation was considered for both soil types to consider the thermal resistance difference. The calculation resulted that the difference for heating length is significant in size, which makes up the cost of the pump power and pipe length to reach the building. The geothermal well will be sized for 63,667.4 Ft for the Penn State Lehigh Valley building. For this required amount of length, it was found that 159 wells are needed for 400 ft. of well depth.

Mechanical Depth Part 2 – System Design Loads

Proposed System Level - Mechanical Depth

The proposed geothermal system's coil loads are summarized in table 13. These loads were calculated using IES VE, Energy modelling program using the original engineer's CFM design. The program calculated CFM rates similar to the engineer's specification but for consistency, the engineer's specifications OA minimum requirement was used. The DOAS unit utilizes 100% outdoor air rate, therefore the outdoor air CFM designed by the engineer was used.

Table 13: Proposed System Loads

Proposed	DOAS 1		DOAS 2		DOAS 3	
System	CFM	**10725**	CFM	**4125**	CFM	**14415**
Load	CC	HC	CC	HC	CC	HC
kBTU/Hr	676.1	591.5	246.8	243.9	913.3	826.1
Tons	56.342	49.292	20.567	20.325	76.108	68.842

Note: Additional breakdown of the system annual loads can be found in appendix A: Mechanical Depth.

When the alternative system was modelled on VE, the same CFM and coil sizes are the same. This is expected because both systems utilizes DOAS units and conditioning the same building load. The only difference would be the energy consumption from different equipment. The comparison of the system's efficiency will be covered in the next section, where a conclusive decision will be gathered on the proposed system.

Proposed Zone Level – Mechanical Depth

In addition to the system's centralized loads, individual zones are supplemented with Variable air boxes with air-cooled condenser heat pump to accommodate additional zone's demand. The tables below are the sum total loads from the rooms served per DOAS unit. It is important to note these loads are not the rated coil size because they are sum total of all of the rooms.

Table 14: DOAS-1; Room Coil Size

Pkg System: Heat Pump Cooling/Heating	DOAS-1 Room CC Sum CC Capacity:	DOAS-1 Room HC Sum HC Capacity:
Total kBTU/hr	**468.353**	**359.012**

Table 15: DOAS-2; Room Coil Size

Pkg System: Heat Pump Cooling/Heating	DOAS-2 Room CC Sum CC Capacity:	DOAS-2 Room HC Sum HC Capacity:
Total kBTU/hr	**590.871**	**325.783**

Table 16: DOAS-3; Room Coil Size

Pkg System: Heat Pump Cooling/Heating	DOAS-3 Room CC Sum CC Capacity	DOAS-3 Room HC Sum HC Capacity:
Total kBTU/hr	**627.025**	**489.156**

Note: Additional breakdown of the zone peak design loads can be found in appendix A: Mechanical Depth.

This mechanical proposal will include a DOAS Unit with geothermal system, but two different zone level distribution system. Simply, an air-side or water-side unit will be compared.

- Air-Cooled Condenser Heat Pump (split system)
- Electric Water Chiller/ Boiler (4-Pipe VAV Units)

Mechanical Depth Part 3 - System Comparisons Introduction

This mechanical proposal will be compared to three different designs. The three alternative designs include a new central system and distribution system.

- Mechanical Proposal – DOAS with Geothermal + Air-Cooled Condenser Heat pumps
  - 2nd Alternative – DOAS Unit with Geothermal + VAV [EWC + Boiler]
  - Baseline – Packaged Roof Top units with VAV Electric Reheat
  - Traditional System– DOAS Unit with Chiller/Boiler Loop + VAV [Electric Reheat]

The baseline system, which is the existing mechanical design for the Penn State Lehigh Valley building. The baseline system consist of three packaged rooftop units and VAV electric reheat boxes. The mechanical proposed design will also be evaluated in comparison to a DOAS unit with a water loop supported by a chiller and boiler. This traditional system was evaluated because of the popularity of the system in many commercial buildings. Despite that the traditional system requires a significant mechanical space for the chiller and boiler equipment, this comparison focuses on the energy savings.

The second alternative system is the same mechanical design, with the alternative distribution system, a four pipe VAV box conditioning supplemental loads in the rooms. This design is important to consider for the energy consumption difference for air cooled condenser heat pumps versus an Electric Water Chiller/Natural Condenser Boiler (Natural Gas Fueled). The choice to consider this second alternative design is due to the significant annual load to satisfy in the rooms.

 For this thesis evaluation. The mechanical proposed system with heat pumps and second alternative system will be compared significantly because of its functionality with a geothermal system. The distributed system to support the room loads will be difference for a conclusive decision on which system is optimal.

Heating Comparison

The heating demand is expected to be larger than the cooling demand for most building types. As for a university type building, this would be the same case. The heating comparison is based on the four system's heating demand and the energy consumed to satisfy the building's load. Among the three alternative systems, these include the ground source heat pump, electric reheat, and boiler. The baseline performance will not be explained in detail as it is included as a reference for the difference.

Heating Load

The heating load is satisfied by the ground source heat pumps for the geothermal systems and boilers. For the geothermal system, the boiler load is the load for the heating coil in the DOAS Units. For the alternative system of the geothermal and boiler, the boiler load is satisfy the heating coil of the DOAS units and VAV boxes.
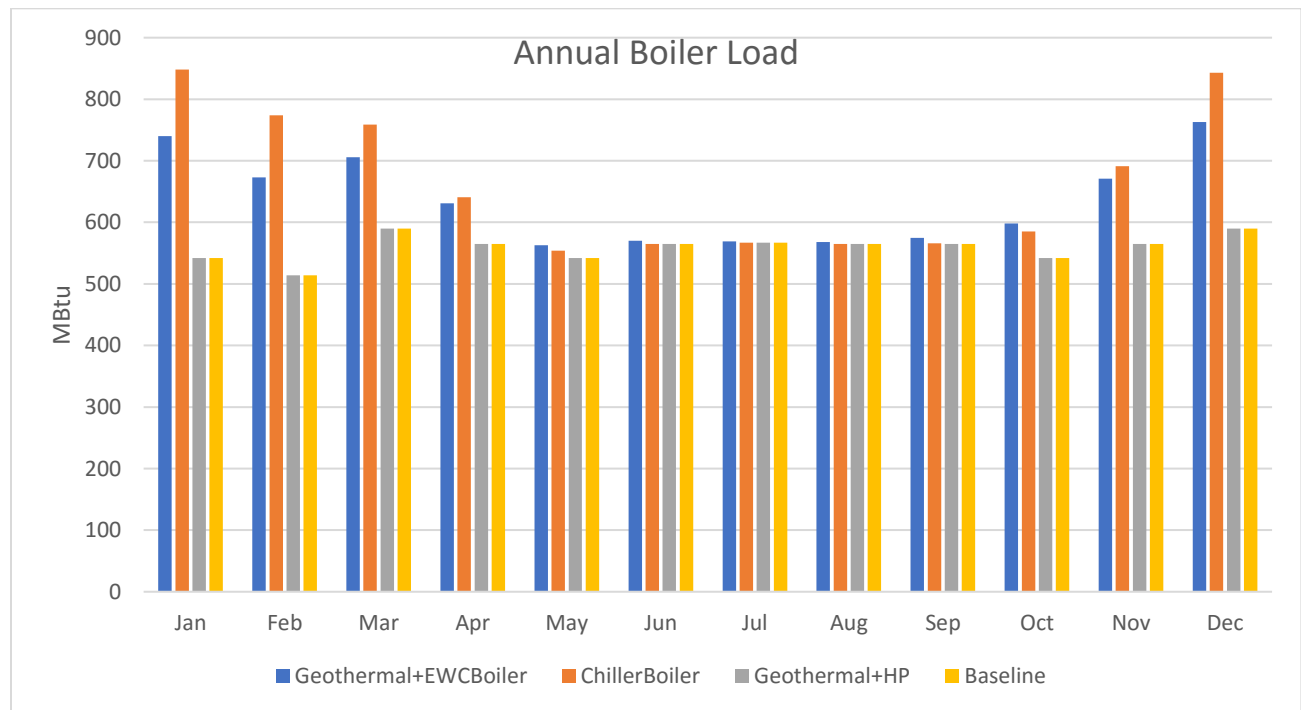
Figure 13: Boiler Load

Heating Energy

The heating comparison evaluated for heating energy is by the system boiler load. Although it is labeled boiler, for a geothermal analysis this would fall under the same category. The boiler system analyzed in IES VE for the geothermal system is the heating energy consumption from the ground source heat pump. Essentially the boiler energy is the heating energy consumed by the system.
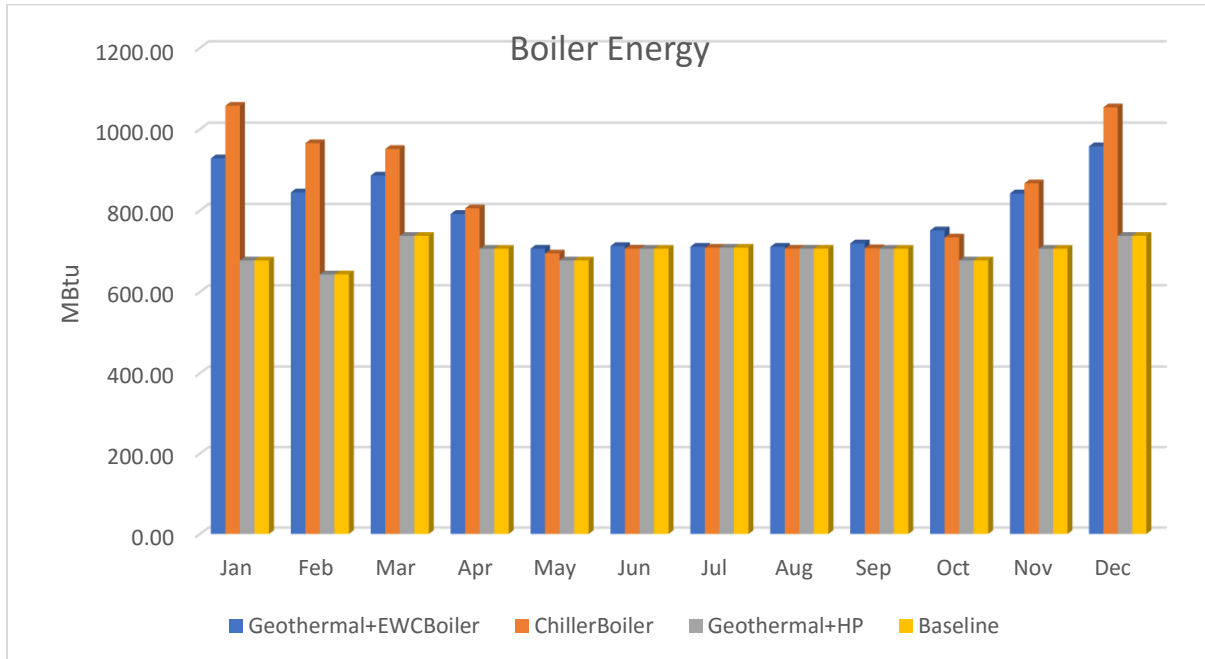
Figure 14: Annual Boiler Energy

Figure 14 compares the four systems based on system boiler energy. The system that stands out in energy consumption would be the system primarily dependent to a chiller/boiler for cooling and heating, alternative system #2. The second largest boiler demand is alternative system #3, which utilizes a chiller/boiler for zone loads.

Table 17 is the energy boiler savings among the three alternative systems. The proposed geothermal system saves 1,568.5 MBtu to the primary chiller-boiler system, alternative system #2. Compared to the geothermal system with chiller/boiler supplement, alternative system #3 the proposed geothermal system saves 1,173.3 MBtu.

Table 17: Heating Season Boiler Energy

Date	Geothermal+EWCBoiler	Chiller-Boiler	Geothermal+HP
Jan	928.42	1057.75	677.26
Feb	844.71	965.68	642.85
Mar	886.01	951.31	737.59
Apr	791.54	805.41	706.01
Oct	751.01	733.68	677.26
Nov	842.15	866.80	706.01
Dec	958.13	1053.69	737.59
Summed total	9561.946	9957.2	8388.666
Difference (Mbtu)	1173.28	1568.534	-

Fossil Fuel will be consumed when operating the Boiler for the two alternative systems. The proposed geothermal system with heat pump does not utilize fossil fuel, but primarily electric for heating and cooling.
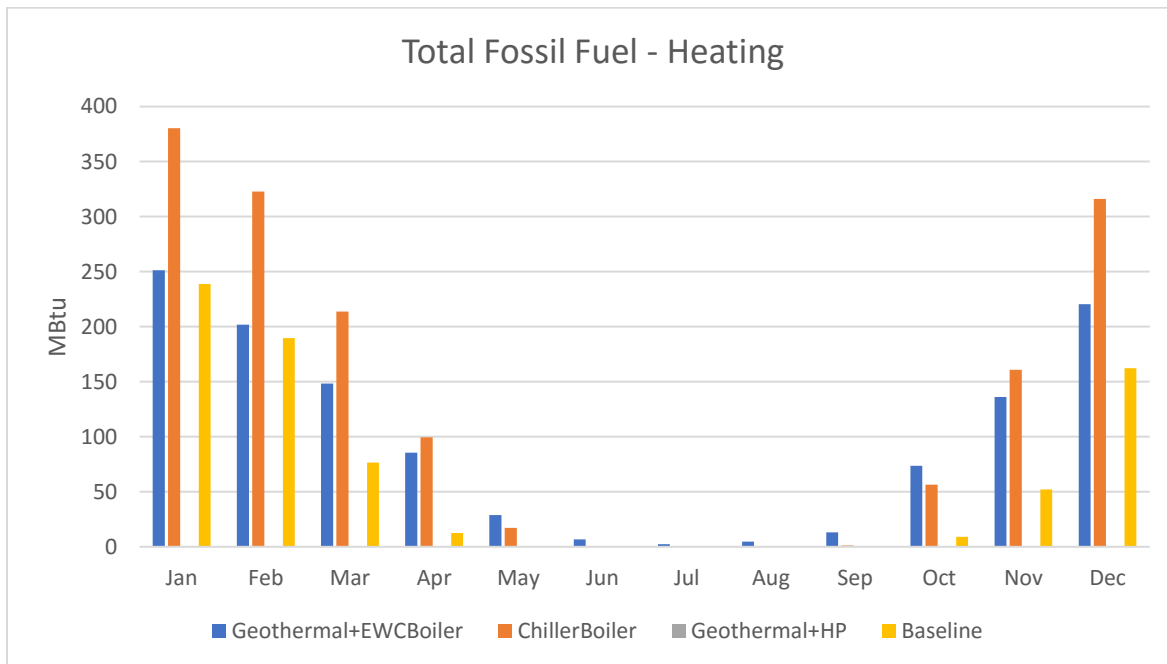
Figure 15: Annual System Fossil Fuel Consumption - Heating
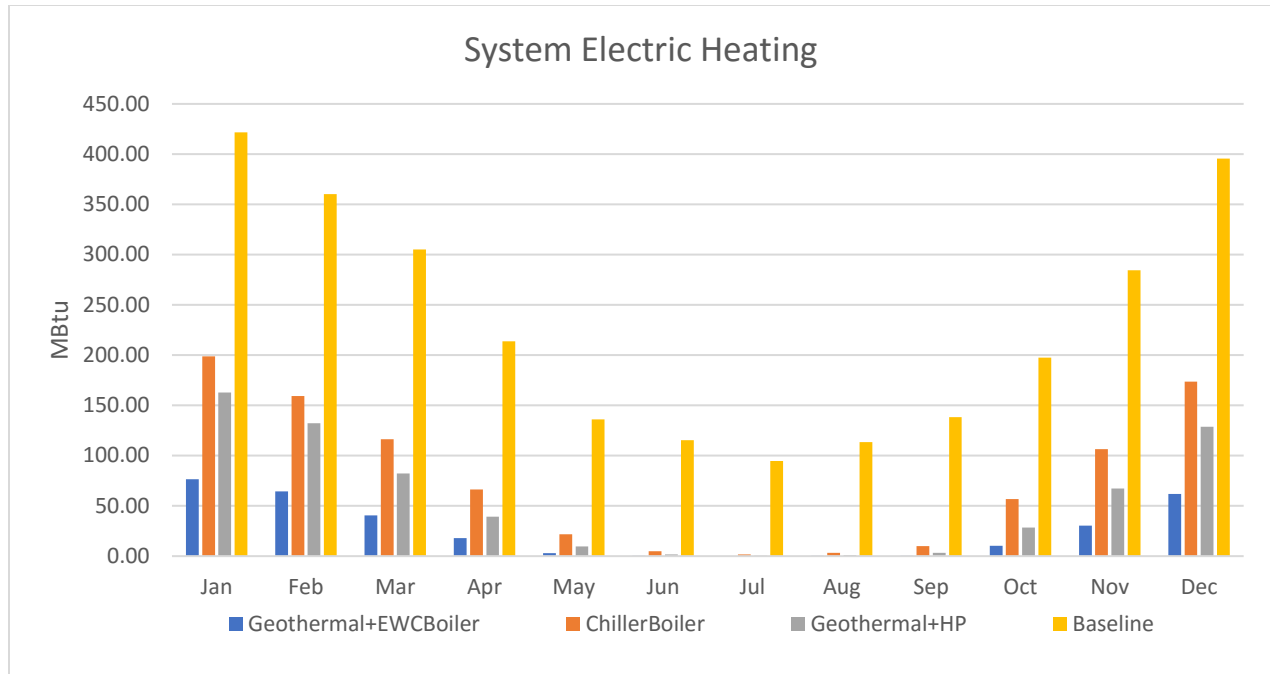
Figure 16: Annual System Electric Consumption - Heating

As opposed to fossil fuel consumption, the proposed geothermal system with heat pumps utilizes more electric than the other geothermal system with chiller/boiler. Both alternative systems require electric to operate the GSHP for heating, with the addition of the heat pump for the other.

In conclusion to the heating demand among the alternative systems; the proposed geothermal system with air-cooled condenser heat pumps does not require fossil fuels to operate its heating system. While the other alternative systems, chiller/boiler and geothermal with chiller/boiler consumes both electric and fossil fuel for heating. The major components that require electric energy are the ground source heat pump and electric reheat. The major components that consume fossil fuel is the boiler. Overall, both geothermal system deemed to be more efficient in energy consumption than the traditional water-side systems for heating.

Cooling Comparison

The cooling comparison evaluates systems system components utilized to satisfy the cooling load of the building. Among the three alternative systems, these include the ground source heat pump, Air-cooled heat pump, and chiller. The baseline performance will not be explained in detail as it is included as a reference for the difference.

Cooling Load

The cooling load in figure 18 are energy produced by ground source heat pumps and chillers among the alternative systems. The ground source heat pump supports primarily the DOAS unit's cooling coil size, although for the alternative system supplemented with a chiller includes the load for the VAV boxes' coils.
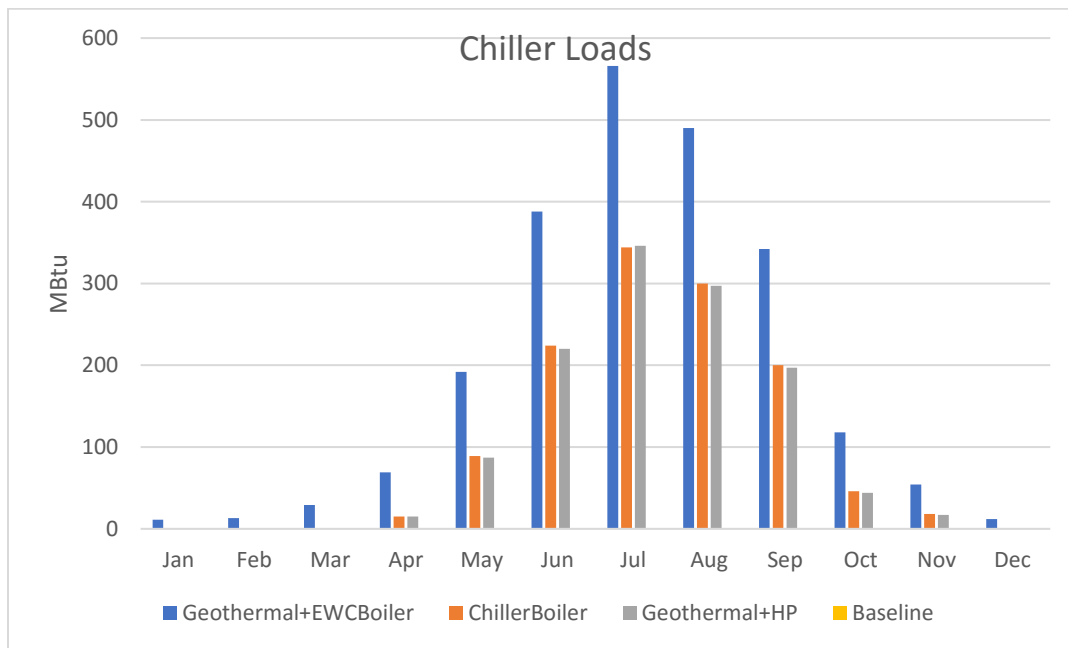
Figure 17: Annual Chiller Load

Cooling Energy
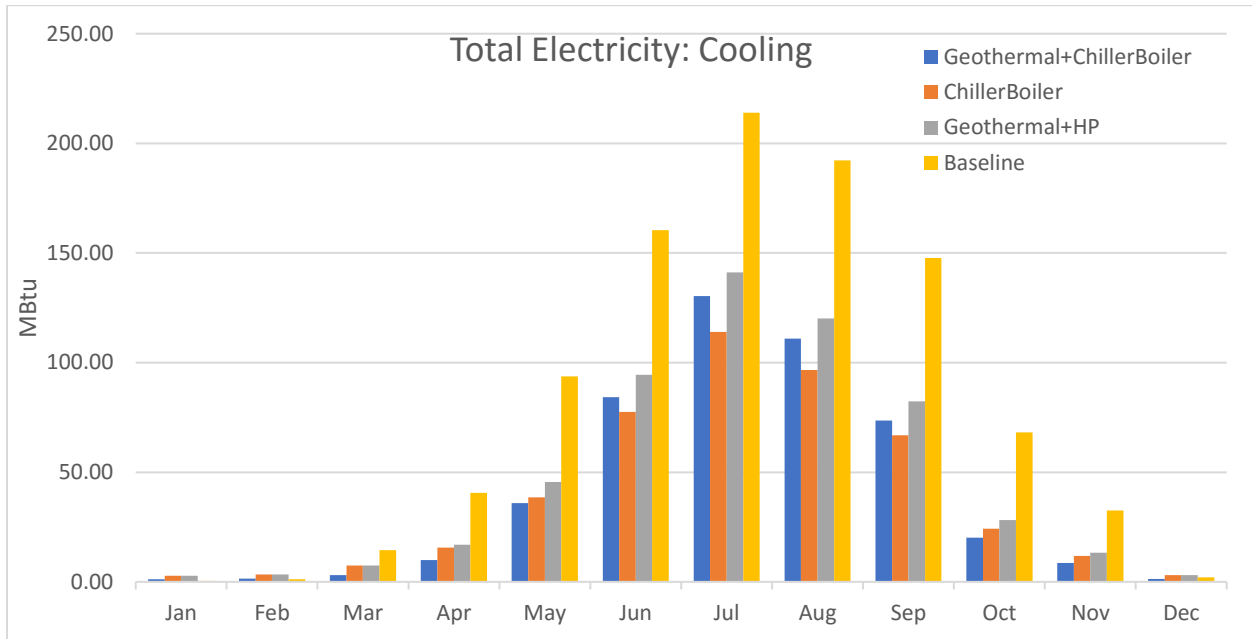
Figure 18: Annual System Electricity - Cooling
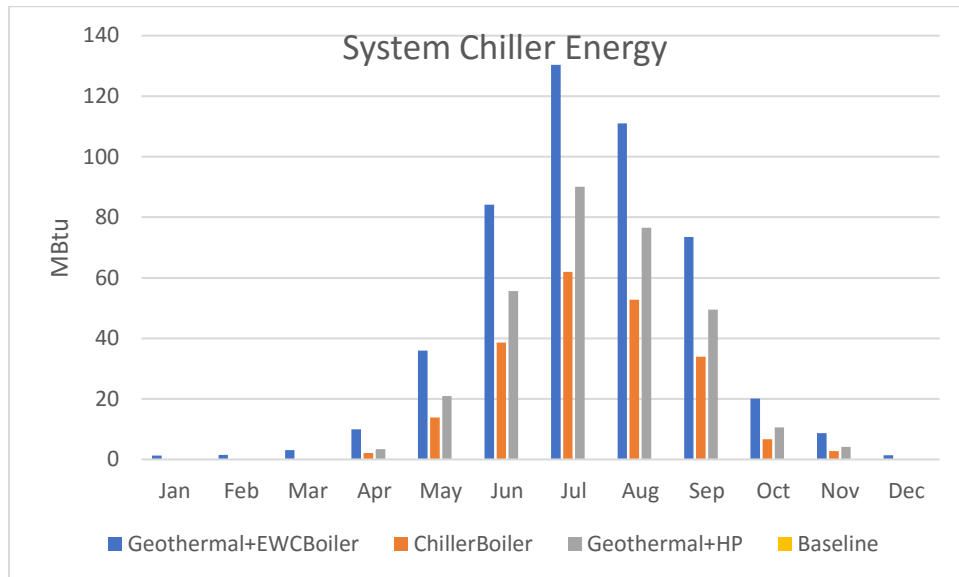
Figure 19: Annual System Chiller Energy

In the figure 19, the annual chiller energy shows a large energy consumed to satisfy the building's cooling load for the geothermal system with chiller/boiler. This is expected due to the electrical energy to operate the ground source heat pump and chiller. While the geothermal system with heat pump is requiring electricity for the ground source heat pump.

An important component that to consider among the three alternative systems for cooling, is the cooling load among the distributed zones. The system with geothermal and chiller with the largest demand in electricity for cooling from figure 20, does not require a distributed system equipment to operate. While since the chiller is already supporting the DOAS coils and VAV boxes.
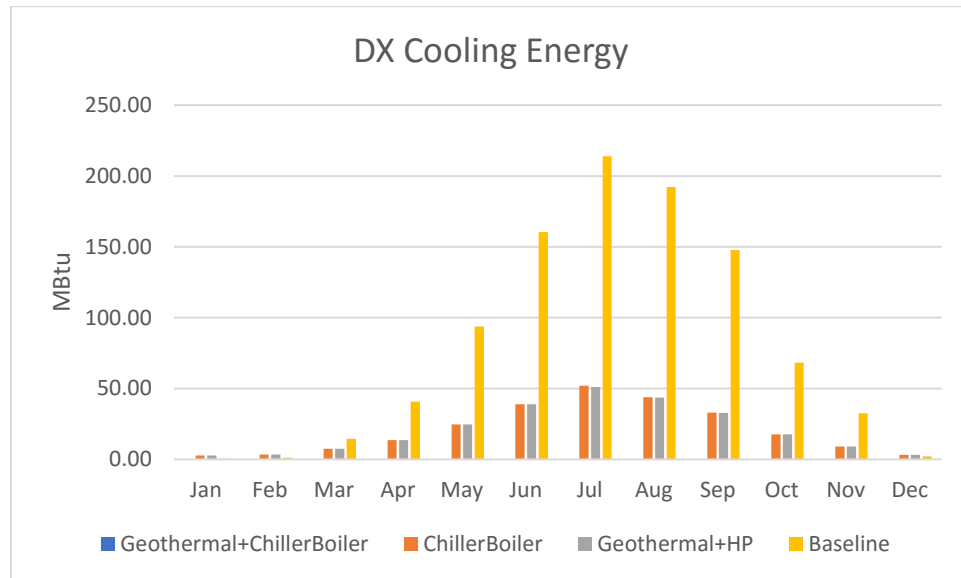
Figure 20: Annual DX-Cooling Energy

In conclusion of the cooling demand for this building, electricity is the primary source of energy to operate the system's cooling load. Therefore, it is optimal for the best system to utilize the least amount of electricity. Based on the energy consumption between the chiller/GSHP and DX-Cooling Heat pump, the geothermal system with chiller has less equipment to operate for cooling.

Energy Efficiency

When selecting a more advance system, it is expected to achieve an energy savings from the existing system. The total energy consumed by the alternative systems is summarized in table 18. The percent in savings from the existing system is shown, where the proposed geothermal system with heat pump saves 25%. The alternative geothermal system with chiller/boiler saves 19%. Both geothermal systems vastly improving the traditional chiller-boiler system.

Table 18: Total System Energy

	Total system energy (MBtu)	Total system energy (MBtu)	Total system energy (MBtu)	Total system energy (MBtu)
	Geothermal+ChillerBoiler	Chiller-Boiler	Geothermal+HP	Baseline
Summed total	10709.88	11670.73	9883.87	13202.87
% vs Baseline	0.19	0.12	0.25	-
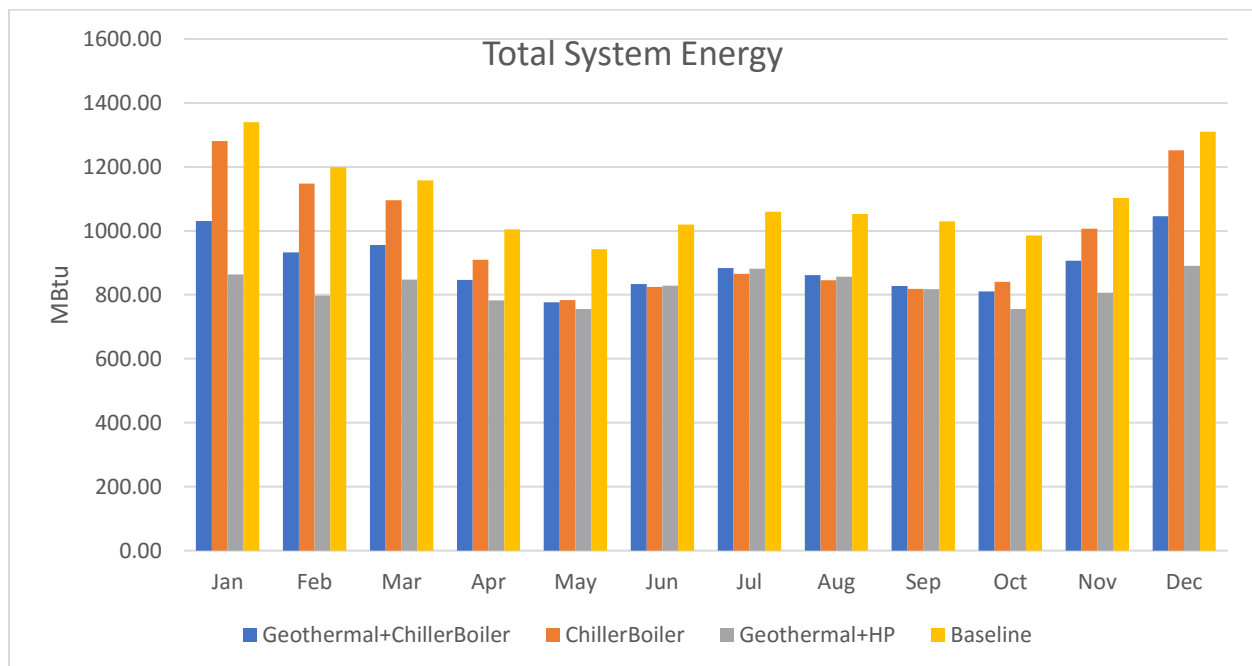
Figure 21: Annual System Energy Consumption

The resulting system energy data among the four systems, the geothermal system with heat pump is the best system to perform in energy usage.

Cost

From the system energy analysis, it was found that the proposed geothermal system with heat pumps saves the most energy versus the existing system by 25%. Comparing the operating cost to satisfy the energy consumption among the different systems. The two best prices are between the proposed geothermal system with heat pumps and the alternative geothermal system. The proposed geothermal system is found to have the best operating cost, including a higher energy savings than the alternative geothermal system.

Table 19: System Operating Cost

Annual Heating/Cooling	Fossil Fuel (Mbtu)		Electric (Mbtu)		Cost		Total
	Heating	Cooling	Heating	Cooling	Heating	Cooling	
Baseline	-	-	3411.93	967.48	$ 90,994.2	$ 25,802.1	$ 107,761.22
Mech. Proposed Geothermal	-	-	657.49	558.86	$ 17,534.9	$ 14,904.4	**$ 32,439.27**
Traditional Chiller-Boiler	1568.54	-	918.47	462.17	$ 41,198.7	$ 12,325.9	$ 53,524.56
Alt. Geothermal+EWC/Boiler	1173.29	-	305.34	480.87	$ 20,637.7	$ 12,824.5	**$ 33,462.21**

For the system comparison, energy rates and cost of operation was only evaluated. It is found that either geothermal systems with a heat pump, or chiller/boiler distribution system to have significant savings in energy and operating cost. Although the proposed geothermal system with heat pump distribution system have a slight performance lead, a significant factor outside of energy savings is the construction and installation cost.

While the proposed geothermal system with heat pump distribution system does not require a large footprint for mechanical space, a geothermal system with chiller/boiler would. New construction of a mechanical space would set back the payback period for the new system.

Referencing 2017 RS Means Mechanical; the equipment and installation cost of the proposed system was estimated to be $3,394,699.7. This includes the DOAS, HP, and geothermal boreholes. Table 20, shows the calculated payback for this system is in 10 years. This timeline is desirable because of the life span of a geothermal well and the expected life span of an educational use building is 25-50 years.

Table 20: Vertical Well Payback Cost

Vertical Well – Payback Calc	Proposed System	Original
Operating Cost	$ 32,439.27	$ 107,761.22
Yearly Savings	$ 75,321.95	-
Equipment & Installation	$ 3,353,074.40	$ 2,642,025.00
Total (Years)	9.4	

Table 21: Horizontal Well Simple Payback Cost

Horizontal Well -Payback Calc	Proposed System	Original
Operating Cost	$ 32,439.27	$ 107,761.22
Yearly Savings	$ 75,321.95	-
Equipment & Installation	$ 2,277,274.40	$ 2,642,025.00
Total (Years)	-4.8	

Breadth: Construction Schedule

For the construction breadth, the construction of the geothermal system and mechanical system will involve construction around existing landscape and the optimal soil type. A majority of the project timeline will involve the construction of the geothermal system because of the deep excavation and installation of the bore holes. From the research in the mechanical depth, the surrounding soils include limestone and silt loam. The conclusion of the calculation deemed the limestone soil is optimal for the thermal resistivity of the geothermal well.

Geothermal Layout

The geothermal bore holes will be the largest component of the construction process. In figure 22, the drawings provided by the Office of Physical Plant shows the existing site layout. This soil analysis summarizes two different soil types surrounding the proposed building at the time.

The geothermal well can be designed in two methods, either by horizontal or vertical wells. It is more cost effective to use horizontal well, but due to the significant length of this geothermal loop a vertical well will be designed. The amount of square footage a horizontal

well would consume during its construction process would disrupt other utility lines as seen in the site plan and would interfere with the parking during the school year. For the sake of project timeline to be finished without disrupting the academic schedule, the vertical loop is deemed to be the best option because of its smaller foot print during construction. Although from the cost analysis, the horizontal payback period is far more attractive for an owner.
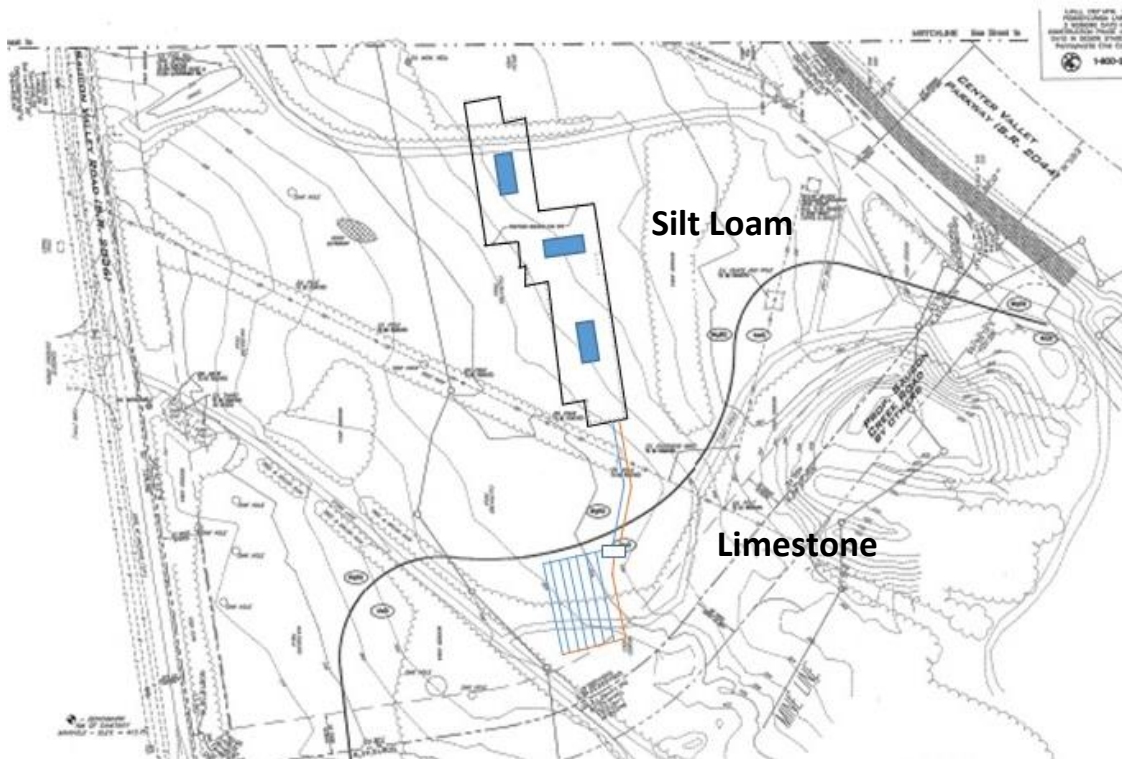
Figure 22: Existing Site Features (Civil Drawings provided by OPP; Penn State Lehigh Valley)

Figure 23 shows the constructed site, with the proposed geothermal borehole location. The location for the proposed geothermal well was found to be in the area of the faculty parking lot. This location is found to be optimal since it does not disrupt any traffic or utility lines. During the construction of the borehole drilling and trenches, the faculty parking will likely be unusable for the entirety of the construction process. Also, a portion of the student parking will be unusable for the utilization of the contractor's office and equipment space. The duration of the construction will involve heavily on the borehole excavation, installation, and refill. This can range from 6 months to almost a year, which will also be recommended to begin

as early of spring to prioritize a majority of the major construction involved during the summer break of the academic year.

For a horizontal well design, the area in yellow would be more suitable for the construction of the horizontal wells. That is because of the significant amount of length, it will likely reduce the capacity of student parking by half.
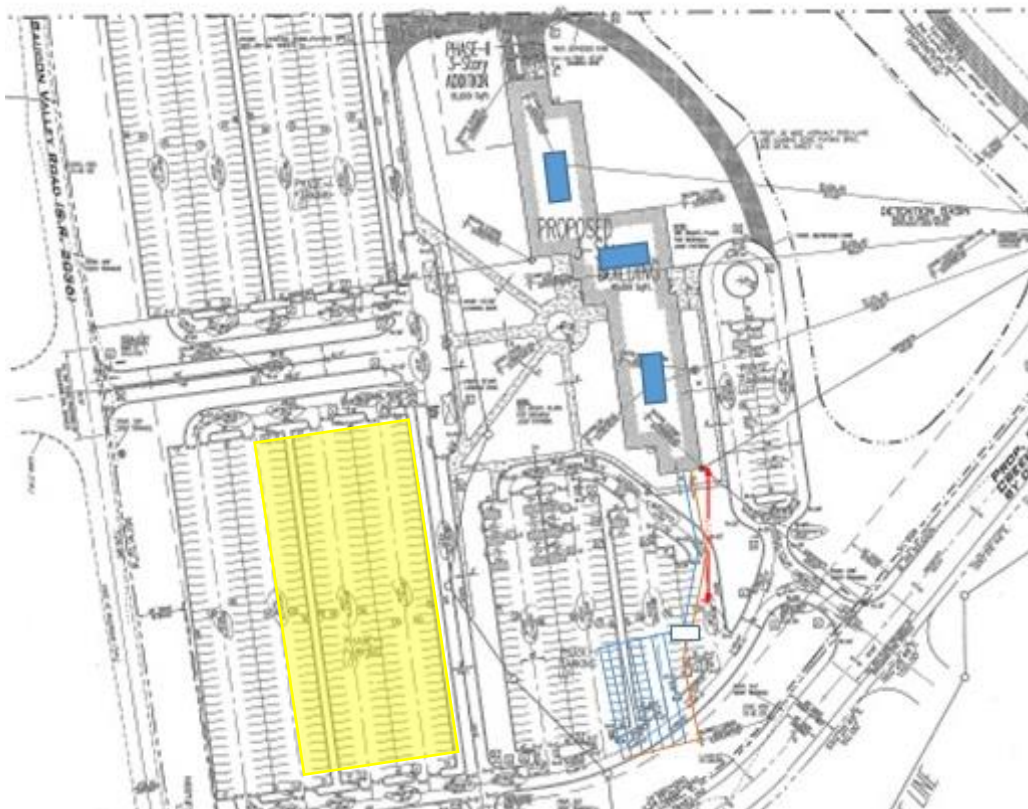
Figure 23: Site Plan (Civil Drawings provided by OPP; Penn State Lehigh Valley)

Breadth: Acoustical Analysis

An acoustical study will be evaluated using the program Pottorff Aim. This study is intended to find the sound increased by the heat pump serving between two rooms. A class room will be modelled and the proper acoustic equipment will be decided if the heat pump would be found to generate too much noise.

For the location of the heat pump installation, it would be best fit to be placed in the hallway space so the sound source would not be generated directly above the classroom. Using Pottorff Aim, it was found that the noise criteria rating of the classroom with a split system heat pump directly above the classroom is too high. While the classroom noise criteria rating is recommended to be NC-30, the classroom with an overhead split system heat pump was rated greater than NC-65.

Table 22: Classroom NC Calculation

	Properties	NC	63	125	250	500	1K	2K	4K	dB(A)
Classroom	**Criteria:NC-30**	29	55	47	30	20	23	16	15	34
Supply Path	**Criteria:NC-30**									
Split System - HP			83	79	86	81	68	62	54	
Rectangular Duct	24"x24"x10'		-2	-2	-1	0	0	0	0	
Duct Silencer -	24"x24"x120"		-18	-27	-48	-49	-54	-55	-39	
Generated Noise			59	53	35	34	37	32	27	
Flexible Duct	16"x3"		0	-1	0	-8	-8	-8	-4	
End Reflection Loss	27" (Flush)		-6	-3	-1	0	0	0	0	
Room Correction	12'x12'x10'		-3	-4	-5	-6	-7	-8	-9	
Sum		29	55	47	30	20	23	16	15	34

After calculating the noise criteria of a typical class room, a duct silencer will satisfy the noise generated by the heat pump. The heat pump would have to create a higher air flow for the pressure dropped caused by the duct silencer, although since the travel distance in the ductwork is not far, from the hallway into the supply diffusers of the room. This should not create many issues.
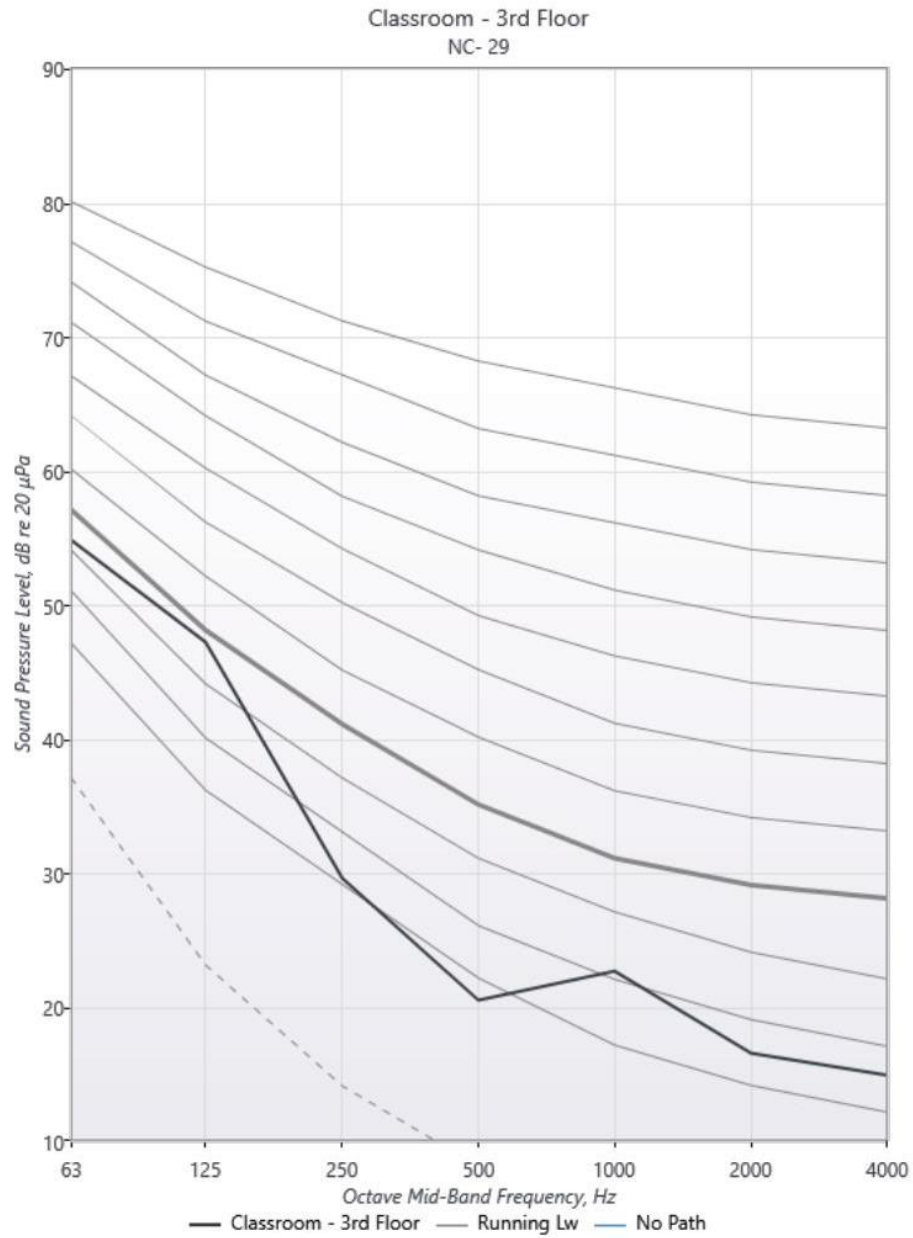
Figure 24: NC Rating Graph

Summary & Conclusion

In summary, this evaluation of the proposed mechanical system; a geothermal system to calculate an energy savings and reduce operating cost. The first constraint is the lack of dedicated mechanical space, and the rooms will need a system to supplement the ground source heat pump load. The two distribution system is proposed with a geothermal serving the central DOAS units:

- Air-Cooled Condenser Heat Pumps (Split System)
- Electric Water Chiller and Boiler (4-Pipe VAV Units)

The two systems is compared for heating and cooling loads, energy consumption and operation cost. It is also evaluated with the existing system and a traditional system for analytical purposes. It is found that the proposed system with a heat pump distribution system provides the best performance with a 25% savings from the existing system and $32,439.27 yearly operating cost.

When including the construction cost and payback period, it is found that the proposed geothermal system with a heat pump distribution system is within the optimal range for a payback period. A geothermal system life expectancy is rated for 50 years, while the payback for a vertical loop is 10 years and a horizontal loop with an immediate payback. This time period would be acceptable for many owners. The operating cost of the existing design and the proposed design was found to have a $75,321.95 yearly savings. The initial cost of the proposed system is significantly high for most mechanical systems for a building this size, but the energy savings is found to be attractive.

Other options that can be considered for a geothermal system is to design the geothermal system to either cool or heat. Which would reduce the size significantly for the borehole length. Ideally it would be reasonable to design a geothermal system for the cooling season since chillers operate on electricity and so does would a ground source heat pump, substituting a boiler would be less efficient since natural gas is found to be more cost effective than electricity.

Appendix A: Mechanical Depth

Annual System Loads

System Cooling Coil - Geothermal Supplied	Total load (MBtu)	Total load (MBtu)	Total load (MBtu)
Cooling Coil	CC000777	CC000779	CC000781
Date	p_3.18.17 [Proposed-DOASx3-GSHP1.0].aps	p_3.18.17 [Proposed-DOASx3-GSHP1.0].aps	p_3.18.17 [Proposed-DOASx3-GSHP1.0].aps
Jan 01-31	0	0	0
Feb 01-28	0	0	0
Mar 01-31	0.091	0.07	0.046
Apr 01-30	5.325	2.093	7.22
May 01-31	31.03	12.269	43.36
Jun 01-30	78.853	30.122	110.808
Jul 01-31	123.913	48.856	172.944
Aug 01-31	107.06	40.731	149.675
Sep 01-30	70.99	27.024	98.829
Oct 01-31	15.893	6.244	22.01
Nov 01-30	6.27	2.373	8.782
Dec 01-31	0	0	0
Summed total	439.425	169.782	613.673
Total Annual MBtu	1222.88		
Total Annual Tons	101906.67		
Total Annual kBTU/Hr	139.60		

System Heating Coil - Geothermal Supplied	Sensible load (MBtu)	Sensible load (MBtu)	Sensible load (MBtu)
Heating Coil	HC002820	HC002822	HC002824
Date	p_3.18.17 [Proposed-DOASx3-GSHP1.0].aps	p_3.18.17 [Proposed-DOASx3-GSHP1.0].aps	p_3.18.17 [Proposed-DOASx3-GSHP1.0].aps
Jan 01-31	109.231	45.041	152.924
Feb 01-28	92.52	38.15	129.528
Mar 01-31	60.249	24.843	84.349
Apr 01-30	27.274	11.246	38.183
May 01-31	4.479	1.847	6.271
Jun 01-30	0.098	0.04	0.137
Jul 01-31	0	0	0
Aug 01-31	0.006	0.003	0.009
Sep 01-30	0.318	0.131	0.445
Oct 01-31	15.453	6.372	21.634
Nov 01-30	45.109	18.6	63.152
Dec 01-31	90.328	37.246	126.46
Summed total	445.066	183.519	623.093
Total Annual MBtu	**1251.678**		
Total Annual Tons	104306.50		
Total Annual kBTU/Hr	**142.89**		

GSHP Absorbed/Rejected Energy

System CC - Geothermal Supplied HT	Total Q addition/removal (kBtu)	Total Q addition/removal (kBtu)	Total Q addition/removal (kBtu)
Cooling Coil	CC000779	CC000777	CC000781
Date	p_3.18.17 [Proposed-DOASx3-GSHP1.0].aps	p_3.18.17 [Proposed-DOASx3-GSHP1.0].aps	p_3.18.17 [Proposed-DOASx3-GSHP1.0].aps
Jan 01-31	0	0	0
Feb 01-28	0	0	0
Mar 01-31	67	84	20
Apr 01-30	2065	5237	7114
May 01-31	11890	30061	42016
Jun 01-30	28927	75758	106497
Jul 01-31	46529	118045	164787
Aug 01-31	38845	102202	142867
Sep 01-30	25885	68054	94730
Oct 01-31	6022	15321	21247
Nov 01-30	2315	6135	8607
Dec 01-31	0	0	0
Summed total	162545	420898	587884
Total Annual KBtu	**1171327**		
Total Annual Tons	97610.58		
Total Annual BTU/Hr	**133713**		

System HC - Geothermal Supplied HT	Total Q addition/removal (kBtu)	Total Q addition/removal (kBtu)	Total Q addition/removal (kBtu)
Heating coil	HC002822	HC002824	HC002820
Date	p_3.18.17 [Proposed-DOASx3-GSHP1.0].aps	p_3.18.17 [Proposed-DOASx3-GSHP1.0].aps	p_3.18.17 [Proposed-DOASx3-GSHP1.0].aps
Jan 01-31	43220	146744	104817
Feb 01-28	36600	124267	88762
Mar 01-31	23663	80341	57387
Apr 01-30	10631	36094	25781
May 01-31	1685	5722	4087
Jun 01-30	29	98	70
Jul 01-31	0	0	0
Aug 01-31	1	5	4
Sep 01-30	101	344	246
Oct 01-31	5903	20043	14316
Nov 01-30	17653	59935	42811
Dec 01-31	35714	121256	86612
Summed total	175201	594850	424893
Total Annual KBtu	**1194944**		
Total Annual Tons	99578.67		
Total Annual BTU/Hr	136409		

Room Peak Loads

Zone Name Served by: DOAS 1	Cooling Coil Load (kBtu/hr)	Heating Coil Load (kBtu/hr)	Zone Name Served by: DOAS 2	Cooling Coil Load (kBtu/hr)	Heating Coil Load (kBtu/hr)	Zone Name Served by: DOAS 3	Cooling Coil Load (kBtu/hr)	Heating Coil Load (kBtu/hr)
1st Floor - RTU1	16.919	21.011	1st Floor - RTU2	19.14	16.866	1st Floor - RTU3	38.472	31.464
1st Floor - RTU1	5.534	6.077	1st Floor - RTU2	16.877	11.215	1st Floor - RTU3	5.573	6.094
1st Floor - RTU1	5.755	6.845	1st Floor - RTU2	3.457	2.638	1st Floor - RTU3	8.025	6.902
1st Floor - RTU1	5.615	6.679	1st Floor - RTU2	13.28	7.94	1st Floor - RTU3	10.945	8.1
1st Floor - RTU1	36.033	27.793	1st Floor - RTU2	10.006	6.653	1st Floor - RTU3	30.885	37.993
1st Floor - RTU1	10.39	9.661	1st Floor - RTU2	12.647	8.557	1st Floor - RTU3	10.249	9.828
1st Floor - RTU1	41.576	38.543	1st Floor - RTU2	3.577	3.197	1st Floor - RTU3	64.09	60.98
2nd Floor - RTU1	60.078	29.195	1st Floor - RTU2	9.837	9.358	2nd Floor - RTU3	69.104	33.565
2nd Floor - RTU1	23.749	23.449	1st Floor - RTU2	11.539	9.089	2nd Floor - RTU3	15.409	7.589
2nd Floor - RTU1	11.355	7.056	1st Floor - RTU2	8.037	5.883	2nd Floor - RTU3	8.419	5.895
2nd Floor - RTU1	7.785	7.519	1st Floor - RTU2	51.839	37.765	2nd Floor - RTU3	14.614	8.038
2nd Floor - RTU1	13.147	7.97	2nd Floor - RTU2	24.804	9.565	2nd Floor - RTU3	43.678	43.171
2nd Floor - RTU1	10.489	7.547	2nd Floor - RTU2	17.612	7.442	2nd Floor - RTU3	10.27	7.611
2nd Floor - RTU1	41.698	31.077	2nd Floor - RTU2	15.002	6.166	2nd Floor - RTU3	64.793	49.064
3rd Floor - RTU1	60.223	31.478	2nd Floor - RTU2	11.532	5.148	3rd Floor - RTU3	67.886	36.245
3rd Floor - RTU1	24.468	25.206	2nd Floor - RTU2	14.783	5.77	3rd Floor - RTU3	15.59	8.278
3rd Floor - RTU1	11.623	7.713	2nd Floor - RTU2	20.953	15.183	3rd Floor - RTU3	8.321	6.48
3rd Floor - RTU1	8.149	8.17	2nd Floor - RTU2	31.194	12.331	3rd Floor - RTU3	14.722	8.548
3rd Floor - RTU1	13.12	8.516	2nd Floor - RTU2	3.615	2.272	3rd Floor - RTU3	44.667	46.558
3rd Floor - RTU1	10.746	9.015	2nd Floor - RTU2	7.979	3.921	3rd Floor - RTU3	10.499	9.073
3rd Floor - RTU1	43.953	36.502	2nd Floor - RTU2	7.995	4.088	3rd Floor - RTU3	67.909	57.66
			2nd Floor - RTU2	45.811	23.176			
Total	462.405	357.022	3rd Floor - RTU2	24.615	10.263	Total	624.12	489.136
			3rd Floor - RTU2	17.669	8.224			
			3rd Floor - RTU2	14.85	6.637			
			3rd Floor - RTU2	11.753	5.704			
			3rd Floor - RTU2	14.791	6.475			
			3rd Floor - RTU2	21.124	16.718			
			3rd Floor - RTU2	34.199	14.507			

3rd Floor - RTU2	3.789	2.642
3rd Floor - RTU2	8.594	5.25
3rd Floor - RTU2	8.646	5.358
3rd Floor - RTU2	49.737	29.911
Total	571.283	325.912

Appendix B: Borehole Length Calculation

Cooling	Limestone	Silt Loam	Difference	Heating	Limestone	Silt Loam	Difference
Fsc	1.04	1.04		Fsc	1.04	1.04	
PLFm	1	1		PLFm	1	1	
Qa [Btu/Hr]	-133713.1	-133713.1		Qa [Btu/Hr]	136409	136409.1	
Rga	0.201	0.225		Rga	0.201	0.225	
Rgd	0.120	0.108		Rgd	0.120	0.108	
Rgm	0.225	0.201		Rgm	0.225	0.201	
Rb	0.09	0.09		Rb	0.09	0.09	
tg	52	52		tg	52	52	
tp	-1.8	-1.8		tp	1.8	1.8	
ELT	78	78		ELT	38	38	
LLT	85	85		LLT	33	33	
qlc [Btu/Hr]	-1532563	-1532563		qlc [Btu/Hr]	1663419	1663419	
Wc [W]	4340	4340		Wc [W]	4340	4340	
Lc [ft^2]	**25478.62**	**23562.02**	-1916.60	Lc [ft^2]	**41053.2971**	**47278.43**	6225.13
safety 15%	29300.41	27096.33			47211.29	54370.19	

Limestone Thermal Resistance Calc							
alpha	0.9	Fourier #1	**435.6**	G1 =	**0.575**	Rga =	**0.201**
T_1	30.25	Fourier #2	**3.6**	G2 =	**0.2**	Rgm=	**0.225**
T_2	0.25	Fourier #f	**52995.6**	Gf=	**0.91**	Rgd=	**0.120**
T_f	3680.25						
d_b^2	0.25						

Silt Loam Thermal Resistance Calc							
alpha	0.6	Fourier #1	**290.4**	G1 =	**0.515**	Rga =	**0.225**
T_1	30.25	Fourier #2	**2.4**	G2 =	**0.18**	Rgm=	**0.201**
T_2	0.25	Fourier #f	**35330.4**	G3=	**0.89**	Rgd=	**0.108**
T_f	3680.25						
d_b^2	0.25						

Appendix C: Annual Energy Consumption Summary

Total System Energy	Total system energy (MBtu)	Total system energy (MBtu)	Total system energy (MBtu)	Total system energy (MBtu)
	p_3.27.17 Proposed2.0.aps	p_3.19.17 Alternative Proposed.aps	p_3.18.17 [Proposed-DOASx3-GSHP1.0].aps	p_3.16.17 Baseline.aps
Date	Geothermal+ChillerBoiler	ChillerBoiler	Geothermal+HP	Baseline
Jan	1030.38	1280.64	863.841	1339.67
Feb	932.74	1147.46	797.172	1199.06
Mar	955.56	1095.86	848.004	1157.32
Apr	846.48	909.42	782.836	1004.22
May	776.46	783.46	755.547	942.43
Jun	833.61	824.98	828.633	1019.70
Jul	883.43	865.75	881.603	1059.81
Aug	861.46	845.86	856.314	1052.59
Sep	827.67	818.72	817.083	1029.44
Oct	810.15	840.29	755.801	986.09
Nov	906.42	1006.67	806.934	1102.37
Dec	1045.53	1251.64	890.097	1310.17
Summed total	10709.88	11670.73	9883.867	13202.87
% vs Baseline	0.19	0.12	0.25	

Total Electricity - Cooling	Total Electricity - Cooling (MBtu)	Total Electricity - Cooling (MBtu)	Total Electricity - Cooling (MBtu)	Total Electricity - Cooling (MBtu)
	p_3.27.17 Proposed2.0.aps	p_3.19.17 Alternative Proposed.aps	p_3.18.17 [Proposed-DOASx3-GSHP1.0].aps	p_3.16.17 Baseline.aps
Date	Geothermal+ChillerBoiler	ChillerBoiler	Geothermal+HP	Baseline
Jan	1.23	2.83	2.83	0.39
Feb	1.44	3.33	3.33	1.12
Mar	3.11	7.51	7.53	14.41
Apr	9.93	15.64	16.96	40.61
May	35.96	38.47	45.61	93.75
Jun	84.19	77.48	94.43	160.45
Jul	130.34	114.03	141.15	213.97
Aug	110.98	96.70	120.08	192.29
Sep	73.54	66.92	82.38	147.70
Oct	20.15	24.27	28.13	68.14
Nov	8.65	11.86	13.29	32.54
Dec	1.35	3.13	3.14	2.13
Summed total	480.87	462.17	558.86	967.48

System Electric - Heating	System Electricity - Heating (MBtu)	System Electricity - Heating (MBtu)	System Electricity - Heating (MBtu)	System Electricity - Heating (MBtu)
	p_3.27.17 Proposed2.0.aps	p_3.19.17 Alternative Proposed.aps	3.28.17 [Proposed-DOASx3-GSHP1.0].aps	p_3.16.17 Baseline.aps
Date	Geothermal+EWCBoiler	ChillerBoiler	Geothermal+HP	Baseline
Jan	76.60	198.82	162.963	421.814
Feb	64.41	159.31	132.271	360.344
Mar	40.67	116.16	82.337	305.123
Apr	18.00	66.20	39.246	213.805
May	2.93	21.72	9.689	136.105
Jun	0.06	4.90	1.595	115.433
Jul	0.00	1.56	0.526	94.764
Aug	0.00	3.24	1.043	113.581
Sep	0.21	9.82	3.268	138.386
Oct	10.23	56.84	28.499	197.654
Nov	30.31	106.32	67.392	284.518
Dec	61.90	173.58	128.66	395.611
Summed total	305.34	918.47	657.49	2777.137

Total Fossil Fuel - Heating	Total Fossil fuel - Heating (MBtu)	Total Fossil fuel - Heating (MBtu)	Total Fossil fuel - Heating (MBtu)	
	p_3.27.17 Proposed2.0.aps	p_3.19.17 Alternative Proposed.aps	p_3.18.17 [Proposed-DOASx3-GSHP1.0].aps	Baseline
Date	Geothermal+EWCBoiler	ChillerBoiler	Geothermal+HP	Baseline
Jan	251.165	380.497	0	238.789
Feb	201.858	322.83	0	189.601
Mar	148.427	213.727	0	76.497
Apr	85.529	99.399	0	12.51
May	28.913	17.078	0	0.335
Jun	6.724	0.394	0	0
Jul	2.353	0	0	0
Aug	4.618	0.025	0	0
Sep	13.254	1.273	0	0
Oct	73.756	56.422	0	9.205
Nov	136.141	160.787	0	52.125
Dec	220.548	316.105	0	162.254
Summed total	1173.285	1568.538	0	741.313

Annual Boiler Load	ApHVAC boilers load (MBtu)	ApHVAC boilers load (MBtu)	ApHVAC boilers load (MBtu)	ApHVAC boilers load (MBtu)
Date	Geothermal+EWCBoiler	ChillerBoiler	Geothermal+HP	Baseline
Jan	740	848	542	542
Feb	673	774	514	514
Mar	706	759	590	590
Apr	631	641	565	565
May	563	554	542	542
Jun	570	565	565	565
Jul	569	567	567	567
Aug	568	565	565	565
Sep	575	566	565	565
Oct	598	585	542	542
Nov	671	691	565	565
Dec	763	843	590	590
Summed total	7625	7958	6711	6711

Annual Boiler Energy	ApHVAC boilers energy (MBtu)	ApHVAC boilers energy (MBtu)	ApHVAC boilers energy (MBtu)	ApHVAC boilers energy (MBtu)
Date	Geothermal+EWCBoiler	ChillerBoiler	Geothermal+HP	Baseline
Jan	928.42	1057.75	677.26	677.26
Feb	844.71	965.68	642.85	642.85
Mar	886.01	951.31	737.59	737.59
Apr	791.54	805.41	706.01	706.01
May	706.17	694.33	677.26	677.26
Jun	712.73	706.40	706.01	706.01
Jul	711.00	708.65	708.65	708.65
Aug	710.81	706.22	706.19	706.19
Sep	719.26	707.28	706.01	706.01
Oct	751.01	733.68	677.26	677.26
Nov	842.15	866.80	706.01	706.01
Dec	958.13	1053.69	737.59	737.59
Summed total	**9561.95**	**9957.20**	**8388.67**	8388.67
Difference (Mbtu)	1173.28	1568.53	-	

Annual Chiller Load	ApHVAC chillers load (MBtu)	ApHVAC chillers load (MBtu)	ApHVAC chillers load (MBtu)	
Date	Geothermal+EWCBoiler	ChillerBoiler	Geothermal+HP	Baseline
Jan	11	0	0	0
Feb	13	0	0	0
Mar	29	0	0	0
Apr	69	15	15	0
May	192	89	87	0
Jun	388	224	220	0
Jul	566	344	346	0
Aug	490	300	297	0
Sep	342	200	197	0
Oct	118	46	44	0
Nov	54	18	17	0
Dec	12	0	0	0
Summed total	2284	1237	1223	0

Annual Chiller Energy	ApHVAC chillers energy (MBtu)	ApHVAC chillers energy (MBtu)	ApHVAC chillers energy (MBtu)	ApHVAC chillers

				energy (MBtu)
Date	Geothermal+EWCBoiler	ChillerBoiler	Geothermal+HP	Baseline
Jan	1.231	0	0	0
Feb	1.443	0	0	0
Mar	3.113	0.036	0.048	0
Apr	9.927	2.131	3.434	0
May	35.962	13.841	20.928	0
Jun	84.185	38.638	55.652	0
Jul	130.337	61.98	90.125	0
Aug	110.983	52.805	76.513	0
Sep	73.535	33.978	49.506	0
Oct	20.149	6.716	10.546	0
Nov	8.653	2.782	4.18	0
Dec	1.35	0	0	0
Summed total	480.867	212.907	310.931	0

DX Cooling load	ApHVAC DX cooling systems load (MBtu)	ApHVAC DX cooling systems load (MBtu)	ApHVAC DX cooling systems load (MBtu)	ApHVAC DX cooling systems load (MBtu)
	p_3.27.17 Proposed2.0.aps	p_3.19.17 Alternative Proposed.aps	p_3.18.17 [Proposed-DOASx3-GSHP1.0].aps	p_3.16.17 Baseline.aps
Date	Geothermal+ChillerBoiler	ChillerBoiler	Geothermal+HP	Baseline
Jan	0	11	11	0
Feb	0	13	13	1
Mar	0	28	28	25
Apr	0	52	52	109
May	0	102	102	322
Jun	0	164	164	607
Jul	0	220	215	815
Aug	0	190	188	748
Sep	0	142	141	568
Oct	0	72	72	218
Nov	0	35	36	96
Dec	0	11	11	3
Summed total	0	1040	1033	3511

Annual DX Cooling Energy	ApHVAC DX cooling systems energy (MBtu)	ApHVAC DX cooling systems energy (MBtu)	ApHVAC DX cooling systems energy (MBtu)	ApHVAC DX cooling systems energy (MBtu)
	p_3.27.17 Proposed2.0.aps	p_3.19.17 Alternative Proposed.aps	p_3.18.17 [Proposed-DOASx3-GSHP1.0].aps	p_3.16.17 Baseline.aps
Date	Geothermal+ChillerBoiler	ChillerBoiler	Geothermal+HP	Baseline
Jan	0.00	2.83	2.83	0.39
Feb	0.00	3.33	3.33	1.12
Mar	0.00	7.47	7.48	14.41
Apr	0.00	13.50	13.52	40.61
May	0.00	24.63	24.68	93.75
Jun	0.00	38.84	38.78	160.45
Jul	0.00	52.05	51.03	213.97
Aug	0.00	43.90	43.57	192.29
Sep	0.00	32.94	32.87	147.70
Oct	0.00	17.56	17.59	68.14
Nov	0.00	9.08	9.11	32.54
Dec	0.00	3.13	3.14	2.13
Summed total	0.00	249.26	247.92	967.48