UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

ME 470: SENIOR DESIGN

Energy Source Options

Final Design Report

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EXECUTIVE SUMMARY

In 2020, the University of Illinois released its most recent version of the Illinois Climate Action Plan (iCAP), an ongoing plan to reduce greenhouse gas emissions and reach carbon neutrality before 2050. In the interest of reducing campus emissions, one goal of the iCAP focuses on increasing building efficiency and decarbonizing the current energy generation systems. Numerous departments are conducting feasibility studies to determine the best way for the University to reach these goals.

Experts have suggested that using compressed CO_2 as a refrigerant may be a cleaner alternative to the current energy systems which consist of the chiller plant system for space cooling and the Abbott Power Plant for space heating. The chiller plant system currently uses refrigerants R-22 and R-134a. Studies have shown that a CO_2 energy system saves 80% of the final energy use in urban areas at a cost lower than the current conventional systems [1]. Over the course of five months, the team has explored the usage of CO_2 as a replacement refrigerant for steam and chilled water .

The team has investigated whether implementing a CO_2 district system is a viable option for the University. The team's primary deliverable was to provide a detailed review of the current energy systems, as well as the design of a CO_2 network system with a vetted heat source. Once a thorough understanding of the existing systems and technologies was achieved, a design and feasibility study was conducted to evaluate replacing the steam and chiller systems for the Grainger Engineering Buildings. This feasibility study includes a detailed cost analysis as well as a description of the needed infrastructure in order for the team to determine whether the selected system could help the University work towards the energy goals specified in the iCAP. Finally, recommendations as to potential next steps and suggestions are also outlined and presented. The team concluded that some of the components in the proposed system are favorable, but due to the heating demand from Grainger buildings, CO_2 is not a viable option.

1. INTRODUCTION AND PROBLEM STATEMENT

The Illinois Climate Action Plan (iCAP) is a strategic plan that outlines how the University will achieve carbon neutrality. The report was originally published in 2010 by the Institute for Sustainability, Energy, and Environment (ISEE) and Facilities and Services (F&S) in the hopes of making realistic yet demanding environmental goals to instigate change within the University. This document was updated for the third time in 2020 to reflect current progress and include additional goals. The report outlines 56 specific goals organized into 8 themes: Energy, Transportation, Land & Water, Zero Waste, Education, Engagement, Resilience, and Implementation. One of these goals is to have 30% of the annual power demand of the University come from clean, renewable sources before Fall 2025 [2].

A main source of power for the University is the Abbott Power Plant located on the southwest end of campus. This is a cogeneration facility, meaning it produces both steam and electricity. Abbott produces energy for the University in order to offset the cost of purchasing that energy. If the cost of electricity from other sources is cheaper than running the plant, the University will buy it; if electricity is expensive, Abbott Power Plant will produce it.

The University is powered by three renewable sources. Two solar farms produce an estimated 7,200 MWh/year (2% of annual electric demand) and 20,000 MWh/year (6% of annual electric demand). The third source is the Rail Splitter Wind Farm that sells wind-generated electricity to the University, accounting for 8.6% of campus electrical demand. Contracted for a 10 year period starting in November 2016, this agreement brings in 25,000 MWh annually [2]. Since renewables are currently incapable of producing the required energy load, fossil fuels are still heavily relied upon. Both wind and solar require an immense amount of space; just one campus solar farm spans 54 acres and costs $20 million [2]. Due to cost and lack of space, the University must research other ways to reach net zero besides the construction of wind and solar.

One possibility is to use CO_2 as a refrigerant for heating and cooling. The team will analyze potential district systems utilizing a heat source that will exchange heat with CO_2 which will then exchange heat with water for heating and cooling. For this project, a district system is characterized by a central plant that produces heating and cooling to a network of buildings. This report will evaluate whether the engineering campus can be connected to a district energy system utilizing a CO_2 refrigerant.

2. BACKGROUND INFORMATION

2.1 CURRENT LOADS AND OPERATIONS

The University currently has two separate systems that provide heating and cooling for campus buildings. Space heating is currently achieved by utilizing steam produced at the Abbott Power Plant which provides 24.55 MW of peak load to the Grainger Engineering campus. The Abbott Power Plant has three natural gas boilers and three oil fired boilers that convert water to steam in addition to two gas turbines that connect to a heat recovery steam generator (HRSG). While each turbine produces electricity, the HRSG functions to capture hot exhaust gasses from the turbine and use that heat to generate additional steam. The steam is then routed directly to campus buildings where it is exchanged at building level heat exchangers with hot water in order to provide spatial heating.

Space cooling is achieved from five water chiller plants located throughout campus and requires a peak load of 21.81 MW for the Grainger Engineering campus. The chiller plants currently use refrigerants R-134a and R-22 through either vapor compression or absorption refrigeration cycles to remove heat from the liquid. Once the liquid is cooled, it is routed through its own underground pipe network to individual campus buildings where it passes through air handlers, fan coil units, and other types of air conditioning systems to provide spatial cooling.

For sake of narrowing the project's scope, the team focused solely on analyzing the Grainger Engineering campus which consists of 23 buildings which are shown in **Table 1** in the **Appendix B** along with their respective peak load requirements derived from the 2015 facilities and services master plan [33]. The Electrical and Computer Engineering Building was constructed after the master plan was drafted which is why there is no available data concerning its required peak load. The original master plan data was given in tons for chilled water and pounds per hour for steam and these were both converted into megawatts using the conversions below [34]. See **Appendix C** for calculations.

2.2 EXISTING EFFORTS

2.2.1 UNIVERSITIES

Universities around the United States have been taking the initiative to become net zero and further mitigate climate change. Stanford University recently developed an energy system in which 65% of their campus energy is derived from renewable sources. Moreover, they have implemented a heat recovery system that will meet more than 90% of the campus heating demands [3]. By the same token, Princeton University is executing upon its efforts to reach net-zero carbon emissions by 2046 by replacing its "inefficient" steam distribution system with one that operates at a lower temperature that requires less energy, and gathering heat through newly installed geo-exchange bores that contain a "closed-loop system of piping that recirculates water through the ground" [4].

2.2.2 BUSINESSES

In addition to Universities, the team researched various corporate sector companies and their efforts to reduce greenhouse gas emissions. Top tech companies including Apple, Amazon, Google, Meta, and Microsoft, have committed to reducing their emissions to net zero by the year 2050, paralleling the goals of the University of Illinois [5]. Out of the above companies, Amazon and Microsoft have provided the most public information regarding these specifics. The newest buildings built by Amazon in Seattle are heated using recycled energy from a nearby data center, making it four times more efficient than traditional heating methods. Dubbed a "district energy" system, the process works by capturing heat generated at a neighboring non-Amazon data center and recycling the heat through underground water pipes instead of venting it into the atmosphere [6].

In order to address its goals, Microsoft has purchased carbon removal tools and invested in Climeworks, which operates the "largest direct air capture plant", specializing in removing CO_2 from the air and trapping it in rock underground [7]. Currently, there are 19 direct air capture plants in operation globally, which capture approximately 100,000 metric tons of carbon dioxide annually.

2.2.3 NATIONAL EFFORTS

Other nations are spearheading initiatives to reach the common goal of carbon neutrality within the next decade. Two provinces in the Northern Netherlands are focused on utilizing emissions-free hydrogen as the next generation of natural gas [8]. Due to high investment costs, the plan consists of numerous subprojects to begin by first producing hydrogen by means of natural gas and then transitioning into using the electrolysis of water. The plans are to build small and large scale electrolysers incorporated into hydrogen wind turbines that produce hydrogen as opposed to power. Rising prices in natural gas have made the green hydrogen cheaper to produce which is why the Dutch government in accordance with companies like Shell plan to implement electrolysers by 2024.

3. PROJECT GOALS AND CONSTRAINTS

The team's project supports the identification of additional heat sources that provide for campus thermal energy while substantially reducing carbon emissions. To achieve this, the team evaluated the practicality of using CO_2 as a refrigerant in heating and cooling cycles. The deliverable of this project is a feasibility study that will outline a potential heat source, a CO_2 network system, and a cost estimate. The potential heat source must preheat a chosen refrigerant in order to reduce the energy input to the system. The CO_2 network system must complete an efficient heat pump/refrigeration cycle using an electrical input in combination with a heat source to distribute thermal energy. The team must also consider how the CO_2 network system will interact with existing infrastructure such as steam tunnels and building level heat exchangers. Another consideration for the team must be routing the CO_2 to the campus buildings from the central plant.

3.1 CO_2 AS A REFRIGERANT

As the threat of climate change intensifies, refrigerants pose a growing concern. The main environmental aspects that refrigerants are judged upon are their global warming potentials and their ozone depleting potentials. Global warming potential (GWP) is defined as the heat absorbed by greenhouse gasses in the atmosphere as a multiple of the heat absorbed by the same mass of carbon dioxide. This means that the GWP of CO_2 is 1. The ozone depleting potential (ODP) of a refrigerant is a measurement of how damaging a chemical is to the ozone layer. CO_2

has an ODP of 0 [24]. A low GWP and ODP proves that CO_2 is an environmentally friendly refrigerant. R-22 has been a popular refrigerant in heat pump systems for the past few decades but its use has been curtailed due to its adverse environmental impacts. Unlike CO_2, R-22 has a GWP of 1700 and an ODP of 0.05 [24]. The benefit of using R-22 comes from its thermodynamic properties. A high quality refrigerant will be stable under operating conditions and have a high latent heat of vaporization. R-22 has a critical point of 96.1°C (204.98°F) and 49 bar (710 psig). R-22 also has a latent heat of vaporization of 215.65 kJ/kg at 15°C (59°F) [25]. For this project, a desirable refrigerant will have a high critical temperature and pressure as well as a low latent heat of vaporization. CO_2 has a critical point of about 31.1°C (87.98°F) and 73 bar (1058 psig). The latent heat of vaporization of CO_2 is about 175.9 kJ/kg at 15°C (59°F) [26]. Since R-22 is a manufactured refrigerant, it has very desirable thermodynamic properties. However, due to its environmental impact, it is being discontinued and scientists and engineers are looking to more natural refrigerants like CO_2.

3.2 PROJECT CONTRAINTS

Currently, there is no renewable heat source providing heat to the 23 Grainger Engineering buildings so there is no existing temperature constraint on the heat source. The main constraint for the heat source is geographical viable sources of heat. Typical energy sources for district heat pump systems are water bodies (lakes or ponds); however, UIUC does not have a large body of water available so the thermal energy must be sourced elsewhere. For this project, the team looked at the viability of geothermal energy from deep boreholes into the underlying sandstone bedrock. The current energy demands of the Grainger Engineering buildings include a supply of hot water temperatures ranging from 60°C (140°F) to 82°C (180°F) and a supply of chilled water temperature of 6.2°C (43°F). These hot and cold water supply temperatures are the main constraints on the CO_2 based network system.

In addition to meeting these initial water temperature requirements, the system also needs to decrease the carbon emissions produced. The team believed that this goal could be achieved by using CO_2 as a refrigerant to heat and cool the buildings. Although CO_2 usage would result in a decrease in the emissions, it is necessary to take into consideration the impacts a new system would have on the community. First constraint for system installation would be the space currently available for the system, whether that is piping in the system tunnels or room for excavation to install geothermal wells. In addition to spatial constraints, the team also had to consider the safety constraints for using CO_2 as a refrigerant and potentially running it throughout campus. Ensuring that it is safe for the surrounding community while still being environmentally friendly is an important consideration for this project.

4. SOLUTION PROCEDURE

The project can essentially be split into two main parts, the CO_2 network system and the heat source. The CO_2 network system will include a refrigeration cycle, a piping network, and machinery to integrate CO_2 into the existing building network. The heat source will provide an input temperature to the CO_2 network system. The heat source will also have its own piping network to connect to the CO_2 network. Both the CO_2 district system and the heat source went through multiple design iterations to determine if they were feasible options. The team was able to narrow down their designs of each of these systems in order to come to a final proposed design.

4.1 CO_2-BASED DISTRICT SYSTEM

Initially, the team had set up Pugh's controlled convergence matrices in order to evaluate different CO_2 network options. These can be seen in **Appendix A.** After some iteration, it was found that most of the designs had a prohibiting factor making the design infeasible for the University. As a result of this, the team mainly considered these prohibiting factors in making their decision rather than comparing extensive metrics. The main metrics the team considered were: ability to meet campus load, safety, efficiency, and cost.

4.1.1 SMALL CLOSED LOOP CO_2 - MAN ENERGY SOLUTIONS

The team first evaluated a system that utilized CO_2 in a small loop that would then produce hot and cold water that could be used for heating and cooling. MAN Energy Solutions's system pumps CO_2 through a small heat pump cycle (at a centralized plant) and the CO_2 is exchanged with hot/cold water which can be used for district heating and cooling. The efficiency of their system came from the fact that they had designed a high speed motor compressor integrated with an expander. Due to the efficiency of this compressor, MAN systems could see COPs up to 5 [27].

This system would require a heat and electric input and would output hot and cold water that could either be stored in thermal storage tanks or delivered directly to buildings as seen in **Figure 1** below. The thermal storage tanks offer a unique incentive because they allow for the flexibility to run the compressor at times where the electricity is less expensive and store the thermal energy for when it is needed.

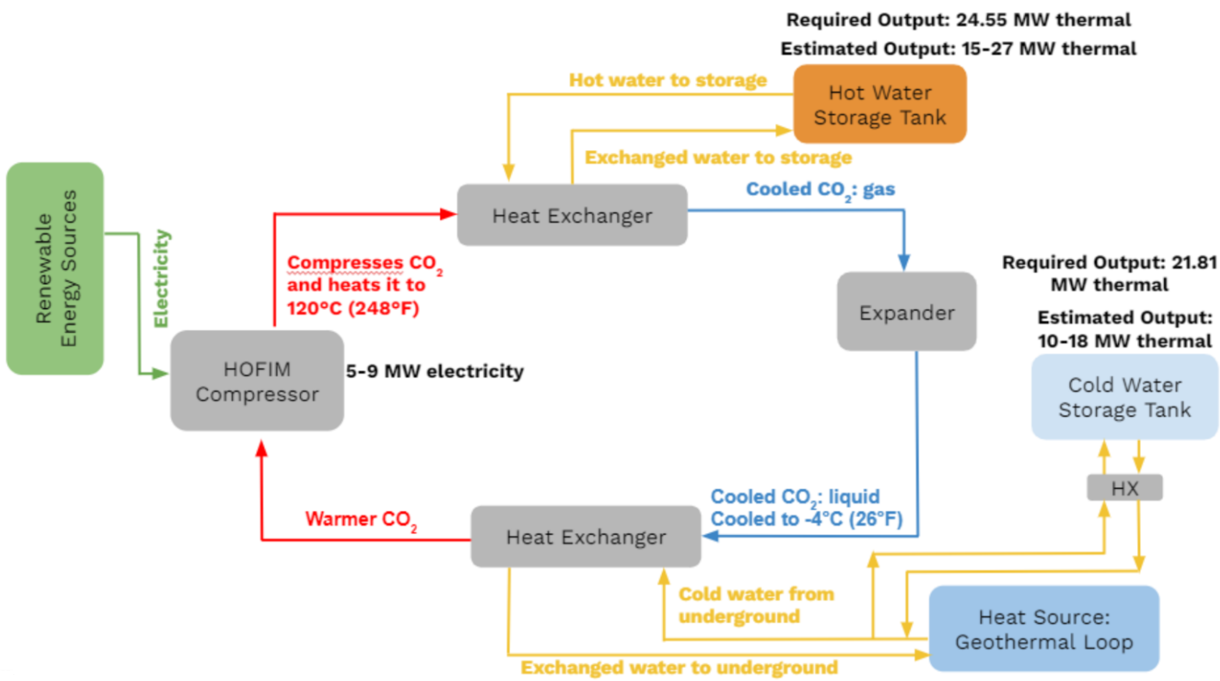

Figure 1. MAN Energy Solution Heat Pump System [27]

4.1.1.1 FEASIBILITY ANALYSIS

While this system was predicted to result in a high COP, the system was deemed to not be the best option as those COPs were only achieved when the CO_2 in the system was operating at higher temperatures ranging from 120 °C (248°F) to 150 °C (302°F), but for the campus's system, the maximum required temperature of water input is 60 °C (140°F). **Figure 1** contains the estimated thermal outputs of the system based on the compressor size provided by MAN. Also shown are the required thermal loads for campus. It can be seen that the required output is in range of the estimated output for the heating but not the cooling. If this system were to be installed, the University would likely have to go with a larger compressor size which would not be desirable as the system is already operating in an inefficient range. In terms of safety, the

MAN system requires very little maintenance. MAN designs compressors for subsea operations so their systems are very reliable. Since the CO_2 is in a small closed loop, there is a lower chance of a large leak due to the small amount of refrigerant being circulated in the system. Through consultations, the team was able to receive a cost estimate for the system to be anywhere between \$8 million and \$18 million. The team deemed this to be an infeasible solution due to its high cost and operation outside the maximum efficiencies based on University constraints.

If the University were to allow higher supply building water supply temperatures, MAN could be a very efficient solution. A large advantage to the MAN system is their ETES (electro-thermal energy storage) system. This system is not yet on the market but allows not only for electric energy to be converted into thermal energy, but also for that stored thermal energy to be converted back into electric energy. The system would allow more flexibility to store/produce energy when it is cheap and store it thermally for when it is needed. This could be a very useful addition if the University were to produce more renewable energy at one time than is needed in the future. Currently, the University consumes all of the renewable energy that it produces but this may change in the future.

4.1.2 CO_2 NETWORK

One alternative scenario investigated was to have a larger CO_2 refrigeration cycle where the CO_2 would be routed to the buildings and exchanged with the hot/cold supply water directly. The idea was to have the CO_2 system more closely model the steam system. This is a fairly new technology and has not been inputted widely in the US yet. As a result, the team relied on multiple published papers in order to design the system.

4.1.2.1 LITERATURE REVIEW

The concept is based on two publications; both feasibility studies claimed to be able to provide district heating and cooling to the surrounding city with CO_2-based district energy systems. The first feasibility study addressed the potential of a CO_2 -based district energy system in the City Centre of Geneva, Switzerland [9]. The concept is based on the premise that the latent heat of vaporization can be used to provide heating and cooling applications. In addition, the report describes specifics about what type of buildings are connected to the district energy system and their required energy input. Operation of the district energy system is expected to reduce energy consumption by 84.4% when compared to the current system of boilers and chillers. Overall, the CO_2-based system was determined to be feasible and lower cost for the city. One key aspect was that a cascade energy system was evaluated where R410a refrigerant was used in conjunction with CO_2 and water. The team found that the EPA plans to phase out the use of R410a by 2023 in new systems and therefore would not be feasible design for the university at this time [10].

The team also evaluated another feasibility study that examined a district energy system CO_2 refrigerant and the respective cost savings that may come with it [11]. The application of CO_2 in district energy uses waste heat and estimates the projected utility costs while also evaluating the energy consumption. These heat sources included groundwater, river water, and sewer water. The energy system included 2 supply lines, one circulating mostly vapor and the other mostly liquid, that ran from a central plant where it was either heated or cooled, and then distributed to buildings. The study evaluated three different options: 1) CO_2 returned from the network of heat exchangers using R410a refrigerant in the heat pump via a evaporator/condenser (this is similar to a cascade heat pump), 2) CO_2 returned from the network using direct heat exchange, or 2) CO_2 is used in a two-stage heat pump. The team realized that of the options evaluated within the study, the best option to evaluate for the building needs may be option 1. Overall, the team suggests the operations suggested in this study may not be as easy to execute due to the mixtures/phase change complexities believed to be present in the pipes. The use of gas and liquid phases simultaneously could pose potential flow issues, which also requires specialized equipment. The team also took into account that both of these studies are theoretical in nature and were not yet tested in large-scale demonstrations.

4.1.2.2 THERMODYNAMIC ANALYSIS

The critical point of CO_2 is at 31.1°C (87.98°F) and 73 bar (1058.78 psi) [26]. Since the hot water supply temperature to the building is 60°C (140°F), the CO_2 must operate above the critical point in order to heat the campus buildings. This forces the CO_2 cycle to be transcritical. When CO_2 is in a transcritical cycle, it is operating in the superheated range. This means that for the majority of the cycle, CO_2 is a nebulous vapor which is more dense than the gaseous state of CO_2. When CO_2 is operating above the critical pressure, specialized equipment must be implemented to ensure it can withstand the pressure. This adds a rather large complexity to the system as the equipment is very expensive. Custom engineered equipment is also more expensive to repair and it often takes more time to be serviced.

If CO_2 were to be operating in the two phase region, it would see full phase changes from liquid to vapor. The cycle could operate within the liquid vapor dome which provides a constant temperature and pressure throughout the cycle. This is one reason why efficiencies are greater inside of the liquid vapor dome. Moreover, there is a better chance CO_2 could operate under the industry pressure standard of 50 bar (725 psig). As a general rule of thumb, most industry equipment is rated for about 50 bar (725 psig) and any pressure higher than that would require custom engineered equipment.

For the team's purposes, CO_2 must operate in a transcritical cycle. Therefore, the team must ensure that the efficiency of the system is high enough to merit such high costs and added complexities. One possible solution is to integrate an internal heat exchanger. An internal heat exchanger is an exchanger used to transfer heat between the low side pressure and the high side pressure of a cycle. This would allow for some added cooling before the CO_2 reaches the expansion valve and some added heating before the CO_2 reaches the compressor. Another possible solution would be to evaluate a cascade heat pump system. This system splits the heating and cooling load between heating/cooling mediums in order to operate under the conditions where each is most efficient.

4.1.2.3 SYSTEM REFRIGERATION CYCLES

The team utilized an Engineering Equation Solver (EES) for preliminary refrigeration cycle calculations throughout this project. Code utilized for this project can be seen in **Appendix A**. One drawback of this software is the inability to calculate state points of transcritical cycles. As a result of this, the team referenced a study by Simarpreet Singh that compared the efficiencies of a transcritical CO_2 cycle, a transcritical CO_2 cycle with an internal heat exchanger, and an ammonia refrigeration cycle [28]. A transcritical CO_2 cycle without an internal heat exchanger yielded a COP of about 2.3. When adding an internal heat exchanger, the COP increased to about 2.9.

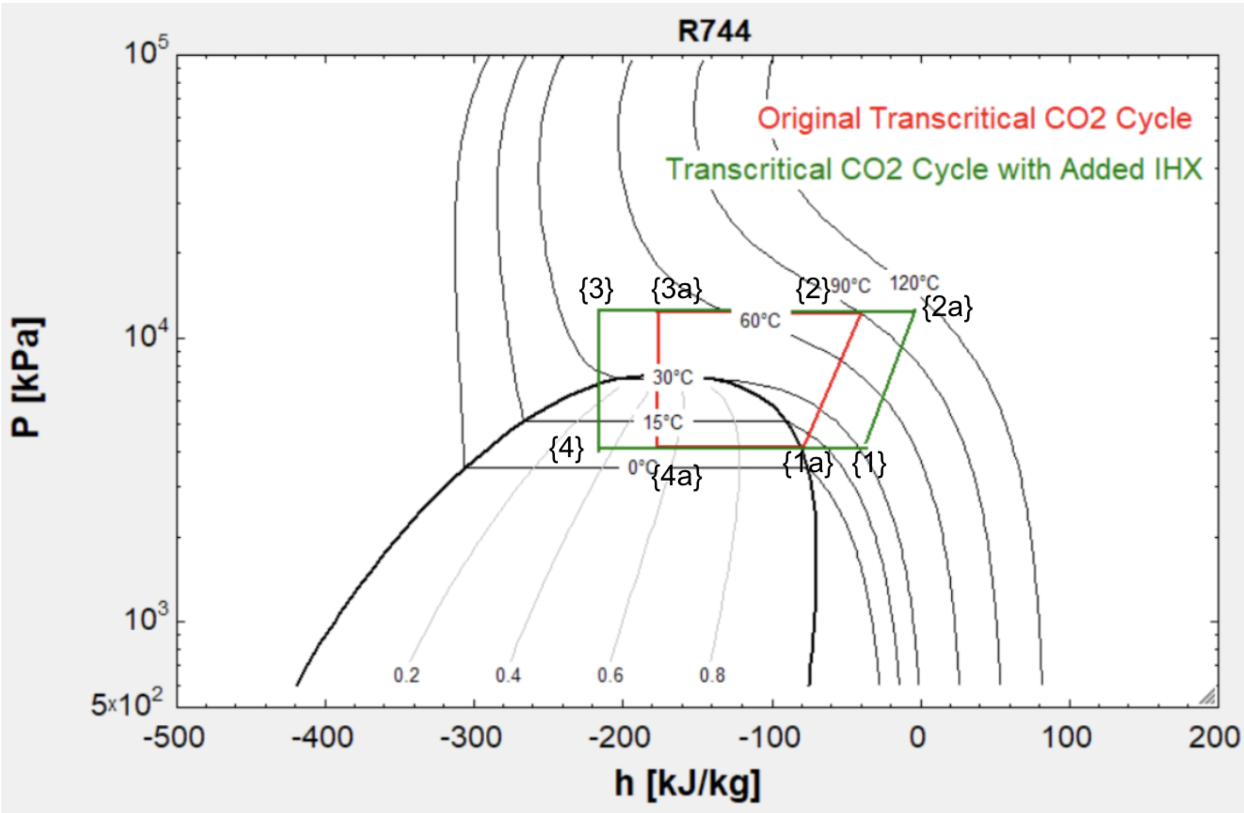

Figure 2. Transcritical CO_2 Cycles with and without an Internal Heat Exchanger

When looking at **Figure 2**, it can be seen that the entire area enclosed by the green curve is greater than the area enclosed by the red curve. This shows that the work inputs and energy outputs of the system have increased. The combined equation for the COP of heat pump and refrigeration cycle is:

$$COP = \frac{Q_{out} + Q_{in}}{W_{in} - W_{out}} \tag{1}$$

$$Q_{out} = h_3 - h_2 \tag{2}$$

$$Q_{in} = h_1 - h_4 \tag{3}$$

$$W_{in} = h_1 - h_2 \tag{4}$$

$$W_{out} = h_3 - h_4 \tag{5}$$

The internal heat exchanger allows for additional cooling before the expander. This additional cooling is reflected in the line between state points {3} and {3a}. The internal heat exchanger also allows for additional heating before the compressor. This is reflected in the line from state point {1a} to {1}. The lengthening of both of these lines increases the total Q_{out} and Q_{in} to the system. Q_{out} is the line between {2} and {3} and Q_{in} is the line between {4} and {1}. With the addition of the internal heat exchanger, the total work input to the system also increased. This can be seen as the slope of the line from {1} to {2} decreased, thus increasing the enthalpy change. The line from {1} to {2} is denoted as W_{in}, the work input to the system. Although the work input increased, the Q_{out} and Q_{in} increased much more dramatically which caused the increase in COP.

The team then modeled this cycle to how it might be integrated into the current building operations. **Figure 3** is a very simplified process flow diagram of the CO_2 network integrated into the campus system.

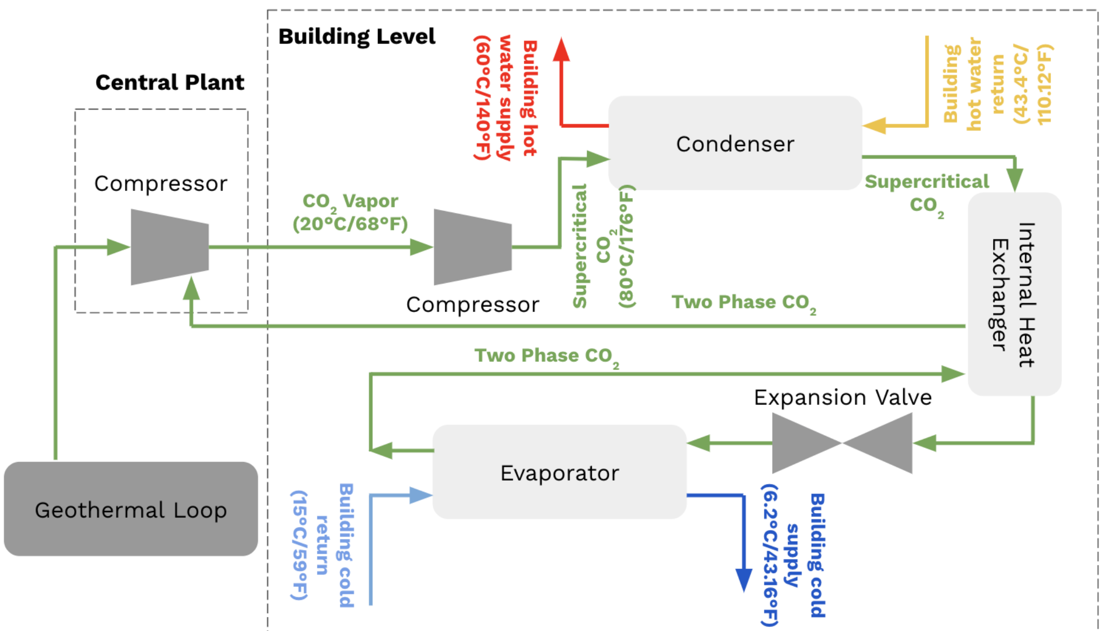

Figure 3. Simplified Process Flow Diagram: CO_2 Refrigeration/Heat Pump Cycle with an Internal Heat Exchanger

The cycle shown in **Figure 3** will start at the geothermal loop where CO_2 will be exchanged with hot Earth brine to bring it up to an input temperature. The geothermal loop will be explained in detail in **Section 4.2.1.1** below. After the geothermal loop, the CO_2 will flow to the central plant. The team has determined the central plant to be in the basement of the Mechanical Engineering Laboratory (MEL). The central plant will act as a starting point for all of the individual CO_2 connections to branch from. Each building will have their own refrigeration loop, the starting place for which will be the central plant. Once the CO_2 is compressed at the central plant, it will flow to its own respective building. Here the CO_2 will be compressed again to about 90°C-120°C (194°F - 248°F) before it enters the condenser. The condenser is a heat exchanger that will exchange hot CO_2 with the building return hot water (110°F/34.3°C) in order to produce the supply building hot water at a temperature of 140°F/60°C. After the evaporator, the CO_2 will move through the internal heat exchanger and expansion valve before it reaches the evaporator. Similar to the condenser, the evaporator is a heat exchanger that will exchange cooler CO_2 with the building return cold water (59°F/15°C) to provide the building supply of cold water at a temperature of 43°F/6.2°C. After the evaporator, the CO_2 will flow through the other side of the internal heat exchanger before returning back to the central plant where the cycle will start over again.

Although the COP increased when adding the internal heat exchanger, the team deemed the COP increase was not high enough to merit the additional cost and complexity of running a transcritical cycle. It would not be efficient to choose a refrigerant which needed specialized equipment when other refrigerants could achieve the same COPs while operating in the two phase region. For this reason, the team feels that CO_2 is not the best refrigerant to be integrated with current building operations.

4.1.3 PIPING AND BUILDING INTEGRATION

In addition to evaluating a heat pump and refrigeration system, the team also developed a proposed pipe network for routing the CO_2 refrigerant directly to and from buildings in the engineering campus (**Figure 4**). Each of the 23 buildings in the engineering campus is connected directly to the steam tunnel network which serves as a basis for the proposed network.

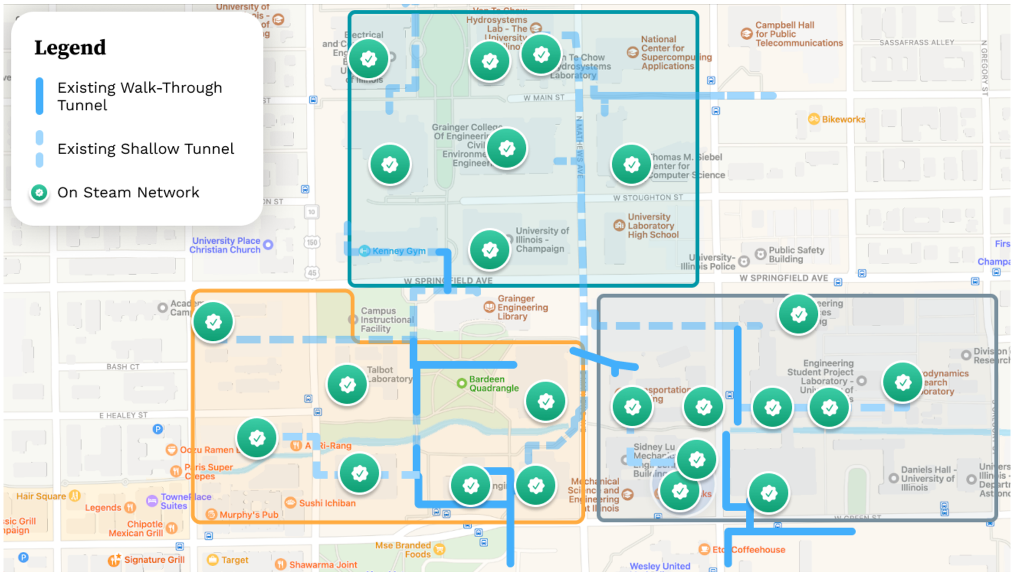

Figure 4. Engineering Campus Buildings and Steam Tunnels

To reduce capital costs, the team explored the viability of repurposing the steam tunnels for the CO_2 network but, after consulting with Director of Utilities Production for the University of Illinois Mike Larson, ultimately found it unfeasible due to lack of space within the tunnels. Additionally, the CO_2 refrigerant must operate at high pressures of up to 73 bar (1058 psig) which would require specific piping in order to mitigate risks of leaking. The alternative solution is to directly bury a new pipeline along the existing path of the steam tunnels using 10 inch diameter ASTM A312 stainless steel pipes; while these pipes are the most highly recommended for use with CO_2 as a refrigerant, they come at a cost. While not a direct comparison, 8 inch diameter A312 SCH80 pipes, when spaced to cover the full 5.25 miles of interlinked piping between the 23 required buildings, would cost a little less than $8 million to integrate within the system; this figure considers only the cost of material and not the additional associated excavation/burying costs [35]. When routing the fluid to and from campus buildings, an important constraint to consider is how fast it will be traveling within the pipes. The fluid must not exceed a maximum erosional velocity in order to prevent internal damages from occurring within the pipe. For the liquid phase of CO_2 this velocity is 6 m/s and for vapor phase CO_2 the maximum velocity is 20 m/s. These velocities were determined from a study done at Utrecht University that analyzed both gaseous and dense liquid transport for point-to-point CO_2 pipelines [29].

4.2.1 HEAT SOURCE

As stated, the CO_2 district system requires a heat source; the output temperature of this heat source should be as high as possible to increase efficiency during the heat exchange process. In the duration of the project, the team has evaluated many potential sources of heat, most notably geothermal and solar thermal. The team has concluded deep direct-use geothermal as the most technically and economically feasible heat source for the University.

4.2.1.1 GEOTHERMAL ENERGY

The team evaluated different geothermal energy technologies before deciding on a deep direct-use geothermal energy system. When comparing the available technologies, the team considered implementation costs and outlet temperature as the most important parameters, but certain prohibiting factors prevented systems from being considered altogether. A standard geoexchange loop, the technology utilized by the UIUC Campus Instructional Facility (CIF), was first considered due to its familiarity and known construction costs and energy output [12]. Based on specific thermal conductivity data from the CIF boreholes, it was estimated that every 400 vertical feet of piping would achieve 3 tons of cooling [12]. The engineering campus has a higher peak heating load compared to cooling load, and was therefore used to size the system. Based on the CIF data, the engineering campus peak heating load of 67 MMBtu/hr would require 1,489 boreholes at 450 feet deep, demanding a large amount of land that is not currently available. In an attempt to reduce the number of wells needed, direct exchange geothermal was also considered, which circulates CO_2 in the pipes instead of a water-glycol mixture. In theory, this improves the efficiency of the geothermal system as the additional heat exchange step between the water-glycol mixture and the CO_2 is eliminated. Additionally, this system would use metal pipes, which would be more conducive to heat transfer. However, the team determined that this system would also not be feasible due to the piping requirements as copper pipe is much more expensive, difficult to install, and does not last as long as HDPE pipe [13].

Finally, the team focused on a deep direct-use (DDU) geothermal energy technology, which uses heated water (brine) from the Earth as the fluid for transferring thermal energy to the above-ground CO_2-based energy system. It is comprised of a two-well (doublet) system for extracting brine, and injecting returned fluids after exchanging the thermal energy with the CO_2. Shown in **Figure 4**, 2000 ft below the entirety of UIUC is the St. Peter Sandstone Aquifer [14], which would be the targeted subsurface geology for the DDU system. This sandstone aquifer contains brine at around 78-82℉ (26-28°C) and a recent report regarding the feasibility of a DDU system at the University indicates the brine temperature drops by less than 1℉ when transported from the extraction and injection wells in insulated HDPE pipe [14].

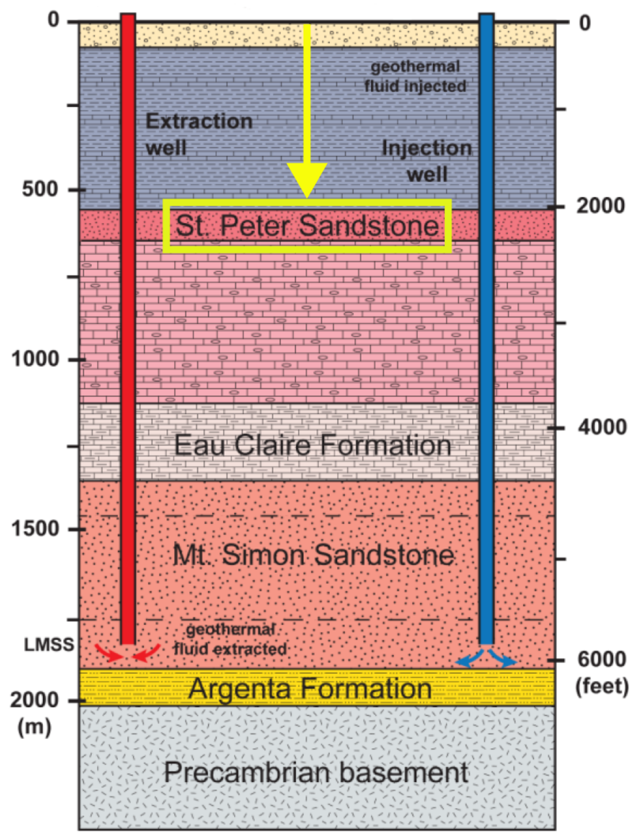

Figure 5. Deep Direct-Use Depth [14]

As previously mentioned, the engineering campus peak heating load was used to appropriately size the geothermal energy system. This peak load of 67 MMBtu/hr was converted to barrels per day which was used to determine that approximately nine doublets would be required for the DDU system (see **Appendix C** for calculation details) [14]. Note that in this calculation, 80% of the peak load was used as it can be assumed that not every building will be running at peak load at the same time.

The Bardeen Quad was chosen as a location for the extraction wells because of its close proximity to MEL, where the thermal energy from the extracted brine will be exchanged with the CO_2. The extraction and injection wells must be at least 0.5 miles apart so that the cooler temperature of the injected brine does not interfere with the temperature of the extracted brine [14]. Because of this, the South Quad was selected as the location of the injection wells, which is approximately 0.6 miles away from the Bardeen Quad (see **Figure 5**). Note that the exact spacing between injection wells (as well as extraction wells) cannot be determined without pressure sensitivity analysis which is completed as part of the pre-construction phase [14].

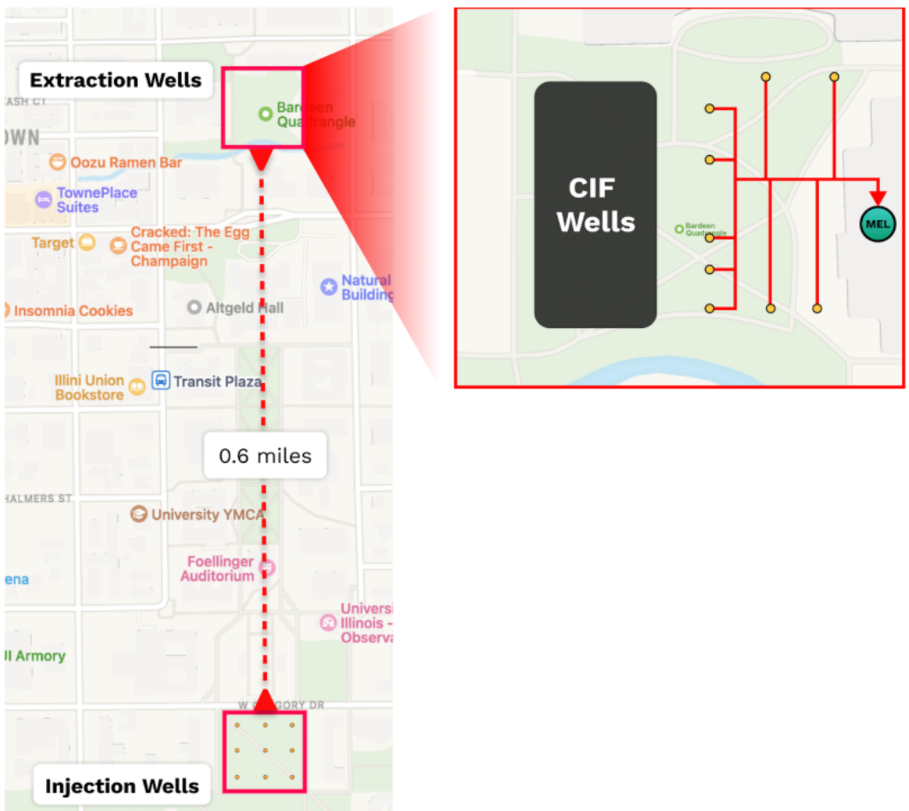

Figure 6. DDU Well Locations

The injection and extraction wells require 6 inch inner diameter HDPE pipes with 17 inch diameter boreholes [14]. HDPE piping is durable, easy to install, and will have a lifespan of at least 50 years. **Figure 6** below shows a side view of the geothermal loop.

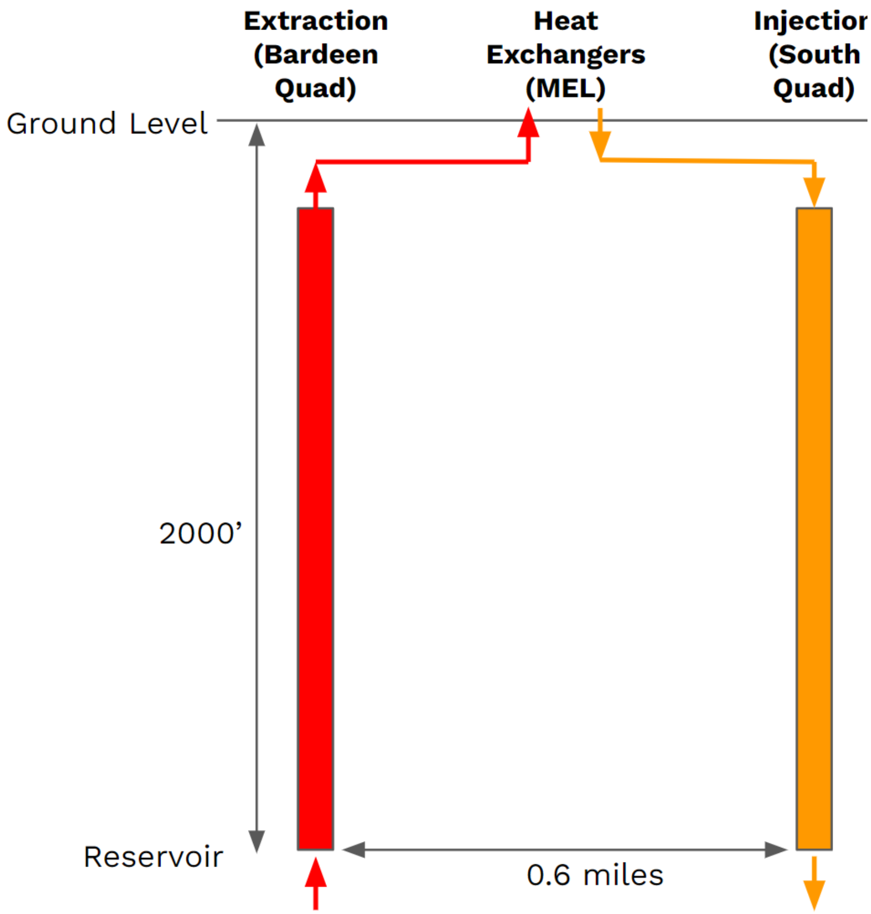

Figure 7. Geothermal Piping

The heated brine will be extracted from 2000 feet underground and will be brought to the surface into pipes just below ground level at the Bardeen Quad. Here, the pipes will feed to the basement of MEL where there will be nine heat exchangers, one for each extraction pipe. Once the thermal energy is exchanged with the CO_2, the brine will leave MEL and flow underground along buried pipes to the South Quad where it will be injected in nine wells back into the reservoir. It is also important to note the permits required for installation of the geothermal system. On the federal level, there is no permit required, but on the state level, the Illinois Environmental Protection Agency (IEPA) will permit the brine injection under a UIC (underground injection control) Class I certificate [14].

4.2.1.2 SOLAR THERMAL HEAT SOURCE

Concurrent to the exploration of geothermal heat sources, the team also researched the viability of solar-based heat source options. Solar, in general, has long been associated with the sustainable energy movement; as such, it was natural for the team to explore its place within the context of this endeavor. While traditional photovoltaic solar converts absorbed light directly into electricity, solar thermal solutions absorb sunlight and use the energy as a heat source, making this avenue more pertinent to the team's research. Flat plate panels absorb 67% of sunlight and cost approximately $400 per panel [15]. Based on the 21.81 MW of peak cooling load and 24.55 MW of peak heating load that the Engineering Buildings on campus require, the current 75 acre, $15.5 million flat-panel solar farms are not an adequate solar thermal source. Scaling the Solar Farm size and respective output to meet the demands of the Grainger Engineering Campus, let alone the overall University of Illinois campus, would ultimately be cost-prohibitive as a solution.

5. COST ESTIMATION

The team has evaluated each part of the system to develop an estimated total system capital cost. The costs included in this estimation are based on various research and company consultations.

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5.1 MECHANICAL COMPONENTS

The mechanical components for the CO_2 district system total at just under $1 million [16-20]. This includes the evaporator, condenser, compressor, and internal heat exchanger. The costs for these items were calculated based on industry averages. These systems are assumed to operate in standard conditions and are not prices for transcritical operation. Specialized equipment for transcritical operation is priced through consultations. The costs provided serve as a baseline for the equipment needed. Since every building will have its own refrigeration cycle, the University would need to purchase 23 of each component.

5.2 PIPING AND BUILDING INTEGRATION

The cost estimation for the amount of CO_2 required by the system was found by using the square footage of the Grainger Engineering Campus buildings. According to manufacturing.net, approximately 7,000 pounds of CO_2 is needed to cool a 200,000 square foot warehouse [21]. The engineering campus has a net square footage of about 1,600,000 [22] which would require a total of 56,000 pounds of CO_2. The cost of CO_2 refrigerant is 2 dollars per pound which yields a total cost of $113,000 [23].

5.3 GEOTHERMAL ENERGY SYSTEM

The piping cost (including materials, insulation, and installation) and the excavation cost (including trenching and backfilling), per doublet well pair, is approximately $1 million [14]. The surface infrastructure, which includes heat exchangers and pumps, is calculated to be approximately $650,000 per doublet. With nine doublets, the total geothermal energy system cost is estimated to be around $24 million. These estimates are based on a 2019 feasibility study conducted for the campus, which found DDU geothermal to be technically and economically feasible at UIUC[14]. Note that the team has included a 30% premium charge to account for recent cost increases from supply chain issues.

5.4 TOTAL COST

The total estimated capital cost of the system is just over $33 million, as seen in **Table 2**. This cost includes the mechanical components of the district system, CO_2 required for the system, district piping, and geothermal system, as well as workforce development. The workforce development cost is included because it is assumed that existing University technicians will have to be trained to learn how to operate the new system. The team assumed that 8 workers would be able to monitor all 23 buildings, and would require approximately a week of training. If paid $70/hr, the total workforce development cost would be just over $22,000. Note that this cost does not include labor costs for implementing the CO_2 district system or the excavation of the pipes, only the geothermal system labor costs are included. Therefore this baseline cost will likely be much higher.

Table 2. Total System Cost Estimate

	Estimated Cost per Unit	Total Cost	% Of Total
Evaporator	$1,000	$23,000	0.07%
Condenser	$1,500	$34,500	0.10%
Compressor	$36,500	$839,500	2.53%
Expander	$400	$9,200	0.03%
Internal Heat Exchanger	$1,500	$34,500	0.10%
CO2 (per pound)	$2	$113,000	0.34%
8" SCH80 Stainless Steel Piping (per 240 inches)	$5,651	$7,832,286	23.58%
Workforce Development (per person)	$2,800	$22,400	0.07%
	Estimated Cost per Doublet		
HDPE Piping	$1,041,300	$9,371,700	28.21%
Excavation	$1,010,100	$9,090,900	27.36%
Surface Infrastructure	$650,000	$5,850,000	17.61%
Total		**$33,220,986**	100.00%

6. LIFECYCLE

Since this system aims to be an environmentally friendly solution, important life cycle aspects such as disposal and reliability were evaluated. The geothermal system is a consistent source of energy with its underground infrastructure having a lifespan of approximately 50 years. As mentioned earlier, the HDPE piping used is durable and easy to install allowing the system to require relatively little maintenance. In the case of the geothermal system being decommissioned, the HDPE pipeline can either be removed via excavation or repurposed depending on the new system's criteria. Similarly, the CO_2 network has its own pipeline making the disposal process similar to the geothermal system. However, since the CO_2 pipeline operates at considerably high pressures, the increased risk of leaks would require frequent maintenance to ensure safety. The heat pump system's mechanical components require constant surveillance in all 23 buildings by a team of technicians mentioned above. Once certain mechanical components reach the end of their lifespan (on average 15 years), they can be disposed of and replaced with new equipment [36]. The disposal process involves addressing the refrigerants and heat pump components separately: any leftover refrigerant must be reclaimed by licensed HVAC technicians, as required by the Environmental Protection Agency, and mechanical components must be deconstructed, separated, and then specifically recycled [37]. Components like stainless steel piping can even be recycled such that it is reused in the form of scrap metal to create newer stainless steel [38].

7. STANDARDS

Implementation of this system would require it to adhere to various standards. Although certain system components would be viable such as the DDU geothermal system, the relevant standards would be better determined with a tangible engineering design. In any case, the project would likely need to adhere to ASTM F1668-16 Standard Guide for Construction Procedures for Buried Plastic Pipe, given that the geothermal system would involve buried plastic piping, and the piping to engineering buildings will be directly buried. Additionally, ASTM Volume 4.12 Building Constructions, Asset Management, Sustainability, Technology and Underground Utilities would be relevant to implementation of this system. The volume includes standards related to not only preservation and performance of the system, but also standards on sustainability, operations of green buildings and environmental life cycle assessment. With this project aiming to support the goals outlined in the 2020 iCAP, it would be important to follow standards related to sustainability and green equipment.

8. WHY CHANGE?

As outlined above, the Illinois Climate Action Plan established by the University of Illinois at Urbana-Champaign strives to reduce greenhouse gas emissions and reach carbon neutrality by the year 2050. In order to achieve this goal, the University of Illinois, as well as many other schools and organizations around the world, must begin to research and implement more sustainably sourced energy options now. While change of the required magnitude will take an incredible level of time and capital to accomplish, the proposals outlined in this feasibility study at least provides a path forward to the progress that must be made over the next 30 years. Based on this team's exploration of CO_2 as an alternative refrigeration source, as well as the proposal to explore the viability of ammonia in the same function, it is clear that there is not yet a direct solution that can be easily implemented on the Grainger Engineering Campus. However, the data does indicate that changing from steam and water refrigeration to an alternative, as well as implementing a geothermal heat source, can help reduce overall emissions without hindering the energy needs of the University.

9. RESULTS AND CONCLUSIONS

The overall goal the Energy Source Options team has been aiming to answer is if CO_2 is a viable refrigerant to heat and cool the Grainger Engineering buildings. The team was able to determine that some parts of the system would be viable while others were not. For example, the geothermal loop using deep direct-use technology would be a viable heat source option. The team was able to determine a solution with 18 wells that would be able to provide a stable input temperature into the system. On the other hand, the team concluded that CO_2 itself was not a viable refrigerant option due to the heating demand of the buildings. Since the supply hot water temperature to the buildings is over the critical temperature of the refrigerant, the cycle is required to operate in the transcritical range. The COP calculated by the team was not high enough to merit the added complexity and cost of installing such a specialized high-pressure system. CO_2 would be a viable refrigerant to supply cold water to the buildings as the cold water supply temperature would allow the refrigerant to operate in the two phase region. Another large concern with using CO_2 in such a large refrigeration system is the safety concern. The exposure limit for CO_2 is about 40,000 ppm (parts per million) [39]. At this level, CO_2 is deemed hazardous for life and health as it can cause asphyxiation as it replaces oxygen in the blood. Since high pressure CO_2 would be connected to every Grainger Engineering building, there is a large risk of a high pressure leak scenario in a small confined space. This could be partially mitigated by extensive leak detection devices but it is a hazard nonetheless due to the constant population of these buildings.

10. FUTURE RECOMMENDATIONS

While the initial plan of using CO_2 in combination with an internal heat exchanger did not seem to be a profitable option, the team does have ideas on how to move forward. The team has identified 2 potential avenues that this project may follow: utilize a different refrigerant or implement a cascade refrigeration system. These two options do not have to be mutually exclusive as the solution may in fact utilize the suggested refrigerant of Ammonia in a cascade system.

10.1 AMMONIA AS A REFRIGERANT

While CO_2 was selected for its low environmental impact and non-toxic nature, the high pressure and velocity of the system present dangers to the community's health even though it is ranked as an A1 refrigerant [30]. With those safety concerns in mind for CO_2, using Ammonia (R717) as a potential refrigerant shows promise even with its corrosive nature as a flammable, toxic gas and ranked as a B2L refrigerant [30]. Even though Ammonia is corrosive, it does have a pungent scent indicator, occurring before harm is caused, that can help detect leaks while CO_2 relies solely on mechanical detection devices. In addition to its scent indicator, Ammonia also has comparable ODP and GWP values to CO_2 (see **Table 4**) meaning a limited environmental impact, as well as having the capability of operating as a two-phase cycle rather than a transcritical (see **Figure 7)**. In regards to its flammability, there are a few current large industrial uses and food preservation and due to specialized piping should ideally not pose a threat to the community but should be further evaluated. This two-phase is possible due to Ammonia's high critical point positioned at 132.41 °C (270.34 °F) and 113.57 bar (1647.2 psig) [31], which is higher than the required hot water supply temperature of 60 °C (140°F) allowing it to achieve an approximated COP of 3.5. Visually, it can be seen that the refrigeration cycle in **Figure 7** provides a higher COP than the cycle in **Figure 2** due to **Eq (1)**. **Figure 7** demonstrates large Q_{out} and Q_{in} lines while showing a rather low W_{in}.

Table 4. Properties of Ammonia and CO_2

	R-774 (CO_2)	**R-717 (Ammonia)**
Global Warming Potential (GWP)	1	0
Ozone Depletion Potential (ODP)	0	0
Safety Classification	A1	B2L
Critical Temperature [ºC]	31.1	132.4
Critical Pressure [bar]	73	113.6

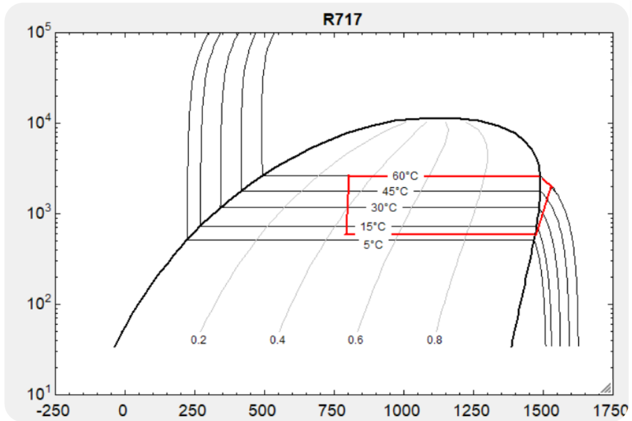

Figure 8. Ammonia Cycle

10.2 CASCADE REFRIGERATION CYCLE

If the team were not to have pursued the option of using an internal heat exchanger, another alternative solution may have been using a cascade refrigeration system. A cascade refrigeration system utilizes 2 working fluids that both go through phase changes to meet the heating and cooling requirements by running 2 cycles parallel to each other. These refrigerants are connected by a cascade heat exchanger. Using this type of system has the capability to allow a higher temperature range and a better efficiency by utilizing the critical point and freezing point to the system's advantage. See **Figure 8** for an example of what this system could look like.

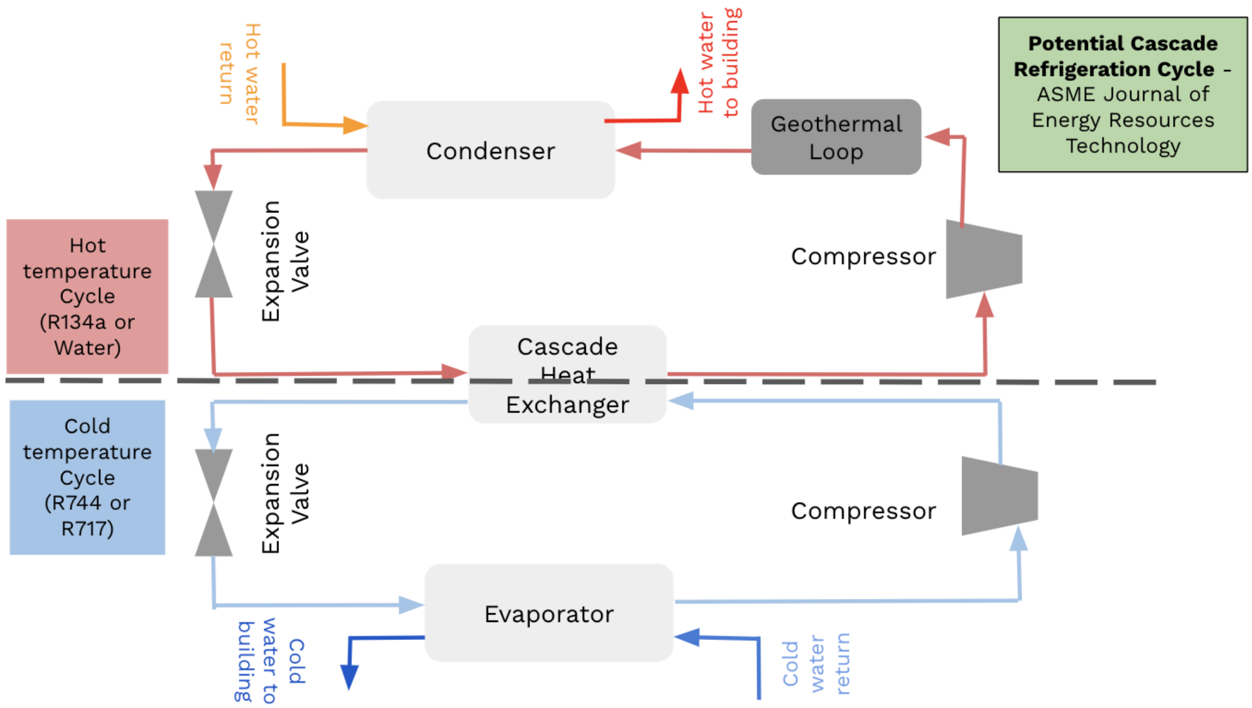

Figure 9. Cascade System

The ASME study [32] found that one of the best combinations for such a system is water for the hot temperature cycle fluid with Ammonia (R717) as the cold temperature cycle. This combination results in the highest COP as well as the smallest volumetric flowrate on the cold side. If wanting to incorporate CO_2 into this process, R134a is a common pairing used for the hot cycle of the system.

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12. APPENDIX

APPENDIX A - CO_2 DISTRICT SYSTEM

TABLE 4: Initial Matrices				
	DATUM		**MAN ES System**	
	Chiller System	Hot Water/Steam System	Chilling	Heating
Power Output [MW]	21.81	24.55	30	50
Max Output Temperatures [°F/°C]	59/15	140/60	302/150	
Power Input [MW]	60	60	4-18	
Cost [$]	150,000-12,700 ,000	78300000	8-18 Million	
Maintenance [Years]	5-10 years	5 years	10	
Familiarity	-	-		
Total Emissions			0	
Efficiency [COP]		3.4	5	
Physical Space [ft^3]	6 plants; 23 miles of distribution piping, 6.5M gallon thermal energy storage tank	6 boilers, 2 HRSG, serves 2.2 square miles	130 x 65 x 32	
Future Proofing	-	-		
Reliability			Full aftermarket crew in US	
Safety			No fear of CO2 leak	
Integration Into Current System				

Installation Time	3-5 days per chiller		2 years
Lifespan [years]	20-30	5-30	25
Disposal	Replace with large, variable speed chillers at end of life	Coal boilers to be demolished and replaced with natural gas	No official plans laid out; should be able to be regularly disposed of

```
$TabStops 0.2 2.5 in
$UnitSystem SI C kPa kJ mass

$ifnot ParametricTable
T[1]=10[C]                                "evaporator temperature"
$ShowWindow Arrays
$HideWindow Parametric
$endif

R$='R717'                                 "string variable used to hold name of refrigerant"
"! Compressor"
x[1]=1                                    "assume inlet to be saturated vapor"
P[1]=pressure(R$,T=T[1],x=x[1])           "properties for state 1"
h[1]=enthalpy(R$,T=T[1],x=x[1])
s[1]=entropy(R$,T=T[1],x=x[1])
P[2]=pressure(R$,T=T[3],x=0)              "this is the pressure in the condenser"
h_2_ID=enthalpy(R$,P=P[2],s=s[1])         "ID for ideal identifies state as isentropic"
W_c_ID=(h_2_ID-h[1])                      "energy balance on isentropic compressor"
Eff=0.8                                   "Isentropic efficiency"
W_c=W_c_ID/Eff                            "definition of compressor isentropic efficiency"
h[2]=h[1]+W_c                             "energy balance on real compressor-assumed adiabatic"
s[2]=entropy(R$,h=h[2],P=P[2])            "properties for state 2"
T[2]=temperature(R$,h=h[2],P=P[2])

"!Condenser"
T[3]=71.378"known temperature of sat'd liquid at condenser outlet"
P[3]=P[2]                                 "neglect pressure drops across condenser"
h[3]=enthalpy(R$,T=T[3],x=0)              "properties for state 3"
s[3]=entropy(R$,T=T[3],x=0)
Q_Con=h[2]-h[3]                           "energy balance on condenser"

"!Valve"
h[4]=h[3]
P[4]=P[1]                                 "energy balance on throttle - isenthalpic"
x[4]=quality(R$,h=h[4],P=P[4])            "properties for state 4"
s[4]=entropy(R$,h=h[4],P=P[4])
T[4]=temperature(R$,h=h[4],P=P[4])

"!Evaporator"
   "[kPa] neglect pressure drop across evaporator"
Q_Evap=h[1]-h[4]                          "[kJ/kg] energy balance on evaporator"
COP=abs(Q_Evap/W_c)                       "definition of COP"
```

Figure 10. Screenshot of Engineering Equation Solver (EES) Code

APPENDIX B - BUILDING DATA

Table 1. Grainger Engineering Buildings and Peak Load

Building	Chilled Water Peak Load (MW)	Steam Peak Load (MW)
Talbot Laboratory	NR	0.844
Engineering Hall	0.566	0.672
Newmark Civil Engineering Building	1.695	2.151
Mechanical Engineering Laboratory	1.146	0.982
Material Science and Engineering Building	0.654	1.177
Everitt Laboratory	1.783	1.444
Transportation	0.046	0.655
Nuclear Radiation	NR	NR
Ceramics	NR	0.700
Materials Research	2.068	3.281
Loomis Laboratory of Physics	1.663	1.236
Superconductivity Center	0.338	0.529
Computing Applications Building	NR	0.686
Mechanical Engineering Building	0.672	0.749
Coordinated Science Laboratory	1.094	0.909
Civil Engineering Hydrosystems Laboratory	0.292	0.309
Engineering Sciences Building	1.667	2.325
Laboratory for Optical Physics and Engineering	NR	0.160
Digital Computer Laboratory	2.050	1.249
Micro Nanotechnology Laboratory	3.935	3.226
Electrical and Computer Engineering Building	NR	NR
Siebel Center for Computer Science	2.054	1.109
Aerodynamics Laboratory	0.088	0.154

Total Engineering Campus Peak Load	**21.812**	**24.545**

APPENDIX C - CALCULATIONS

Campus Building Data

1 Ton Ac = 12,000 Btu/hr Cooling

34,500 BTU/h (33,472 Btu/hr) = 34.5 lb. steam/hr

1 Watt = 3.413 Btu/hr

Geothermal Conversions

Engineering campus heating load = 67 MMBtu/hr
15 MMBtu/hr = 30,000 barrels/day [14]
Barrels/day needed = 67*(30,000/15) = 133996.8 bbl/day
30,000 bbl/day = 2 doublets [14]
Doublets needed = 133996.8*(2/30,000) = 8.933 ≈ **9 doublets**