Roads to Renewable Energy: Solving the Geothermal Heat Deficit with Solar Thermal Asphalt

i2E Roads to Renewable Energy Team

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I. Executive Summary

As UMass makes the shift to become carbon neutral by 2032, one of the most important considerations is how to heat campus sustainably, given that 80% of total emissions are attributed to heating and cooling demands. One of the main ways this will happen is through the transition from the current Central Heating Plant to a more sustainable geothermal heating and cooling system (GHX). However, the proposed geothermal system will not produce enough heat to supply campus on its own. Our team is proposing implementing solar thermal asphalt in Mullins Way, adjacent to this system, to supplement the geothermal heat. This road will be able to provide supplementary heat to the underground reserves with minimum disruption on campus, and at a fraction of the cost of other proposed solutions.

II. Introduction

` As the population and campus of UMass Amherst continues to grow, so will the demand for heating and cooling buildings on the campus. In order to meet this demand while maintaining Chancellor Subbaswamy's goal to reach net zero emissions by the year 2032, UMass plans to replace burning natural gas for heating and cooling in favor of a geothermal cooling and heating system (GHX) [1]. Unfortunately, geothermal heating will not be a sustainable solution to our heating problem on its own, so an efficient supplemental heating source needs to be implemented as well. To address this problem, we propose augmenting the current GHX system with a solar thermal asphalt system, in which we will harness absorbed heat from the ground to provide an additional heat supply. Although the Carbon Mitigation Plan mentions other heating alternatives meant to address the lack of heating, asphalt solar collectors are a more cost-effective option. In this paper, we will propose where solar thermal asphalt should be installed on campus, how the solar heat should be captured, and present cost estimates and comparisons to other proposed systems. Successful implementation of solar thermal asphalt will bolster the heating capacity of the geothermal system to better suit UMass Amherst's heating and cooling demands in a cost-effective, sustainable way.

III. Problem Statement

Because we live in a colder climate, our annual heating demand exceeds our annual cooling demand. Over time, the GHX will decrease in effectiveness and sustainability. This happens because in the winter, we will be pulling more heat from the ground to heat the campus than we put back into the ground in the summer while cooling the campus. After many years, the ground will cool down, and we will not be able to pull as much

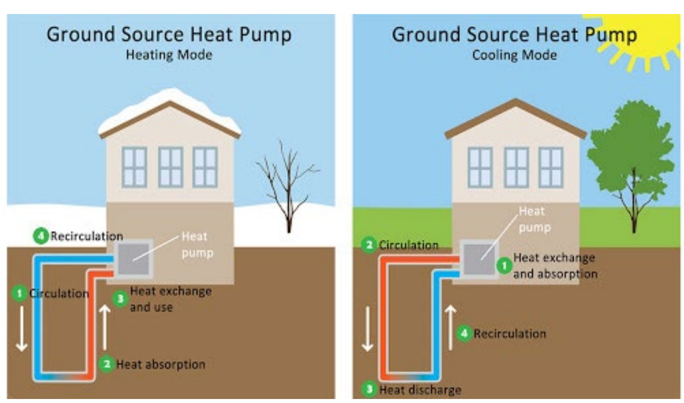

Figure 1. The heat extracted from the ground in the winter will exceed the amount of heat replenished in the summer, resulting in a net cooling of the ground below [2].

heat out of it. So, while the proposed geothermal system could provide over half of our campus cooling load in 2032, it would provide only about 20% of the annual heating load [1]. This means that we will need other sources of heat to fully heat our campus. To be able to use the geothermal process to its full potential, there will need to be a supplemental heat source assisting in the summer months by replenishing its heat reserves. This supplementary form of energy should also function synchronously with both the GHX and wastewater recovery systems so we can ensure that both systems complement each other's functionality.

In addition, our campus only has a limited amount of space, so we need to find a way to supplement that geothermal energy without disrupting more existing infrastructure. Even with the limited amount of space, building more sites causes a disruption to the environment and leads to larger impacts on ecosystems that would need to be accounted for. Currently, the proposed geothermal system requires the drilling of 2,490 bore holes, each 800 feet deep, in 25 acres of existing athletic fields [1]. The alternative proposed supplementary sources of heat would also require a lot of space. For example, wastewater recovery requires the installation of a new 12,000-gallon underground wastewater holding tank [1]. Our goal is to find a solution to the heat deficit that will not cause so much disruption to existing infrastructure or nature on campus and can instead be integrated into existing infrastructure.

Right beneath our feet, there is an energy source that is not only overlooked as a renewable source of heat but is contributing to carbon emissions on campus. It is widely known that the roads get hot on a sunny day, but is often looked at as just a fact, where we see it as an opportunity. The asphalt that is used to pave our roads can reach temperatures of up to 70 degrees Celsius on an average summer day [2]. Not only does this mean that there is untapped energy already existing in our pavement on campus, but it also contributes to a 'heat island effect' that increases the temperature in the surrounding area [3]. In turn, this increase in temperature leads to an increase in air conditioning usage on campus, which releases greenhouse gas emissions [3]. Finding the best way to harness this energy would both help cool down the surrounding area in the summer and increase the capacity of the geothermal system to heat buildings on campus in the winter.

While we believe this is a viable supplement to the proposed geothermal system, there is still research that needs to be done to determine the effectiveness of solar thermal asphalt on the UMass campus. We need to locate the optimal place to implement it, find out what type of asphalt would be the most effective at harnessing solar thermal energy, and decide how exactly to store that energy. Since UMass will be spending time and money implementing this project, implementation should be done so that the system is as efficient as possible. Studies conducted at Worcester Polytechnic Institute show that the energy collected from solar thermal asphalt can vary depending on pipe diameter, heat exchanger installation depth, and type of material used in paving the road [4]. To build from this, we need to find the optimal choice for each of these factors before implementing this solution at UMass.

IV. Solution Tech and Implementation

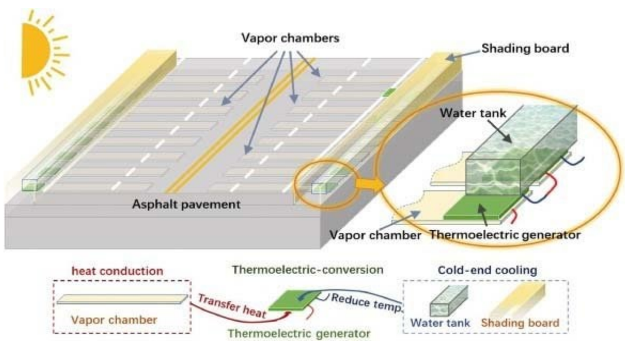

Figure 2. A cross-section of a solar thermal asphalt system [6].

Solar thermal asphalt works by harnessing the untapped energy resource via water flowing in tanks underneath the asphalt. As seen in figure 2, water chambers installed below the asphalt, sandwiched between shading boards and thermoelectric generators, are filled with water that heats up as the sun beats down on the road, producing low-temperature hot water [6]. This solution has the potential not only to assist with hot water and heating loads in nearby buildings, but it also reduces the temperature of the asphalt above by up to 10 degrees Celsius in the summer and has the potential to melt snow and ice collected on the road in the winter [6].

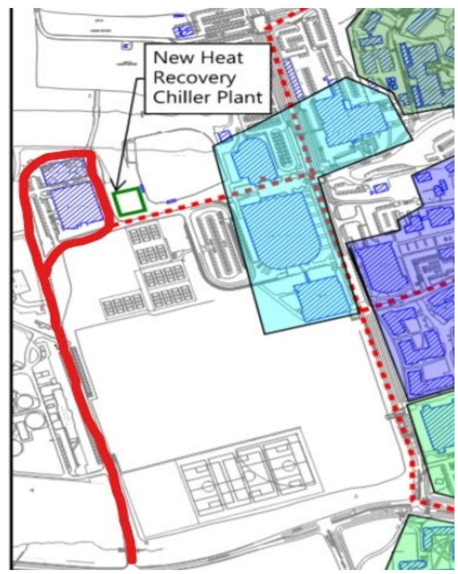

Figure 3. Proposed location of solar thermal asphalt shown with solid red line.

While UMass has many miles of roadways under its jurisdiction, it will not be cost-efficient to retrofit all these roads with solar thermal asphalt. It costs about $140 to install a square meter of solar thermal asphalt [7]. Therefore, retrofitting all of UMass' 18.8 miles (260 thousand square meters (about the area of a large shopping mall)) of roadways would cost approximately $36.4 million, which is unreasonable [8]. Instead, we propose retrofitting only the asphalt on Mullins Way, as seen in figure 3, to capitalize on the proximity to the geothermal system that will be installed adjacent to the athletic fields near the Central Heating Plant [1]. This would result in a total of about 8,200 square meters of solar thermal asphalt, costing an additional ~ $1.15 million, which is comparable to other solutions outlined in the Carbon Mitigation Plan. Also, because roads need to be repaved every 10 to 12 years regardless, the university could save on labor costs by implementing this system during scheduled maintenance of Mullins Way [5]. According to the American Road and Transportation Builders Association, it costs ~ $1.25 million per mile to mill and resurface a four-lane road [9]. The length of Mullins Way is 0.7 miles, and it is a two-lane road, so the cost will be ~ $437,500. Because this is a cost that the university will already be spending, it does not need to be considered when thinking of the cost to retrofit a road with solar thermal asphalt. Overall, the $1.15 million price tag for this project is reasonable and worth it to spend in exchange for the clean energy that will be produced.

A Study done in 2013 by a team of researchers in the Netherlands gave backing to solar asphalt roads as a feasible and efficient means of heating. Their claim also holds true to UMass implementation as our own calculation indicates savings in cost for a considerable gain in energy production. The results of the study found that their solar asphalt collectors resulted in 50% reduction in cost related to energy and greenhouse gas (GHG) emissions [11]. They were able to generate 288W per square meter of energy by implementing 2250 square meters of solar asphalt with an inlet water temperature of 15C at a construction site located in the Netherlands [11]. The asphalt collectors were also capable of producing 288 watts of energy per square meter, which was a total of 63,000 watts generated by their road. Based on the assumption taken from the study, we can estimate that our 8200 square meter asphalt collectors will generate 9184 MWH of energy, which would account for 2% of the campus total energy needs and a 5% contribution towards GHG heating. A 2% GHG reduction in the carbon Mitigation plan would mean it is on par with waste heat recovery at 3.8% and higher than Air source cooling at 1.7%, thus eliminating the necessity for air source cooling/heating and reducing the scale of heat recovery for heating and cooling [1]. This would mean that the $2.6 million budget allocated for Air Source Cooling could be allotted towards solar thermal asphalt collectors without incurring any additional cost for over a 1% margin in energy savings. This is also without taking into consideration the added energy production because of optimizing the parameters mentioned previously.

Our Asphalt roads would be strategically placed close to the Central heating plant and GHX system to minimize the cost and size of pipes which connect to the LTHW distribution systems. If it is implemented next to the Central Heating Plant and geothermal system, we believe it would be feasible to feed the produced low-temperature hot water into the new Heat Recovery Chiller Plant with slight modifications to the distribution piping and pumps that will already be installed to accommodate the geothermal heating and cooling system [1]. From there, the low-temperature hot water can be distributed to buildings via the new hot water distribution piping proposed in the Carbon Mitigation Plan [1]. This way, we can conserve space and save money by utilizing existing space in the Central Heating Plant and piping that UMass is already planning to install.

Roads are typically repaved every 10 to 12 years, so the solar thermal asphalt system could be installed when Mullins Way is scheduled for repaving [5]. When building solar asphalt collectors there are additional factors which need to be considered to maximize the efficiency of this system. Factor which includes choosing a composition of concrete that best captures solar energy, establishing length and depth of pipes used underground as well as establishing the best route that allows for connection with GHX recovery chillers. Thus, a successful implementation of the solar asphalt collector will require input from a host of disciplines and professionals which UMASS faculty members can take an active role in. A well will require collaboration with an array of disciplines in which faculty members can contribute to. Accounting for these variables will likely lead to subtle deviations in the cost but the cost increase will be offset by improvements in its ability to generate energy. Since we are still in the initial phase of developing our implementation, it would be exceedingly difficult to predict how cost will be subject to change after optimizing all these factors. That being said, we have compiled studies which provide ways of optimizing several of the factors involved in the implementation along with numbers that support their claim. Among the studies is a research conducted at Worcester Polytechnic Institute which concluded that incorporating a highly conductive aggregate, such as quartzite, into the asphalt makes the heat transfer in solar thermal asphalt more efficient, as does painting the surface of the pavement with a reflectivity reducing paint [11]. Another factor in maximizing the temperature of the fluid flowing through the asphalt is the diameter of the pipes in which the fluid is flowing—a smaller diameter results in a higher temperature [12]. The heat-absorption capacity of the fluid used is also a consideration, and as such we propose using either water, glycol, or hydrocarbon oils to flow through the asphalt [13]. Finally, placing the heat exchanger at an optimal depth below the surface will help make the system as efficient as possible [11]. Bearing in mind road safety and quality, the Solar Asphalt collectors need to be implemented in such a way that does not pose any dangers or hazard for cars, so making sure that the roads are structurally sound and congruent with the rest of UMass roadway is extremely important.

Implementation of this solar thermal asphalt would be the most efficient way that UMass can offset its heat deficit problem. We hope to take advantage of the repaving of roads that occur every 10 to 12 years to convert the roads to allow for more energy generation. If optimized, this solution stands out as a strong candidate for an alternative heating supply to the geothermal heating systems.

V. Project Pros and Cons

Through our implementation plan, we will attempt to make our solution as efficient as possible to make it one of the most viable solutions. While no solution is perfect, we believe that the pros of solar thermal asphalt outweigh the cons because of the project's relative simplicity and the few negative social and environmental impacts compared to the benefits of the clean heat produced.

The main benefit of this project is that it will produce clean energy that can be used on campus and contribute to UMass' goal to be carbon neutral. Because solar thermal asphalt systems can generate 288 watts per square meter, implementing 8200 square meters (about the area of a Manhattan city block) of solar thermal asphalt in Mullins Way will result in the production of 9446 megawatt-hours of clean energy [7]. This would account for 2% of the total energy needs for the UMass campus, and 5% of the energy needs for the geothermal heating and cooling system [1]. This transition to clean energy use will reduce the 120,000 metric tons of CO_2 currently emitted from the Central Heating Plant every year [1]. Thus, it is helpful in reaching our goal of campus carbon neutrality.

Another pro of this project is the minimal disruption of the area of installation. This, in turn, makes most of the negative environmental impacts so minor that they are negligible. However, to maintain full transparency, it is still important to mention them and acknowledge them.

A new issue in the environmental community that has started to become more apparent in the last few years as more research comes out is the substantial amounts of CO_2 that is contained in the soil, and when you disturb that soil, you will be releasing that CO_2 into the atmosphere adding to the greenhouse gas effect. Since the project will be built off an existing road, there will not be as much of a depth dug, but there will still have to be some due to the installation of the pipes and the transportation pathways. According to a study done by the Department of Primary Industries and Regional Development in Australia, the highest percentage of CO_2 is found in the top 10 cm (about the length of the long edge of a credit card) of soil [14]. Taking this into account, it can be noted that that level of disturbance has already happened during the initial installation of the road, so this factor is not one that needs to be taken heavily into account.

Because solar thermal asphalt collectors absorb and transfer heat away from the road, the temperature of the road will not fluctuate as intensely, and the lifespan of the road will be increased. Solar thermal asphalt can therefore reduce maintenance costs associated with repairing roads in the summer by displacing heat from the surface of the road. A decrease of 5 degrees Celsius in the surface layer is expected to extend the life cycle of the pavement by up to 5 years [15]. However, we still must consider factors that can cause damage to the roads when the system is implemented. There are a few common damages to the road such as cracking, rutting, disintegration, etc. [16] And they are the sequences of inaccurate pavement thickness, or weak asphalt mixtures [16]. Placing the heat pipes inside the roads takes some extra volume and might change the conventional amount of asphalt mixtures to construct the roads. Thus, when implementing solar thermal asphalt into the roads, consultation with the road repaving team is necessary to ensure the longevity of the roads.

As these new roads are implemented more, to add to our clean energy output, we will also see a decrease in the 'heat island' effect [5]. This will in turn reduce the annual campus cooling load because students will use air conditioners and fans less frequently if the outside temperature is cooler, and that will in turn reduce our emissions even further.

In terms of cost, based on our research, solar thermal asphalt collectors will generate as much energy as alternative sources of heat mentioned in the Carbon Mitigation Plan for a fraction of their cost. We looked at the cost of implementing the roadways across 8200 square meters and we estimated the total to be in the ballpark of $1-1.5 million dollars. Our calculations were based on a case study implementation done in a construction site in the Netherlands which factored in costs of materials and labor to arrive at an average cost of $140 per square foot of installations [7]. Assuming we use the same parameters as the study, our cost would reflect a total of $1.14 million but considering further adjustments we are likely to make to better suit our needs, we suspect that the cost will be closer to $1.5 million. Based on the cost analysis we provided in our solutions section, the implementation of solar asphalt collectors is an economically viable option.

For many environmental projects, the focus of the issues will fall mainly on the impacts on the environment, and the surrounding community is not considered. Through this project, there are minimal social equity impacts because of the location of implementation. As mentioned often in this explainer, the large benefit of this solution is how no additional infrastructure needs to be implemented. This is an added social benefit because there will be no displacement of homes, businesses, or recreational areas as there would be if a new facility needed to be built as well. One disruption that would need to be taken into consideration would be during the time of construction. Mullins Way happens to be the only access road to the Wastewater Treatment Plant. During the time of implementation, the employees of the plant would not have access to their building. However, we have decided that this con is very minimal because access to the road will only be restricted to a few days at maximum. This issue can also be reduced by the specific time that the work is put in place.

VI. Conclusion

Seeing all the work that has been done in the past year by the Carbon Mitigation Taskforce, faculty, students, and administration truly is remarkable. The world is facing a crisis in the form of climate change and the dedication and collaboration that is happening right now gives us hope for the future. There are many possible solutions to the initial problems found in the Carbon Mitigation Plan, so it takes many minds from many disciplines to find and solve them. Each member of our team is from a different background and a different concentration area and that has helped us be able to address the issue from all sides.

Our investigation into the viability of installing solar thermal asphalt on the UMass Amherst campus has shown that it is not only viable but is also a sensible and cost-effective way to help solve the problem we focused on. To maintain cost-effectiveness, we recommend implementing solar thermal asphalt under Mullins Way when it is next scheduled for repaving to save installation time and cost.

Getting the university to net zero carbon emissions will not be easy and will not be accomplished by a singular solution. Because the heating and cooling load accounts for 80% campus's emissions, it is imperative that we implement a new and reliable source. Combining the GHX system and solar thermal asphalt will bring us closer to our goal of net zero emissions.

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VIII. Acknowledgements

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IX. Appendices

1. Calculation for total area in square meters of Mullins Way:

Total Length of Mullins Way: 0.7 miles
Width of standard 2-lane Road: 24 ft
Miles to Feet Conversion: 1 mi : 5280 feet
Feet to Meters Conversion: 1 ft : 0.3048 m
Total Road Length in m = 0.7 mi * 5280ft/1 mi * 0.3048m/1 ft = 1126.54 m
Total Road Width in m = 24 * 0.3048m/1 ft = 7.32 m

Total square m = 1126.54 * 7.32 = 8240.87 ~ 8200 square meters

2. Calculation for repaving cost of Mullins Way:

Total Length of Mullins Way: 0.7 miles
Cost to repave standard four-lane road: $1.25 million/mile
$1.25 million * 0.5 (half the number of lanes) * 0.7 = $437,500

3. Calculation for total KWH of energy produced:

Conversion assumption: 250 W/m^2 ~ 1000 kWh [12]
Predicted energy generation per square meter: 288 W/m^2 = 1152 kWh
Energy across entire planned road: 1152 kWh * 8200 m^2 = 9446 MWh (9.44e6 kWh)

4. Calculation for the cost per metric tons of CO2:

Conversion equation: 7.09×10^{-4} metric tons CO2/kWh [17]
Metric tons of CO2 = ($7.09 * 10^{-4}$ metric tons CO2/kWh) * (9184 MWh * 1000kWh / 1MWh)
= 6511.46 metric tons
Cost per metric ton of CO2 = $1,150,000 / 6511.46 metric tons CO2 = $177 / MTCO2e