Geothermal Heating at UMass Amherst: Is It Worth It?

University of Massachusetts Amherst

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Section 1: Executive Summary

Chancellor Subbaswamy has laid out an ambitious plan to reach net-zero carbon emissions for the UMass campus by the year 2030. Even though Massachusetts law only requires all state agencies to reach net-zero emissions by the year 2050, the Chancellor's charge is in response to UMass Amherst being the largest industrial emitter in the state. After an extensive study, UMass' Carbon Mitigation Task Force has concluded that a Geothermal Heat exchange system (GHX) will be the optimal replacement for the current Central Heating Plant (CHP).

One immediate problem with this solution is the substantial initial investment required. As such, the question arises: Is it economically and environmentally "worth it" to install this new geothermal system? After all, the carbon emissions produced by the CHP can be offset by other, potentially cheaper technologies such as carbon capture and storage (CCS).

However, CCS is still an emerging technology, and it remains uncertain what direction this technology will take in the future. Indeed, CCS has not yet been implemented by any institution of higher education, period. Furthermore, relying on CCS will not make UMass independent of fossil fuels because it relies on the CHP, which would continue to burn fossil fuels in a CCS future. In contrast, the GHX system provides a tested and reliable technology that removes UMass' dependence on fossil fuels, though the campus would rely more on the electricity grid. In addition, a GHX system will save UMass money in the long term by minimizing the effects of the social cost of carbon while avoiding the maintenance and fuel costs of the CHP. Due to these reasons, we recommend that installing a GHX system is indeed "worth it" as the optimal solution.

Section 2: Introduction to Geothermal Technology within UMass

Six years, 235 days, 12 hours, and 38 minutes. As we write this paper, that is all the time humanity has left to prevent climate change from becoming irreversible [1]. Last September, the Metronome clock in New York City was replaced with this "deadline" as a desperate plea to humanity [2], for if we do not make drastic changes soon, we will be forced to face the unavoidable consequences. Failure to act would not only lead to drastic global warming on the scale of at least 1.5°C, but it would provide the foundation for human suffering, natural disasters, and ecosystem damage estimated to have a cost of *$54 trillion* [2].

Despite the terrifying deadline ticking down, the New York "Deadline" clock also gives a message of hope: "The Earth has a deadline. Let's make it a lifeline" [3]. The clock displays the number 12.27%, which represents the percentage of the world currently powered by renewable energy. If we want to protect the future of the planet and life upon it, as the designers of the clock advocate, that number needs to approach 100% as quickly as possible [3].

Figure 1: *A snapshot of the time written on the New York "Deadline" Clock website from May 10, 2021 [1]*

The University of Massachusetts Amherst advocates for the same mission as the individuals who launched the clock. UMass currently produces 14% of the fossil fuel emissions for all state institutions in Massachusetts (making it the largest contributor for statewide emissions) [4], but they hope to turn that around by making the campus carbon neutral in a decade [5]. The university aims to fight climate change head on, but how does it hope to achieve its ambitious goal? One component of their plan is an approach against the fossil-fuel-burning Central Heating Plant (CHP), for it provides 100% of the heat on campus along with around 85% of the campus emissions (as shown in Appendix Part 1) [4,6]. The Carbon Mitigation Task Force (CMTF) proposes that UMass install a geothermal heat exchange (GHX) system to transition away from the CHP and to a renewable future. As we analyze the Task Force's suggestion, we ask ourselves: Is GHX a good fit for UMass? What are the costs of applying this technology on campus? Are there any better alternatives to a GHX system? To properly answer these questions, we performed research in the fields of engineering, thermodynamics, and economics. We also studied the CMTF's plan for UMass' net-zero mission to investigate the relationship between geothermal heating and the campus's future. After the conclusion of our investigation, we advise that UMass implements a GHX system as proposed in the Carbon Mitigation Plan. Despite the high initial price tag of the system, our analysis suggests that the technological, environmental, and long-term-financial benefits will be “worth it” for UMass’ heating demands and carbon mitigation goals.

Section 3: Problem - Geothermal is a Double-Edged Sword (But Which Edge is Sharper?)

The Serious Heating Demands on Campus

Through the Fall 2019 semester (before the COVID-19 pandemic began), over 31,000 students and 3,000 faculty/staff considered themselves a member of UMass’ bustling campus [7]. Along with these many individuals comes a significant bill for electrical, heating, and cooling demands. For example, UMass currently produces roughly 1.2 billion pounds of steam per year *for its heating demand alone*, which is an amount of energy sufficient to provide electrical power to over 40,000 homes in the Northeast for a year (as shown in Appendix Part 2) [6,8,9].

What is more, UMass’ heating demand is responsible for 85% of the campus emissions (shown in Appendix Part 1), for the CHP produces the steam that heats the campus with natural gas and other fossil fuels [4,5]. If the university’s population continues to grow in the coming years, this heating demand will only continue to grow along with it. Furthermore, if the university currently plans to phase away from the CHP in its carbon-neutral mission, we will need to find a new means to provide for 100% of the campus heating demand [5]. This is where the CMTF’s Carbon Mitigation Plan (CMP) steps in.

Means to Meet the Demands - The Limitations of Resistive Heating

While burning fuel is out of the question for a renewable future, UMass could potentially generate its heat by running their electricity through a resistive conductor – a process called *resistive heating*. In theory, we could use carbon-neutral electricity so that the campus does not need to rely on fossil fuels. The limitations of solar and wind technology make it impractical for UMass to produce this electricity [10,11,12], but it may be possible that electricity could be purchased from the grid with Renewable Energy Credits to guarantee that it is green [5].

Resistive heating technology has an efficiency of around 80-90% [13], making it more efficient than the CHP (which is around 75% efficient, as shown in Appendix Part 3). In other words, for every unit of energy that is put into a resistive heating system, around 0.8 - 0.9 units of heat are emitted. The ratio of heat output versus energy input is called the *Coefficient of Performance*, and it is used to measure the capabilities of a heating system. (For example, the resistive heater we just described has a COP of 0.8 -

0.9.) No matter how good our system is or how well-made the technology is, a resistive heater's COP must be less than or equal to 1 because it creates all its heat from scratch (electricity -> heat).

Even so, what if there was a technology with a COP greater than 1? What if a system could produce *more heat* than how much energy is put in? This is where geothermal heating comes in. A Geothermal Heat Exchange (GHX) system pumps fluid through to draw heat from underground, where the temperature remains constant at approximately 54°F year-round [14]. By utilizing the underground heat, a GHX system can output more energy than is put, granting it a COP of around 3-4 [15]. In short, a GHX system *moves* heat while a resistive heater *creates* heat. This would not only allow for a GHX system to potentially provide 20% of the campus heating load, but it could also mitigate 37% of UMass' carbon emissions (more than any other component of the CMP, as shown in Figure 2) [5]. The potential of a geothermal heating system could prove immensely beneficial for UMass' heating needs as the campus hopes to veer away from fossil fuels, but what are the costs?

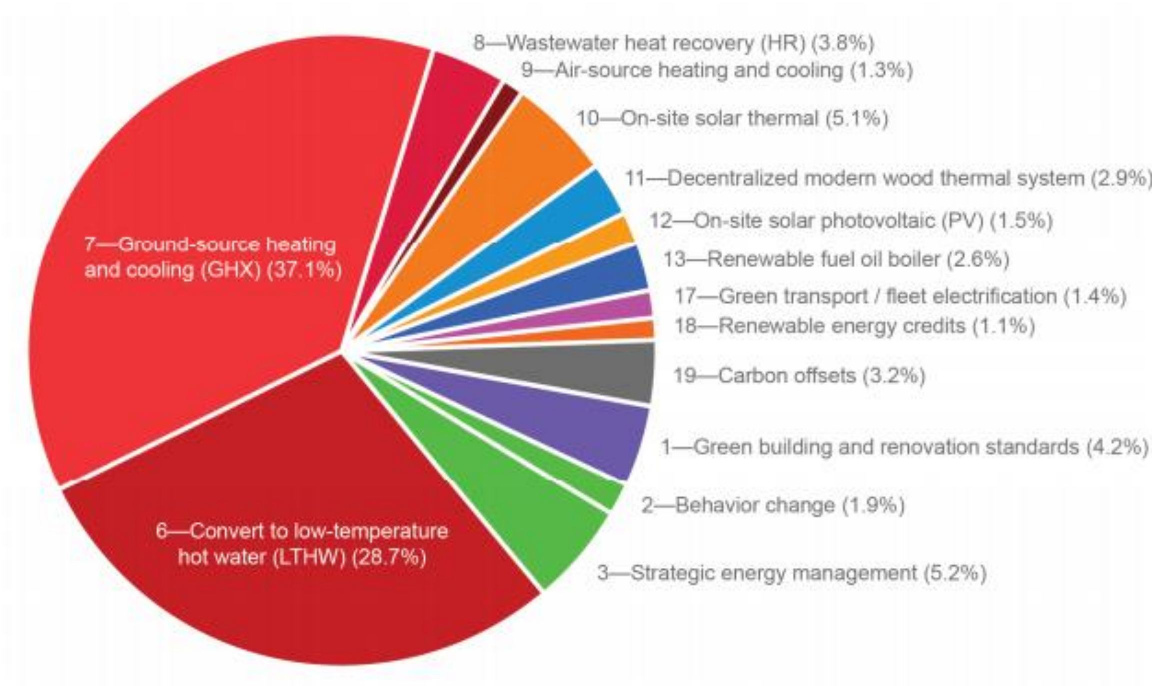

Figure 2: *Ground-source heating and cooling accounts for 37% carbon emissions mitigation, the highest amount of all solutions. Pie chart from Ref. [5].*

The Costs - Is Geothermal Worth It?

While a GHX heating system could serve as a major advantage to UMass' Carbon Mitigation Plan, its cost could serve as a major obstacle. For starters, the authors of the CMP estimate that the GHX installation cost (capital expenditure or CAPEX) would be around $96 million by the time the system is up and running [5]. Furthermore, based on UMass' HVAC budget and the geothermal system installed at Ball State University, we estimate that the GHX system would cost approximately $2.1 million per year to maintain and operate (as shown in Appendix Part 4) [5,16,17]. While this estimated operational cost (i.e., OPEX) of the GHX system is less than the cost to maintain the CHP [5], this GHX facility also only provides one-fifth of the heating load provided by the CHP. Furthermore, the CAPEX of the GHX system is one of the largest costs on the CMP and it would render the Central Heating Plant as a stranded asset. So, if you are reading this right now, you may be asking the same question that we asked before: Is the GHX worth it?

Section 4: Analysis - Comparing Costs Between Geothermal and Carbon Capture

What does it mean to be "Worth it"?

When measuring the worth of a system, it is important to fully understand the metrics of what is valuable when determining that worth. For the proposed geothermal system at UMass, factors including capital and annual operating costs, the number of metric tons of CO_2 avoided, and the social cost of carbon (SCC) were considered. The SCC is a value, in dollars, assigned to the economic harm that one metric ton of carbon dioxide has once it has been emitted into the atmosphere [18]. This is important in helping to determine the worth of the system because SCC is not unique to the GHX system, but rather for all emitted CO_2. Because of this purported value, an economic comparison can be made not only between the price per metric ton of carbon avoided and the SCC, but also between two distinct technologies for carbon mitigation.

Carbon Capture and Storage - A Possibility for Carbon Mitigation

Because the proposed GHX system is estimated to reduce over one third of emitted carbon dioxide, other potential solutions must be comparable regarding carbon mitigation. Carbon capture and storage (CCS) technology does just that, as it can reduce carbon dioxide emissions by 80-90%. [5]. In addition to this, the CCS system would be used in conjunction with the existing CHP. The implementation of this technology would negate the need for the CHP to be replaced, and thus remove the need for UMass to invest in the expensive geothermal solution. As an independent technology, the costs of a CCS system are low when compared to the GHX system as well, with an estimated CAPEX of $18 million and an estimated OPEX of $6.3 million annually [12]. To understand what this means for UMass, financial projections for carbon capture as well as GHX have been calculated.

Financial Projections for GHX, CCS, CHP, and Social Cost of Carbon

After financial analysis of each of these systems, concerning their capital investments, operational costs, price per metric ton of carbon avoided, and value of these costs in comparison to the SCC, conclusions were reached regarding their worth to the campus and its goal to reach carbon neutrality. First, it is important to note that the SCC is expected to steadily increase annually for the duration of our calculations; we adopt the estimate of a 5% annual increase from the Carbon Mitigation Plan. Secondly, it is critical to note that the mathematical projections begin in 2032 – the year by which the GHX system is expected to be constructed and fully operational.

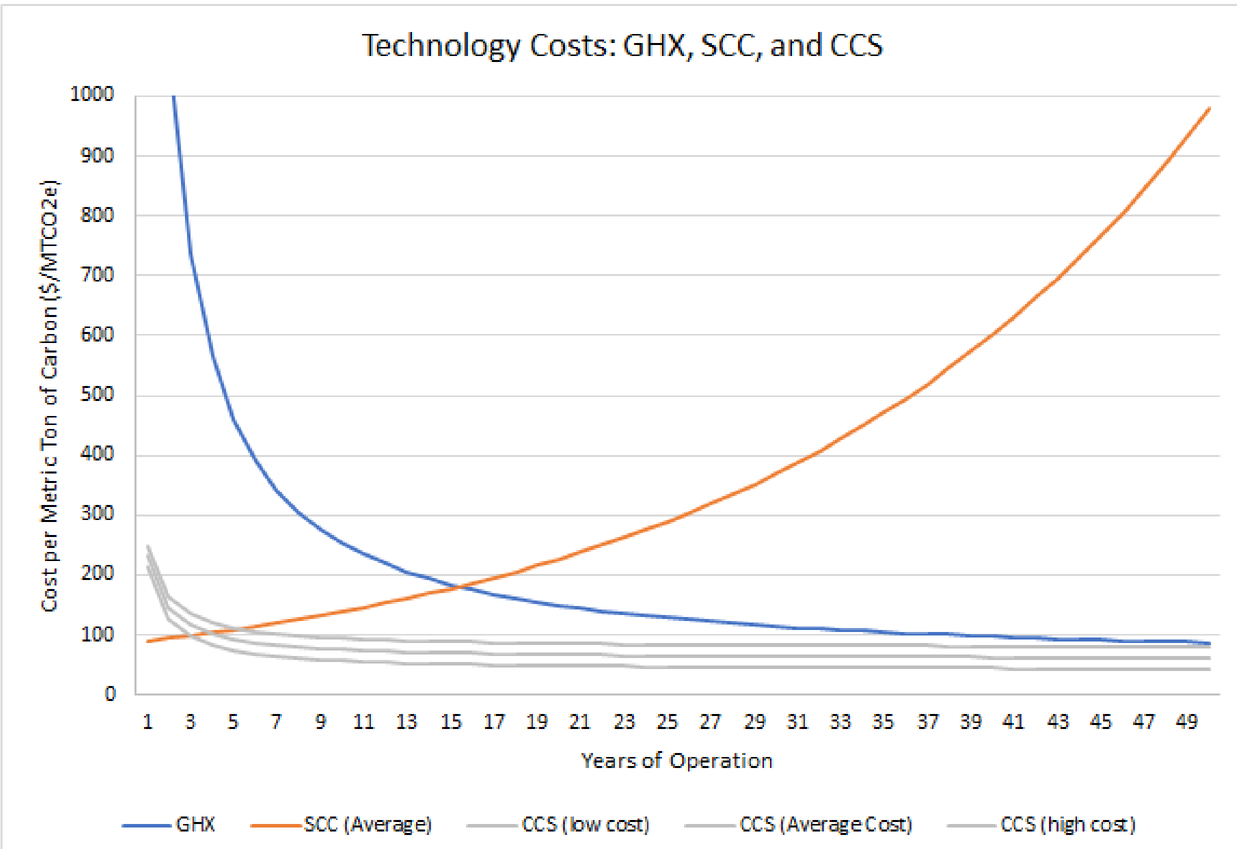

Figure 3: *A comparison of the price per metric ton of C02 of GHX and CCS systems with the SCC*

We found that the GHX system has the highest price/MTCO$_2$e avoided during its first year of operation, being $2,100/MTCO$_2$e. This is much greater than the price/MTCO$_2$e for carbon capture and storage which would be $230/MTCO$_2$e in 2032. Both costs are greater than the SCC, which is estimated to rise to $89/MTCO$_2$e by 2032. After further analysis however, it is seen that the price/MTCO$_2$e for the GHX system will fall *below* the SCC by the year 2047, with the costs becoming $179/MTCO$_2$e and $186/MTCO2e, respectively. During this time, the price/MTCO$_2$e for carbon capture and storage is estimated to become \$69/MTCO_2e, which remains far lower than the SCC and GHX (Appendix, Part 5). As Figure 3 notes, the price/MTCO_2e in the GHX system decreases significantly over time while the SCC increases exponentially.

Also seen in Figure 3 are three projected financial trends for CCS over the same time period. Estimates for carbon capture OPEX costs range between \$4.5-\$8.4 million/year with an average of \$6.6 million/year [12]. These estimates are represented by 'low, 'high,' and 'average' costs in the graph. It is important to note that for these projections, the OPEX for the CHP (including, e.g., ongoing natural gas costs) have not yet been considered. In other words, for an "apples-to-apples" comparison (meaning a comparison that is fair and balanced on both sides), we need to consider the costs of ongoing energy and mitigating carbon emissions. On one hand, this means we will need to incorporate the OPEX costs for the CHP along with the CAPEX and OPEX for CCS. On the other hand, this also means we will need to incorporate electricity costs with the GHX CAPEX and OPEX. (This is because the CHP produces heat and electricity while the GHX system could only produce heat.)

Figures 4 and 5 detail the comparison between the cumulative operating costs through the year 2050 of every factor necessary for an approximate "apples-to-apples" comparison. For starters, Figure 4 includes the cumulative costs (how much money UMass has paid all together) for CCS, CHP, GHX, purchased electricity (to replace the electricity generated by the CHP), and RECs (for new purchased electricity). At the same time, it also includes the cumulative costs of CCS + CHP combined and GHX + 70%E (purchased electricity) + RECs combined. The purpose of these combined costs is to depict the two "roads" UMass could take for its heat and electricity demands. It is important to note that our "apples-to-apples" comparison assumes that the GHX system proposed in the CMP takes on 100% of campus heating instead of 20% as planned [5]. This assumption is made not only for simplicity, but because the growth of cost for a growth in GHX heating demand is currently unclear. (Plus, the development of GHX technology could change prices or heating capacity in the future, providing for uncertainty.)

As shown in Figure 4, the cumulative operating cost for the combined CHP and CCS technologies exceeds the operating costs of both the GHX system and the CCS technology when working independently of the CHP. Because the CHP is not being newly constructed, its CAPEX is not accounted for in this calculation, yet the cumulative operating cost for the two systems (CCS and CHP) is \$600 million by 2050 [5,12]. This is much higher than the \$260 million cumulative cost of the GHX system plus electricity and RECs [5,16,17,19]. (The methodology for these calculations is explained in Appendices 6 and 7). Figure 4 elaborates further on the *actual* costs shown on Figure 3, detailing that the CCS technology is not as cost effective as it looks superficially when compared to GHX. (Figure 5 emphasizes this point by only showing the combined costs.)

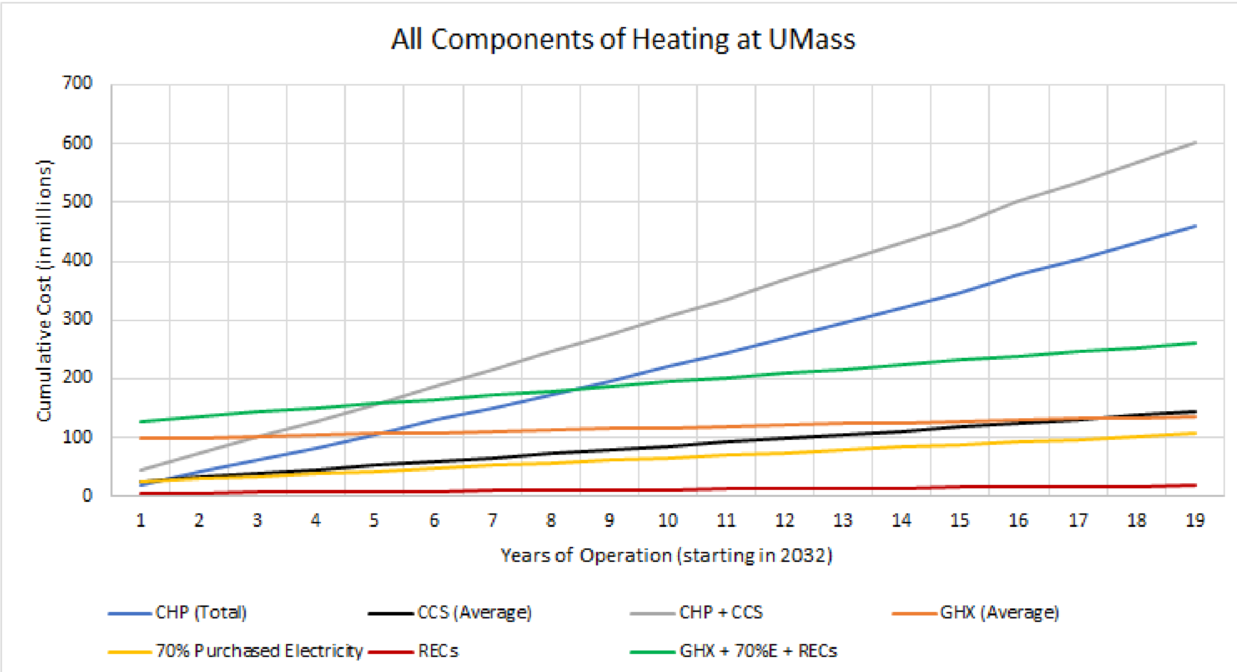

Figure 4: Components of Heating and Electricity for UMass (Comparing Financial Trends for Utilizing GHX or CCS)

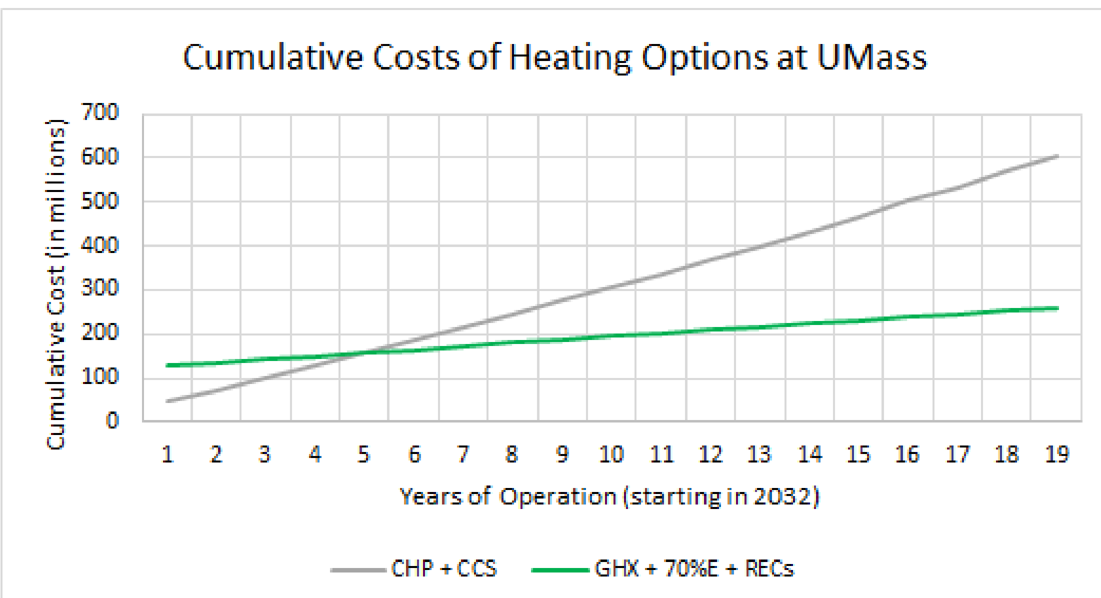

Figure 5: Components of Heating and Electricity for UMass (Combined Costs only)

Section 5: Recommendations - Our Answer to "Is it worth it?"

Revisiting UMass' Goals for Net-Zero Carbon

In deciding whether a geothermal heating system is worth it or not for UMass, it is important to base reasoning in the context of Earth's, the State of Massachusetts', UMass', and Chancellor Subbaswamy's goals. A solution must be found that can provide sufficient heating and cooling efficiently and in a timely manner. [5]. This solution ideally should also be composed of renewable resources and avoid, reduce, replace, or offset carbon emissions [5].

Meeting UMass' Goals

A CCS system would make use of an already existing Central Heating Plant's steam and natural gas system but come with cons and uncertainties [5]. This solution would save money with reduced capital investments compared to a GHX system but would ultimately cost more in maintenance and operation in the long run [5]. This system also fails to avoid the use of fossil fuels and does not capture 100% of carbon emitted [5]. A carbon capture and storage system may be an initially cheaper option, but it fails to meet the goals of a net-zero carbon emission campus.

Alternatively, a GHX system does meet the net-zero goals. Instead of creating carbon emissions and storing some percentage of those emissions, a GHX system avoids creating direct emissions, and could use electricity created by renewable sources. The system will be powered by electricity that will be sourced from renewable sources by the year 2050, according to a state mandate, before then purchasing RECs will compensate for the electricity bought from the grid that is not sourced from renewable sources. Since GHX systems move heat from the ground, which is a stable and renewable source of heat, and uses RECs to compensate for its electrical emissions, the system will meet the standards and requirements of UMass' goal [5]. A GHX system will provide heating and cooling from renewable sources efficiently and while avoiding carbon emissions. Figure 6 demonstrates the costs of a GHX system vs a steam system over time for Carleton College. This system is estimated to cost less than business-as-usual in 19-20 years. Similarly, a GHX system comes with a significant up-front cost and over time the costs will be less than UMass' current method of steam and natural gas through the CHP.

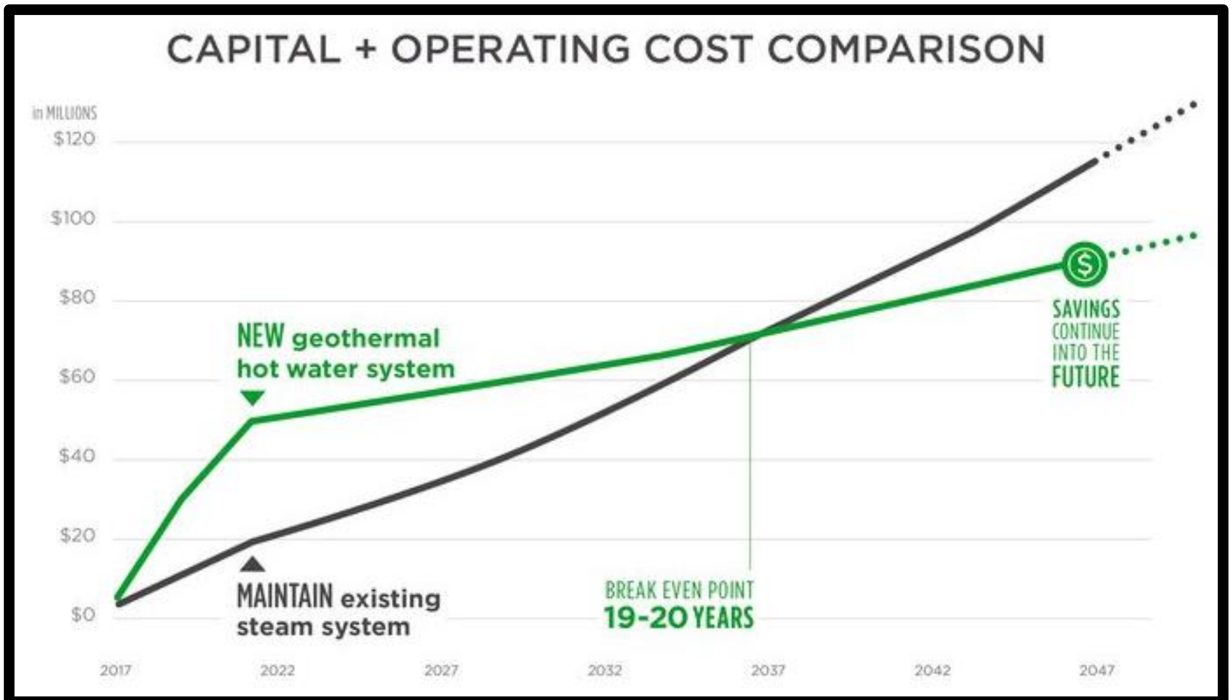

Figure 6 *(Up)****:*** *The Carleton College Utility Master Plan models the Capital and Operating cost comparison between their existing steam system and their new geothermal hot water system from 2017-2047 [20]*

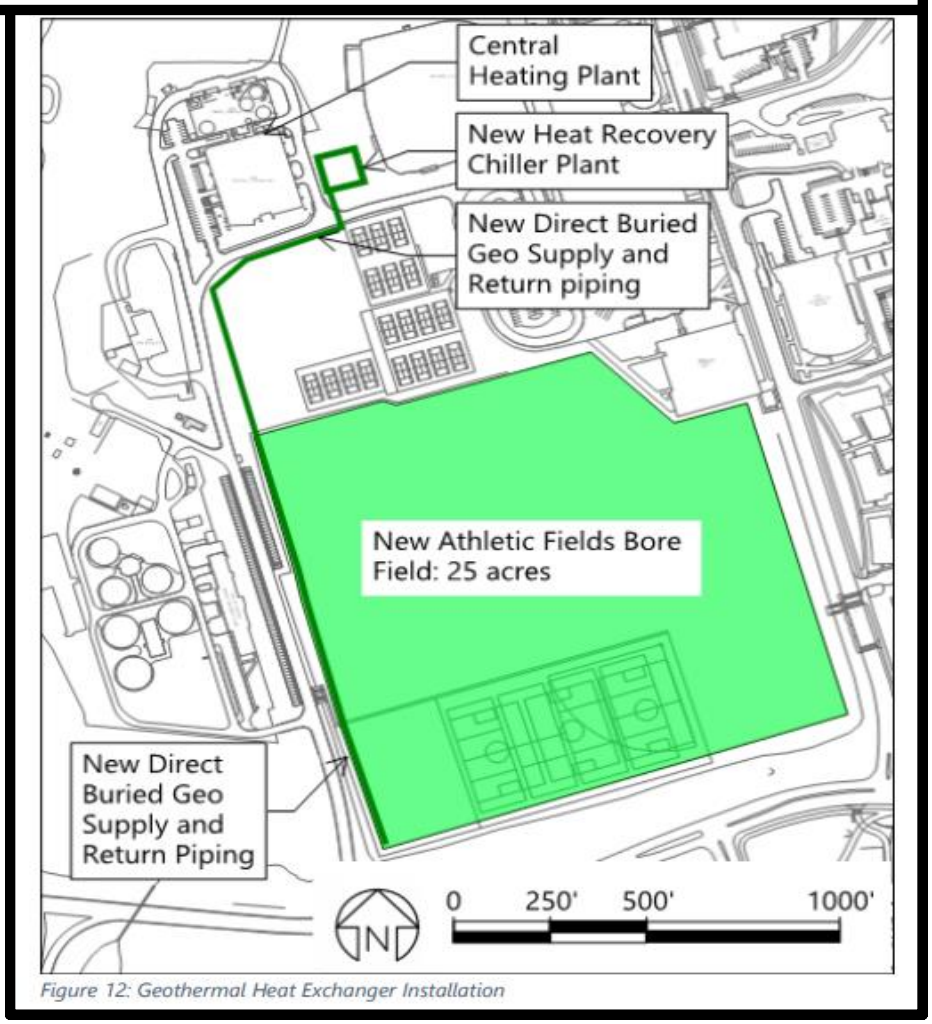

Figure 7 *(Right)****:*** *This figure from the Carbon Mitigation Plan outlines the area of the proposed bore field, piping, and heat recovery chiller plant [5]*

Our Suggestion and Reasoning

Once again, a ground source geothermal heating and cooling system provides heating and cooling efficiently while using renewable sources and avoiding carbon emissions. While this system does bring with it a large capital investment and disruptions to activities and land due to installation, the operational, maintenance, and carbon savings overtime along with the step-by-step approach of installations. offset the large initial cost and lessen community burdens. The physical installation of the bore fields, piping, and heat recovery chiller plant will be done next to the Central Heating Plant and the athletic fields south of the Central Heating Plant, as seen in Figure 7 and the title image [5]. With all these aspects taken into account, a ground-source geothermal system is the best fit for providing heating and cooling to the UMass campus and achieving the goal of a net-zero carbon emission campus by 2030.

Section 6: Conclusion

While a geothermal heating system could prove to be a significant advantage for UMass' heating demands, its initial $96 million price tag leads us to the question "Is it worth it?" To start approaching the answer, we performed an economic analysis of a geothermal heating system to compare the technology to carbon capture and storage. If we consider geothermal heating against the social cost of carbon and carbon capture alone, we find that UMass' proposed geothermal system presents the largest cost of the three until around 2047. However, incorporating the costs of fuel and maintenance for the CHP, we find that the combined operation of the CHP and CCS exceed the cumulative cost of a potential geothermal heating system after only five to six years of operating them both (based on the intercept between the green and grey lines in Figures 4 and 5). Since the CCS technology is founded on the CHP's continued operation, we find a geothermal system to be a financially advantageous option over carbon capture.

We also consider a geothermal heating system to be valuable for UMass' long-term goals and potential for a green future. For example, not only could it mitigate 37% of the carbon emissions of campus, but it would do so by avoiding carbon emissions altogether (given that the system would be powered by a renewable electricity source). On the contrary, albeit the carbon capture technology could reduce the CHP's emissions by 90% [5], it would still allow carbon dioxide to enter the atmosphere and it would not lead UMass to an emission-free future. At the same time, a geothermal system is an integral part of the CMTF's Carbon Mitigation Plan. It is expected to carry 20% of the campus's heating load and 51% of the cooling load, and it is supported by the planned Low Temperature Hot Water System also proposed in the CMTF [5]. The technology even creates the potential for new technologies and ideas that were not included in the CMP. For instance, another iCons team dedicated themselves to researching solar thermal asphalt, a technology not proposed in the CMP, but which could help the geothermal heating system compensate for unbalanced heating and cooling demands [23]. Overall, our evidence shows that a geothermal heating system can not only be incredibly valuable for campus's heating demands, but it can also build the foundation for UMass' future as a university and as a green institution. Therefore, despite the initial price tag, we assert a geothermal heating system to be a *necessary* and *logical* solution for UMass' net-zero mission. Furthermore, if we hope to meet the deadline for 100% renewable energy, a geothermal heating system is a promising means to get us there.

Acknowledgments

We could not have completed this project without the support and guidance of many of our mentors. We would like to thank everyone who helped us demonstrate the potential of geothermal energy for UMass campus.

- ❖ First, we would like to thank Ezra Small, a leader in the Carbon Mitigation Task Force and a friend to all of us on the team. Not only did you provide us with many valuable resources and contacts, but you also were always willing to help us no matter how busy you were. Even through the very end of this project you were always there for us.
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- ❖ Ms. Martha Larson, the manager of campus energy and sustainability at Carleton College, allowed us to have access to information regarding the geothermal heat exchange system implemented on her campus, and allowed us to reference a situation similar to ours when we thought one did not exist.
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Appendix

1. <u>Amount of UMass Campus Emissions Produced by CHP</u> (Source: [4])
   Campus Emissions from Natural Gas for CHP ≈ 69%
   Campus Emissions from LNG = 11%
   Campus Emissions from ULSD = 5%

   Total Campus Emissions from CHP = Natural Gas + LNG + ULSD ≈ **85%**

2. <u>The Power Equivalent of CHP Steam Production</u> (Sources: [6,8,9])
   Steam produced by CHP ≈ 1.2 billion lbs./year
   1.2 billion lbs. of steam * (970.8 Btu/lb. of steam) ≈ 1.16 trillion Btu/year

   Average Northeast household electricity usage = 8211 kWh/year
   8211 kWh/year = 29.6 million kJ/year = 2.801 million Btu/year

   CHP Power = 1.16 trillion Btu / 2.801 million Btu ≈ 41580 homes

3. <u>Estimated Efficiency of the CHP</u> (Sources: [5,6])
   CHP Output (Heat and Electricity)
   Steam produced by CHP (for heating) ≈ 1.2 billion lbs./year
   1.2 billion lbs. of steam * (970.8 Btu/lb.) ≈ 1.16 trillion Btu/year

   Electricity generated by CHP (cogen) ≈ 140000 MWh * 0.7 ≈ 98000 MWh ≈ 0.33 trillion Btu/year

   CHP Input (Fuel)
   Fuel Requirements (Natural Gas+LNG+ULSD) ≈ 2,000,000,000 Btu/year

   CHP Efficiency (Output/Input)
   (1.16 + 0.33) trillion Btu/year / 2.0 trillion Btu/year ≈ 74.9% efficient

4. <u>Estimated Operational Costs of UMass' GHX System</u> (Sources: [5, 15])
   Operational Costs for Ball State Geothermal System: $1.8 million/year

   Capital Investment for Ball State GHX: $82.9 million
   Capital Investment for UMass Amherst GHX: $96 million

   Assumption 1: Size of heating+cooling load at UMass/Same at BSU = UMass CAPEX/BSU CAPEX
   Assumption 2: OPEX proportional to size of heating+cooling load

With these …

Estimated Operational Costs for UMass Geothermal System:

$1.8 million x (96/82.9) ≈ $2.1 million/year

5. Price per Metric Ton of Carbon Avoided (Sources: [5,16,17,19])

GHX price/MTCO$_2$e after first year of operation (starting in 2032)

($96 million + ($1.8 million * $96 million/ $82.9 million) * (1 year) / (46,000 MT/CO$_2$e * 1year) ≈ $2,100/MTCO$_2$e

CCS price (average)/MTCO$_2$e after first year of operation (starting in 2032)

($19 million + $6.5 million * (1 year) / (113,125 MT/CO2* 1 year) ≈ $230/MTCO$_2$e

Social Cost of Carbon (2032)

Assuming discount rate of 5% (constant increase of 5% per year)

$50/MTCO$_2$e (1 + 0.05%)^{12} ≈ $89/MTCO2e

GHX price/MTCO$_2$e by 2047

($96 million + ($1.8 million * $96 million/ $82.9 million) * (16 year) / (46,000 MT/CO$_2$e *16 year) ≈ $175/MTCO$_2$e

Social Cost of Carbon (2047)

$89/MTCO$_2$e (1 + 0.05%) ^{16} ≈ $186/MTCO$_2$e

CCS price/MTCO$_2$e by 2047

($19 million + $6.5 million * (16 year) / (113,125 MT/CO$_2$e * 16 year) ≈ $69/MTCO$_2$e

6. Total Costs of the CHP and CCS Combined (Sources: [5,19])

CHP cost after one year of operation (starting in 2032)

Natural gas + LNG + ULSD + Maintenance Costs ≈ $19.6 million

(Note: Fuel and Maintenance prices vary by year, ranging around $1 million - $7 million)

CHP and CCS cost combined after one year of operation (starting in 2032)

CHP + CCS$_{average}$ ≈ $45.9 million

Total funds paid for CHP by 2047 (including all years from 2032 - 2047)

Natural gas + LNG + ULSD + Maintenance Costs ≈ $376 million

Total funds paid for CHP and CCS combined by 2047

CHP + CCS$_{average}$ ≈ $501 million

7. Total Costs of GHX, 70% UMass Electricity, RECs Combined (Sources: [5,16,17,19])

70% Electricity Cost starting in 2032

(Note: "Business as Usual" (BAU) projections are shown to mimic the conditions under which the CHP produces electricity as much as possible)

BAU Purchased Electricity Cost, projected in **2030** (for 30% of campus) ≈ $6.8 million
BAU Purchased Electricity Cost, projected in **2030** (for 70% of camps) ≈ $6.8 million * (7/3) ≈ $15.9 million

BAU Additional Funds Spent on 70% Electricity Demand ≈ $4.5 million/year (based on linear trend of cost projections)

BAU Purchased Electricity Cost, estimated in **2032** (for 70% of campus) ≈ $15.9 million + ($4.5 million/year * 2 years) ≈ $25.0 million

RECs Cost starting in 2032

(Note: The assumed electricity demands are the same as the amount of electricity projected to be generated by the CHP under BAU conditions. These assumptions are made to make GHX and CHP comparisons as evenly scaled as possible.)

70% of Projected Electricity Demands in **2030** (BAU) ≈ 1.2 x 10^5 MWh
Expected Cost of RECs ≈ $30/MWh
REC Costs for 70% of Electricity Demands in **2030** ≈ $30/MWh * 1.2 x 10^5 MWh ≈ $3.7 million

BAU Additional FUnds Spent on RECs ≈ $0.75 million

REC Costs for 70% Electricity Demands in **2032** ≈ $3.7 million + ($0.7 million/year * 2 years) ≈ $5.2 million

GHX Cost starting in 2032 (first year of operation)

CAPEX + OPEX * 1 year
= $96 million + ($1.8 million * $96 million/ $82.9 million) ≈ $98.1 million

Combined Costs starting in 2032

70% Electricity + RECs + GHX ≈ $128 million

Combined Costs by 2047

Total Funds Paid for 70% Electricity Demand ≈ $92.6 million
Total Funds Paid for RECs ≈ $16.4 million
Total Funds Paid for GHX ≈ CAPEX + (OPEX * 16 years) ≈ $130 million
(*For comparison: Cumulative Costs for CHP and CCS by 2047 ≈ $501 million)*

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