Evaluating Feasibility and WPI Community Opinion for Implementing a Hydrothermal Liquefaction Reactor at WPI

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by
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Abstract

To make Worcester Polytechnic Institute (WPI) more carbon neutral, this project investigates the feasibility of implementing a hydrothermal liquefaction (HTL) reactor on WPI's campus. An HTL reactor takes food and green waste and converts it to biofuel. We interviewed leaders in Chartwells and the facilities department to estimate the total waste available to the reactor. We used these estimates to interview experts in HTL to determine reactor specifications. We also surveyed WPI community members on how they viewed this reactor and if students were willing to help fund it. We found this reactor would be feasible, as we produce enough food waste to justify the use of the reactor, and that there is community support.

Executive Summary

Project Statement

Our IQP group was given tangible findings of an MQP report titled *An Evaluation of Mixed Feedstocks for Producing Bio Crude Oil Through Hydrothermal Liquefaction and Its Potential Use at WPI* that suggested that a hydrothermal liquefaction (HTL) reactor could be implemented on campus to power WPI's vehicles and possibly some of the buildings. This resulted in our IQP researching the social implications and stakeholder consequences of implementing such a reactor at WPI. An HTL reactor would use WPI's food waste and green waste to produce biocrude oil. This oil could be used in traditional heating systems and with a refinement process, can be used in cars and trucks with biogasoline and biodiesel, respectively. In addition to using this oil on campus, this reactor could be converted to make biogas, which could run a generator to produce electricity.

Introduction

Our planet is currently approaching the point of no return to take action against climate change. Within the next hundred years, Earth's temperature could rise by nearly 2 to 4 degrees Celsius if preventative measures are not taken (Parry, Lowe, Hanson, et.al, 2009). Many scientists agree that this increase in temperature will have catastrophic ramifications. Nearly all scientists agree that this warming is a direct result of the greenhouse effect, which is the process of Earth's atmosphere trapping more heat due to an increase in greenhouse gasses. To solve this problem, many scientists recommend taking actions that can help us reduce our carbon footprint (Sources of Greenhouse Gas Emissions, 2021). One solution that seeks to mitigate this rising issue is renewable energy, in the form of bioenergy through the process of hydrothermal liquefaction reactors (Patel, Zhang, Kumar, et.al, 2016). These reactors are capable of taking food and green waste, and converting it into energy in the form of biocrude oil or biogas. Using food waste to produce biofuels also tackles another issue that has been growing in First World countries, food waste.

Here at Worcester Polytechnic Institute (WPI), a small college campus located in Worcester Massachusetts, there is a consistent amount of waste produced each year (Murphy, 2020). To minimize this waste and reduce WPI's carbon footprint, a project studied the possibility of implementing an HTL reactor on campus. The study explored different types of feed for the reaction, and concluded that a ratio of 75% food waste and 25% green waste was ideal for HTL reactions to produce large amounts of biocrude oil yields (Murphy, 2020). Using statistics of the food waste produced on campus, it was determined that if all of WPI's food waste went into producing biocrude oil in this reactor, the project's predictive models showed that WPI would produce enough energy to power all on-campus vehicles for a year. Thus, this project looks to explore the practicality of implementing an HTL reactor at WPI by conducting a feasibility and public opinion study.

Methodology

In order to conduct a proper feasibility and social implications study, our methods were broken into three main objectives, which were completed to fulfil our project goal:

1. Obtained an estimate of the amount of food and green waste WPI produces, and then estimated how much of that waste could be collected for use in a reactor.
2. With waste estimates, the team spoke with experts in the field of hydrothermal liquefaction to determine reactor specifications.
3. Utilizing the new found knowledge, the team sought to gather the public opinion of WPI community members

In order to obtain an estimate of the amount of available fuel, the team spoke to the heads of Facilities, and Chartwells Dining Services, respectively. When speaking with Facilities, the team's objectives were to determine the amount of green waste, where it is currently disposed of, and if it would be possible to redirect to the reactor. In conjunction with the green waste discussions, the team also sought to learn more about the food waste profile here at WPI. When speaking with Joe Kraskouskas, Director of Dining Services, the goal was to determine the amount of food waste, where waste is currently disposed of, how much money was spent disposing it, and if it was possible to relocate the waste to the proposed reactor. After conducting these interviews, the team had an estimate of the available waste to feed the reactor.

Once the waste profile was determined, the following objective was to determine the specifications and costs of implementing a reactor. The team completed this objective by conducting interviews with two different companies specializing in HTL technology. When speaking with the two companies, Mainstream Engineering, and the Genifuel Corporation, we asked questions concerning size, cost, energy production, complications, and utilities requirements. Utilizing these estimates, the cost of funding this machine was determined, identifying the forms of energy produced were presented, and the necessary information to develop a survey for WPI community members was attained.

A survey was devised for students, staff, and faculty to understand the public opinion on implementing an HTL reactor. Understanding the public opinion was a crucial step in the study because campus community members could be directly affected by this reactor’s implementation. The questions pertained to the importance of green initiatives, how waste is disposed of, support of the reactor given noise or smell, and community support if there was academic merit to the machine. Once collected, this information allowed the team to interpret and determine support for the reactor. Combining this information with information the experts had given us allowed the team to come to a conclusion on the feasibility of the reactor.

Key Findings & Discussion

After interviewing with the head of facilities, and the head of Chartwells, we learned WPI produces 75 tons of food waste, and 20 tons of green waste a year. Currently, this food waste is donated to Tyde Brook Pig Farm and the green waste is stored on campus. Tyde Brook and Chartwells have a good relationship and would be unlikely to cut ties, however, if they did, Chartwells would have to pay to throw away its food due to Massachusetts law. As for facilities, we learned it would be possible for them to transport the leaves to an on campus reactor as this would be as simple as moving leaves from one spot to another, something they already do. This information allowed us to talk to our experts at Genifuel and Mainstream Engineering. From them, we learned that this reactor would cost anywhere from 1 to 2 million dollars to build with a loss around a 100 thousand dollars per year due to maintenance and operating costs. However, WPI recently obtained a grant for 2 million dollars to implement a similar type of technology (Holbrook, 2021). Thus, our team believes a similar grant could be used to fund the implementation of an HTL reactor. Our survey found that nearly half of our students would support an increase to tuition or fees of at least 50 dollars. If each student were to pay 25 dollars, a conservative estimate of 4500 undergrads could produce $112,500 dollars per year. Thus, the annual costs could be covered.

After considering cost, the team needed to determine if this reactor could actually be implemented. When we interviewed the HTL experts, we were assured this would not be an issue as both of the companies were willing to make and install this reactor for WPI. The reactor would come in a nearly 500 square foot metal container, where it would be housed. A container would need to be connected to electricity, and have a water and natural gas source. However, these are standard procedures for each of these companies and the experts did not foresee any issues connecting to these utilities.

Additionally, both experts agreed that students and faculty would be the ones who could run this reactor the majority of the time. Moreover, they both suggested training someone in the facilities department about general reactor operations so this person could be on call if anything were to go wrong, and also to perform and plan regular maintenance, suggesting WPI will not need to bring in an entirely new team to implement an HTL reactor.

One thing that was repeated to us by the experts we interviewed was the academic benefits this reactor could provide. The Genifuel team described how WPI could modify and customize the reactor in order to conduct research and run experiments. Beyond that, chemists can learn from the composition and reaction going on inside the reactor.The reactor offers potential to get first-hand experience in learning fluid mechanics and studying how slurries flow. Automation, signal processing, and controls could all be an interesting topic of exploration for electrical engineers. Math majors could make models of the process and expected yields with different amounts of inputs. Systems engineers could find the most efficient method of delivering the food waste to the reactor site. Lastly, software engineers could look at how the machine runs and develop new applications to make it easier to use. The possibilities are plentiful.

The reactor poses community benefits that could arise from a project like this. After taking our survey, Anne Ogilvie, Director for Team Learning in the Integrative & Global Studies department at WPI, reached out to the team and offered feedback and ideas. Anne pointed out that "public engagement is an extremely important component of sustainability, and so it would be excellent if the facility could not just benefit WPI, but our neighbors as well." She asked if other schools and organizations could also take part in donating their food waste. She also asked if this project could be a learning opportunity for local schools. Getting K-12 students learning about what happens to our food waste is important to spread awareness to the food waste problem in the United States.

This reactor has demonstrated to be feasible for WPI's campus. The survey showed significant community support, as well as evidence this project could serve to produce energy and reduce our carbon footprint. Additionally, obtaining more food waste could help this reactor become more efficient, and it allows it to produce more energy. If an alternative source of food can be found, then ties with Tyde Brook Farm will not need to be cut. Lastly, a future project should investigate receiving a grant to buy this technology, and also investigate implementing a "Green Tax" to pay for annual costs.

Conclusion

Implementation of a hydrothermal liquefaction reactor requires a building, funding, operators, logistical systems, and yearly maintenance. The reactor would be housed in a 500 sq. foot metal container, similar to a shipping container. Estimated upfront costs are between $1-2 million and as low as $750,000 with government subsidies or grants. It requires one individual to be knowledgeable about operating the reactor and be on call to handle any problems. A logistical plan will be used to transport food and green waste from collection sites to the reactor storage. Annual operating costs are estimated as $100,000.

The reactor cost may be reduced through government subsidies, grants, and/or tuition increase. For example, a similar project recently received a grant for $2 million dollars (Holbrook, 2021), and about half of the surveyed undergraduate students support an increase in tuition or fees of at least $50. With a $25 tuition increase and an estimate of 4500 undergraduates, $112,500 could annually be portioned to the reactor costs, covering annual maintenance.

Recommendations

We have found that there are many benefits to implementing an HTL reactor at WPI. Beyond the environmental benefits of putting food waste to use, this reactor would open up valuable opportunities for students to put theory in practice that could later be applied to their careers. Since HTL is a growing industry, students who continue to pursue this field would be going into a career with a bright outlook. Students' experiences with this reactor during their education can be applied to their job search even if they do not continue to work with these reactors.

If WPI would like to seriously consider the next steps in implementing the reactor, then looking into which company to work with would be an important next step. In our project, Genifuel and Mainstream Engineering were very helpful, and stated that they are capable of building such a reactor, so we would suggest that WPI put those two companies under consideration. Identifying a place to store the building would similarly be an important decision. Our surveys suggest that the possibility of an odor generated by the food waste stored at the reactor could be a bother to students and staff, but fortunately, both of the experts we interviewed said this would not be an issue.

However, the decision need not be narrowed down to whether or not to implement such a reactor. WPI could conduct another project which investigates more processes to reduce food waste, such as anaerobic digestion or pyrolysis, as alternatives to an HTL reactor. If building something on campus is not desirable, a future project could investigate whether sending food waste off to a local company to process is feasible. These alternatives could offer similar educational benefits, while also giving food waste a better use.

In summary, if WPI was to build this HTL reactor, they would reduce their carbon emissions by offsetting their energy needs with biofuel, create valuable educational opportunities for students and faculty, and could expand this project to involve and benefit other Worcester community members in order to be a model for pursuing sustainability goals.

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Introduction

Pollution is the result of human made processes which expel various pollutants into our ecosystems which can result in harmful and everlasting consequences. Such consequences allude to points of no return, causing climate change catastrophes and other harmful effects for humans and animals alike. The risk of increased pollution is paired with another enemy of a stable climate, food waste. In the U.S alone, 63.8 million tons of food waste is produced annually (Advancing Sustainable Materials Management: 2018 Fact Sheet, 2020). When food waste is sent to landfills, it will decompose and produce methane, which is one of the most dangerous of greenhouse gasses as it is 30 times more effective at trapping heat than carbon dioxide (Yvon-Durocher, Allen, Bastviken, Conrad, Gudasz, St-Pierre, Duc, A Del Giorgio, et.al, 2014). All the energy that goes into producing the food and disposing of it goes to waste with the food, and will serve no purpose, but to contribute to the pollution of the earth.

These alarming figures on food waste are also no different for Worcester Polytechnic Institute (WPI). The campus currently generates 75 tons of food waste and 20 tons of green waste per year. Food and green waste in landfills contribute to the release of greenhouse gasses, such as methane, and so putting the waste to use, through the burning of biofuels, is much more environmentally friendly. Diverting food waste from landfills into alternative uses, such as feeding hungry people, feeding animals, industrial uses, and composting, is the goal of food recovery projects. Currently, WPI pursues the first two through donating edible food to charities, and waste food to Tyde Brook Pig Farm, but currently has no projects which pursue industrial usages for food waste, nor composting food waste. Using food to feed people and animals is the most desirable on a large scale, but it is possible WPI can find a better use for this food.

In an effort to consider how to utilize this food waste rather than send it to landfills, an undergraduate student at WPI, Caroline Murphy, along with her advisor Prof. Michael Timko, did research on an industrial processor for food and green waste; the processor was a hydrothermal liquefaction reactor. Hydrothermal liquefaction (HTL) is a thermochemical process which directly converts biomass to biocrude oil, without requiring the drying step that many similar processes require. The lack of a drying step means such a process would be easier to implement at WPI rather than other alternative processes.

During her project, Murphy considered what exact ratios of food and green waste can be processed in order to produce the greatest yield of crude bio-oil. Through her experiments, she found that the greatest yields of oil resulted from a mixture of 75% food and 25% green waste. After her findings, she then considered how much energy could be produced if WPI considered implementing a reactor on campus, fueled by its green waste. Through her predictive models, she found that if WPI utilized all of its food and green waste for oil production through HTL, they could easily produce enough energy to offset all of the fossil fuel usage from its leased and owned vehicles for a year, along with extra bio-oil. Unused bio-oil would not be beneficial for anyone, however, the possibilities that this reactor opens up for powering the campus, by completely reducing the carbon dioxide WPI produces, while reducing the methane emissions of food and green waste in landfills, was something that Murphy thought WPI could consider in the future.

However, during her project, Murphy never fully investigated the feasibility, the steps required to implement such a reactor, and community support for this reactor. Carrying on her work, our team began a project that would investigate the feasibility and implementation of an

HTL reactor on campus. This project looked to determine whether implementing a reactor on campus was possible, and if it has necessary resources to be implemented. The team looked to understand how WPI disposed of its own food waste. This goal was accomplished by speaking with the heads of facilities and Chartwells dining services to determine how much food and green waste is produced on a yearly basis and how this waste is currently managed. The team took these estimates to experts in HTL reactors to determine reactor specifications. Afterwards, the team reached out to, and surveyed students, faculty, and staff at WPI to measure support, and get an understanding of their position on the implementation of this reactor.

By gaining an understanding of the process required to implement a reactor, the team gathered valuable information for future projects. These projects may look for more methods and ways to reduce the amount of food waste that goes to landfills. Future projects can look to either implement such a reactor, or find alternative methods that could be more desirable for WPI.

Background

Overview

In this chapter, we will discuss the challenges created due to use of fossil fuels, in combination with excessive food waste and the current global initiatives and technologies aimed at reducing them both. Afterwards, we will analyze the current state of affairs at WPI and explore possible techniques to reduce greenhouse gas (GHG) emissions and food waste produced on campus. This information will be useful in understanding the research objectives in the methodology. Our project specifically only investigated one option WPI has to pursue green initiatives: hydrothermal liquefaction. Thus, we only explored what it would take to implement an HTL reactor and if it would be a good option for WPI.

Food waste and Recycling

Global Waste & Initiatives

One key step WPI can take to become more carbon neutral is to recycle and repurpose. In particular, it is important to consider that the United States is the leading producer of food waste in the world; it produced 63.8 million tons of food waste in 2018 (Advancing Sustainable Materials Management: 2018 Fact Sheet, 2020). Food waste is defined to be the amount of food thrown away after retail and consumption (Gustavsson, Cederberg, Sonesson, et.al, 2011). This food waste mostly sits in landfills and creates significant amounts of greenhouse gasses, such as methane, which contribute to global warming, not to mention runoff pollution, soil contamination and other unfortunate effects (Advancing Sustainable Materials Management: 2018 Fact Sheet, 2020). Due to these risks, the EPA is looking into solutions to help Americans reduce and repurpose their waste. One of the key ways the EPA is doing this is by creating a hierarchy of how food should be recycled in what is called the upside down triangle or Food Recovery Hierarchy (Sustainable Management of Food Basics, 2021).

The EPA inverted triangle serves as a hierarchy for where and how food waste should be disposed of. This triangle was developed in an effort to come up with some of the most carbon efficient ways humans could dispose of their food waste. The hierarchy goes as follows, from highest to lowest priority; Source Reduction, Feed Hungry People, Feed Animals, Industrial Uses, Composting, and Landfill/Incineration (Sustainable Management of Food Basics, 2021).

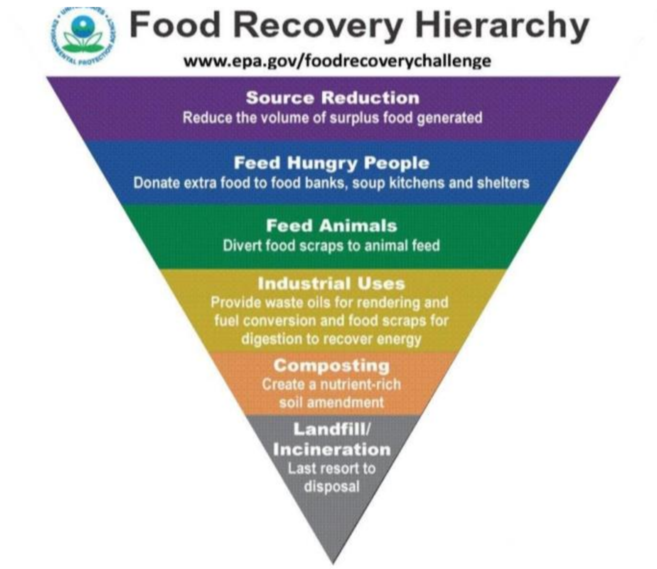

Figure 1: Food Recovery Hierarchy (Sustainable Management of Food Basics, 2021)

The goal of source reduction is to reduce consumption to a level where no waste is produced. WPI could cut portion sizes and food purchases to reduce their level of consumption. Reducing food waste by altering the production process helps to cut out pollution at the source of the problem, which is why it is the most important on the hierarchy. At a larger scale, businesses can help reduce the amount of waste they have by conducting audits, something WPI already does (How to Prevent Wasted Food Through Source Reduction, 2019).

The next step in the hierarchy is to feed hungry people. When food is wasted and ends up in the trash, all of the water, gasoline, energy, and labor that went into producing the food is also wasted. By making sure that all viable food ends up being eaten, the energy that went into producing edible food does not end up wasted (Reduce Waste Food By Feeding Hungry People, 2021). In addition to reducing the amount of food in landfills, it is estimated that nearly 10.5% or 13.7 million households have difficulties providing sufficient food for their family due to a lack of resources (Coleman-Jensen, Rabbit, Gregory, Singh, et.al, 2020). Ensuring that good food does not go to waste not only helps our environment but also helps to feed the hungry.

The next step in the hierarchy is to use our waste to feed livestock. Food that is edible, but not fit for human consumption can be donated to animals who are much less picky. This greatly reduces the amount of food waste going to landfills because using food waste to feed animals eliminates the need for further food production, which produces a significant amount of greenhouse gasses. Recycling food to animals is not a new idea; farmers have been recycling food for years because it saves them a significant amount of money (Reduce Wasted Food by Feeding Animals, 2021).

Moving on in the hierarchy is to use food waste for industrial uses such as for biogas, biodiesel, and electricity production. Wasted food and other forms of bio waste can be converted into fuel which can help offset carbon emissions, and even help organizations save money on fuel costs (Industrial Uses for Wasted Food, 2019). Repurposing this waste to produce energy prevents a significant amount of waste from decomposing in landfills.

The next step is to compost food. Composting food helps build healthier soils which are crucial to growing future crops. In addition, it also helps reduce food waste sitting in landfills, which produce greenhouse gasses. Last on the list, is disposing food the traditional way, by landfill, or incineration. This produces a significant amount of greenhouse gasses, causes bad run off, and does essentially nothing to help repurpose food waste (Reduce Waste Food By Feeding Hungry People, 2021).

WPI Food Waste & Initiatives

WPI has historically produced around 718 tons of food waste, and about 20 tons of green waste a year. To tackle this enormous amount of waste, WPI has developed programs to recycle its food waste in multiple locations around campus. In the year 2017, an Interactive Qualifying Project team investigated the different ways each of these locations recycle food. This required the team to interview Chartwells employees who track exactly where every waste item goes from their kitchens (Trvalik, Penaloza, Rathore, Moseley, et.al, 2019).

The first large initiative WPI took was an attempt to reduce post-consumer food waste, which is wasted food that has been served, in the Morgan Dining hall. The first step WPI took to help reduce post-consumer waste was done by introducing trayless dining which allowed people to grab a plate and serve themselves. The initiative reduced food waste by 40% since an individual could take as much or as little food as they planned to eat. This made sense because it allows the diners to try new foods they might not like or only get a smaller portion of a meal if they are not as hungry (Trvalik, Penaloza, Rathore, Moseley, et.al, 2019).

In the Morgan Dining Hall kitchen, staff follow what they call the "Trim Trax" system, which reduces food waste involved in prepping and cooking meals. There are three categories for this waste: production, overproduction, and unused/out of date inventory. Production waste is anything that stems from prepping and cooking the meals such as onion or carrot peels. Over production waste is food that was not eaten by the consumer. Lastly, unused and out of date inventory comes from mistakes in planning or ordering. Employees do not throw waste directly into the trash; instead, they store everything in containers that allow them to track and record how much waste they are creating. By using this data, they can learn what meals and ingredients generate the most amount of waste and make educated decisions based on the data. Chartwells Food Service, the main food provider at WPI, estimates that about 10% of all food waste goes into the trash because of poor employee training and a high turnaround rate, both of which the first tier of the food recovery hierarchy targets (Trvalik, Penaloza, Rathore, Moseley, et.al, 2019).

After the meals are created, there are three programs that work to prevent it from going into the trash. First, the dining hall has a hallway that leads to the only exit so that all consumers are forced to walk through it. In **Figure 2**, the wall is lined with trash and food waste bins that are easily distinguishable. Students are expected to separate their food waste from napkins or any other trash. A similar program was also implemented into the Campus Center Food Court. Here, there are multiple disposal cans for trash, food waste, and recycling. This allows students to separate waste, and promote food recycling. The food waste of both dining locations is collected in 55 gallon drums which are emptied at Tyde Brook Farms, a local pig farm, every week. The farmers use this waste as animal food (Trvalik, Penaloza, Rathore, Moseley, et.al, 2019).

Figure 2: Morgan Dining Hall Recycling Program

The second program implemented in the Morgan Dining Hall is reusing and/or reserving any of the food that was not taken by students during the meal sessions at a later date. For example, if there was half a tray of carrots that was not eaten during one day, instead of throwing away the food, perhaps the team can incorporate those carrots into the next day's stir fry (Trvalik, Penaloza, Rathore, Moseley, et.al, 2019).

Lastly, if the Morgan crew is unable to re-serve a meal for whatever reason but it is still warm and good to eat, they donate it to nearby organizations such as the Friendly House. The Food Recovery Network, founded in 2016, is a student-led group at WPI that organizes with Chartwells to feed hungry people. Estimates show that between 2016 and 2019, about 5000 pounds of food has been donated (Trvalik, Penaloza, Rathore, Moseley, et.al, 2019).

Global Emissions and Green House Gases

Within the next hundred years, Earth could surpass 2 to 4 degrees Celsius of increase in average temperatures, which according to a majority of scientists, is the point of no return for causing permanent climate change catastrophes (Parry, Lowe, Hanson, et.al, 2009). These small increases in temperature are a result of greenhouse gasses being trapped in the atmosphere. The greenhouse effect is caused by burning fossil fuels used in the production of goods in nearly all of our daily lives. Large scale burning of these gasses causes changes in our atmosphere which allow it to trap more heat from the sun. These changes in our climate have huge ramifications on how our species will evolve. We can expect glaciers and ice caps to melt causing sea levels to rise, as well as an increase in ocean temperature which leads to more catastrophic weather events, and other problems. Currently one of our best solutions is to implement renewable energy sources to help slow the rate of greenhouse gasses going into the atmosphere because they are much more carbon neutral (Sources of Greenhouse Gas Emissions, 2021). The sooner we act, the better chance we have to slow the effects of climate change, and even with immediate action we still have a long way to go (Parry, Lowe, Hanson, et.al, 2009).

Despite the fact that carbon dioxide is currently the largest contributor to global warming, other greenhouse gasses such as methane are even more efficient at trapping heat in earth's atmosphere. Methane has been shown to be nearly 30 times more effective at trapping heat than carbon dioxide (Yvon-Durocher, Allen, Bastviken, Conrad, Gudasz, St-Pierre, Duc, A Del

Giorgio, et.al, 2014). Other than decomposing biomass from wetlands and energy production, some of the largest contributors to methane emissions are waste in landfills, farming, green waste, and the burning of biomass (Methane Tracker 2020, 2020). Estimates suggest that three quarters of today's global methane emissions could be avoided, and that nearly 40% of methane emissions worldwide could be cut for no cost (Basic Information about Landfill Gas, 2021). Taking advantage of these possibilities could have a profound impact on earth's climate. Currently, the biggest obstacles from cutting methane emissions revolve around lack of infrastructure, information, and investment in these new technologies, designed to repurpose waste. In fact, taking full advantages in cutting methane emissions could reduce the temperature rise by about .07°C by 2100 (Basic Information about Landfill Gas, 2021).

Policy Solutions

Over the course of the past half-century, individuals and countries alike have begun to notice the effects of pollution resulting from industrialization. This contamination has led to nine out of every ten people breathing in air which exceeds the World Health Organization's guideline limits of air pollution and accounts for over seven million deaths per year. In order to reduce this enormous death toll, people around the world have been demanding and enacting change to reduce pollution (World Health Organization, 2019).

Numerous countries and cities around the globe have made agreements and enactments to do their part to reduce pollution. One of the most famous agreements, which almost all countries have pledged to be a part of, is the Paris Climate Agreement. This agreement requires all countries to meet certain emission requirements throughout time. Each government sets targets which are known as nationally determined contributions, and aim to prevent the global average temperature from rising by two degrees Celsius to one and a half degrees Celsius (Maizland, 2020). Additionally, this agreement seeks to have all participating countries reach a net zero point of emissions which essentially means all greenhouse gases emitted equate to the amount they remove. Another important agreement which has a focus on climate change is between the United States of America and Canada. The agreement, known as "The U.S-Canada Partnership Roadmap," highlights the importance of climate change and more importantly, pollution. This roadmap anticipates accelerating efforts to combat climate change and specifies that each partnering country must reach net-zero emissions by 2050. Furthermore, the U.S's goals also include reaching net-zero carbon pollution-free power by 2035. These two agreements are among the many and show the world's intent to reduce air pollution and to move towards a better tomorrow (World Health Organization, 2019).

Renewable Energies

With the enactment of these green policies and ideas, the world needs to adopt new ways to create energy, power its vehicles, and heat its homes. Renewable energies are atto the forefront of energy production as they create little to no emissions and are referred to as clean energy sources. Renewable energy is derived from natural resources or processes that are constantly replenished. This has led to developments in solar, wind, hydroelectric, geothermal, ocean, and biomass energy systems.

One of the most common forms of renewable energy is solar. This type of energy, typically consisting of various forms of solar panels, utilizes the sun's powerful rays to transform sunlight into energy using photovoltaic cells. Solar panels are typically found on the rooftop of homes, businesses, skyscrapers and even solar electric farms which can produce enough energy for thousands of homes. Solar supplies a little more than 1 percent of the U.S's electricity generation (Shinn, 2018). One upside of solar energy systems is they do not pose many environmental impacts beyond the manufacturing process.

Another form of energy production is hydro/wave energy. Hydropower relies on fast moving water, usually from rivers or water falling from high heights like dams. This motion spins a turbine which generates electricity. Hydro energy production may have impacts on the environment because it can block fish from moving up and downstream. Wave energy is less harmful; it is a new form of energy production that uses the tides and currents of the oceans. Due to the ocean being so large, there are vast types of techniques to harness this form of energy including underwater turbines and wave movement machines.

One of the cheapest and most popular renewable energies is wind power (Office of Energy Efficiency & Renewable Energy, 2018). Wind power is typically placed in areas with dense or consistent wind such as the midplanes in the United States or the open oceans where wind is the strongest. To generate power, wind turns the blades of a turbine, spinning a generator which produces electricity. Wind power energy production accounts for a little more than 6 percent of all U.S power generation and is set to surpass all other forms of renewable energy in the coming years (Muyskens et al., 2017).

Biomass energy is a renewable energy which consumes biological waste, or biomass, and produces energy. Biomass is an organic material that comes from animals and plants and includes food waste, green waste like grass clippings, and so forth. Biofuel is an alternative for many forms of fossil fuel use, in particular energy production, heating, and especially a replacement for automotive fuels (U.S. Energy Information Administration, 2016). In 2019, biomass provided nearly five percent of primary energy use in the United States. There are many forms of biomass such as thermochemical conversion, chemical conversion, and biological conversion, all of which can be used as fuels similar to fossil fuels. Biomass technology is up and coming and may help different entities reduce their waste by converting it to different fuels.

WPI Actions

WPI, just like many institutions across the globe, wishes to be recognized as a sustainable campus. This has developed into a vision that "WPI embraces a culture of sustainability that extends from the WPI campus and reaches across the globe"(*WPI's Sustainability Plan 2020-2025 Overview*, n.d.). This vision has emerged into three distinctive objectives:

1. Developing our campus as a living and learning laboratory
2. Establishing as a hub for innovation in sustainability
3. Reaching out beyond our campus (locally, regionally and globally)

WPI hopes these objectives will create initiatives that allow advancement in sustainability both abroad and locally. WPI also adheres to the principles of sustainability within its operations and facilities divisions. They employ the practices of preserving resources and promoting a sustainable lifestyle, both of which aim to reduce pollution and waste into the environment. Although WPI is aiming to be sustainable, it still produces a large amount of food waste and green waste, both of which could be reduced or used in a new system. This could help recycle a significant amount of energy.

Food Waste to Energy

Biomass has a lot of potential for creating a greener planet. According to an article titled "Liquefaction of Biomass and Upgrading of Bio-Oil: A Review", biomass "is one of the most important energy sources of the future" (Zhang, Yang, Zhang, Chu, Zheng, Ju, Liu, et.al, 2019). Biomass waste has a number of applications for reuse, including fuel, building materials, and animal feed. Biomass has zero net carbon emissions, and so biofuel is thought of as a carbon neutral fuel (W.H. Chen, Lin, Liu, T.C. Chen, Hung, C.H. Chen, Ong, et al, 2019). Currently, only about forty percent of biomass waste is put towards these processes while the rest is sent towards incineration and landfills. Diverting biomass to be used in other ways both reduces pollution and recovers energy that would otherwise be lost (Zhang, Yang, Zhang, Chu, Zheng, Ju, Liu, et al, 2019).

Converting biomass waste into biofuel is an important procedure that makes it usable. Two well-known processes used to turn organic waste into bio-oil: pyrolysis and hydrothermal liquefaction. Pyrolysis is most effective when decomposing dry organic matter that has a water content of less than ten percent. The reaction is also done in the absence of oxygen at temperatures ranging from 350 to 550 degrees Celsius with normal atmospheric pressures. HTL is different; it is able to convert biomass with up to fifty percent water, and is performed at lower temperatures of 200 to 350 degrees Celsius but at higher pressures of 2 to 20 MPa. Pyrolysis is a viable method to convert food and green waste into energy, however, the inputs would require a drying process before the process can take place (Hognon, Delrue, Texier, Grateau, Thiery, Miller, Roubaud, et al, 2015).

Composting and anaerobic digestion

There are two other processes that break down food and green waste: composting and anaerobic digestion. Both of these methods work by decomposing the inputs through the use of biological organisms. The main difference between the two is the presence of oxygen. Oxygen is present in composting and absent in anaerobic digestion.

In composting, bacteria, fungi, and actinomycetes break down the glucose in the natural components into water and carbon dioxide. Composting is most efficient with approximately 50% moisture content so that a thin film of water can wrap around the waste particles and still have enough room for air, and more importantly oxygen, to reach the organisms. The process is capable of breaking down more complex particles when compared to digestion. The main products are the compost itself, water (both in a liquid and gaseous state), and gasses (mainly ammonia and carbon dioxide) (Coker, 2014).

During anaerobic digestions, different microbes break apart the components but compared to composting, the process is most efficient at 100% moisture since the process only works without the presence of oxygen. It produces the digestate itself, as well as biogas which is mostly made up of methane. The main reason one would use digestion over composting is that they plan to capture this biogas and burn it for heat or electricity. There are new methods being tested to capture some energy from composting, mainly by using the heat it gives off to heat water, but currently, digestion is more straightforward when it comes to energy production (Coker, 2014).

Anaerobic digestion and pyrolysis are both reasonable options for converting green and food waste into energy, however, the focus of this project will be about hydrothermal liquefaction because it is a continuation of a previous MQP which found an optimal ratio of 75% food waste to 25% green waste for producing bio-oil at WPI's campus.

Hydrothermal Liquefaction

Hydrothermal liquefaction is a process which converts biomass into liquid fuels. One of the advantages this process has over other processes is that it does not require that the biomass fed into the reactor be dried (Patel, Zhang, & Kumar, 2016). Drying biomass would be another step in the process of producing biofuel, which would require energy and resources to carry out. When considering the implementation of biofuel production at WPI, the waste collected needs to be considered. Trash on campus is mixed with many types of foods, and so WPI cannot ensure that there is no wet waste in the food waste in the trash collected. Any other method than HTL would require a drying step. Out of the solutions available, the advantage that hydrothermal liquefaction presents is very desirable for WPI (Zhang, Yang, Zhang, Chu, Zheng, Ju, Liu, et al, 2019).

The process of converting the wet biomass to biofuel requires high temperatures (around 250-500 C) and increased pressure (5-25MPa), with some water. The HTL process would be carried out in a specifically designed reactor, which would need to be built on campus. Besides producing biofuel, biochar produced from this system can also have its uses on campus, further reducing the amount of energy and waste. Biochar can be used as a fertilizer. By using the fertilizer produced in this system on campus, WPI reduces pollution simply by being much more self-sufficient in its operation (Zhang, Yang, Zhang, Chu, Zheng, Ju, Liu, et al, 2019).

In an effort to promote the usage of this carbon neutral fuel source, a student, Caroline Murphy, researched mixtures of food and green waste and the fuel yield produced using HTL. In her research, she determined that the mixed feedstock with a ratio of 75% food waste and 25% green waste was the optimal mixture for producing large amounts of oil yields (Murphy, 2020). Using the statistics of the food waste produced on campus, if all of WPI's food waste went into producing bio-crude oil in this reactor, predictive models show that WPI would produce enough energy to power all on-campus vehicles for a year. In fact, with high probability, WPI would produce a surplus of energy needed for its vehicles (Murphy, 2020). If WPI was to put all of its efforts into sustainability, they could use HTL to completely replace all fossil fuels used in powering its vehicles, and perhaps go further and replace fuel used in heating its buildings and in other facilities.

Biofuel

Bio-crude fuel is an alternative form of crude oil that is produced by biomass solvent liquefaction. Bio-crude may be developed into biodiesel and biogasoline. Biodiesel is a liquid fuel that is used in fuel compression-ignition engines, which are those most cars use, and may be blended with petroleum diesel at any percentage. However, at colder temperatures, the greater the biodiesel percentage, the poorer the fuel performs. Common blends of biodiesel are B5 and B20; B100 is used as a blend stock. American Society for Testing and Materials International

(ASTM) allows for up to B5 with no special label, however at higher percentages, specialized products should be used. B20 and lower blends may be used in current engines without modification. B20 is considered the common blend because of the balance of cost, emissions, cold-weather performance, materials compatibility, and ability to act as a solvent. B100 and high-level biodiesel blends require improved hardware such as filters and larger tanks, and may cause engine operation problems. In July 2020, Biodiesel (B20) cost $2.35 per gallon, Biodiesel (B99/B100) cost $3.15 per gallon, and diesel cost $2.22 per gallon.

WPI Implementation

WPI consumes energy in the forms of electricity, natural gas, oil, and gasoline. In an effort to reduce greenhouse gases, an HTL reactor may be implemented. The reactor can produce biofuel or biogas. The biofuel can be refined to any petroleum product such as oil or gasoline. Biogas can be used to power a generator that produces electricity. An HTL reactor allows WPI to recycle its waste by creating an energy source for the school. Refined biofuel may be used in facility vehicles or in building heating systems. WPI facilities operate Ford Ranger, F-150, F250, F350, and F-Series Super Duty vehicles that use gasoline or diesel. The electricity may be used to supplement the school’s electricity needs.

Methodology

Overview

The goal of our project was to test the feasibility of implementing an HTL reactor on WPI's campus. To achieve this goal the following objectives had to be met:

1. Obtain an estimate of the amount of food and green waste WPI produces, and then estimate how much of that waste could be collected for use in a reactor.
2. With waste estimates, the team spoke with experts in the field of hydrothermal liquefaction to determine reactor specifications.
3. Utilizing the new found knowledge, the team sought to gather the public opinion of WPI community members

With this information our team could justly answer whether a reactor was feasible and identify what shortcomings this plan could encounter.

Reactor Fuel

The first step in our investigation process required us to obtain an estimate on the amount of waste WPI produces annually. The team also spent additional resources investigating the disposal techniques of both the food and green waste. This information was crucial as it was key in deciding the necessary size of the reactor. Additionally, gaining an estimate of how much food waste which could be employed within the reactor; if not a sufficient amount the team could explore alternate food waste sources.

To ascertain an estimate of how much food waste WPI's campus produces, our first goal was to speak with leaders within WPI's food service. Our team's main point of contact was Joe Kraskouskas, head of Chartwells dining services, and member of the WPI community since 1995. To obtain the desired information, our team set up an interview with Mr. Kraskouskas, and sent him questions ahead of time. The time allowed him to prepare and garner accurate figures for our discussion. The questions presented to Mr. Kraskouskas were meant to investigate how much food is currently produced on a yearly basis and how that food is disposed of during non-Covid years. A complete list of the questions our team asked Mr. Kraskouskas can be found in **Appendix A.** The reason our team spoke with Mr. Kraskouskas was due to Chartwells being the largest producer of food waste on WPI's campus, and predominantly oversees how food waste is disposed of.

After speaking with representatives at Chartwells, our next step was to investigate the green waste produced on our campus. The following step led to speaking with the head of facilities. This individual oversees facilities, which is partially responsible for maintaining WPI's ground needs. WPI's grounds crew plays a key role in spring/fall clean ups and in maintaining WPI's numerous lawns. These processes result in the collection of a significant amount of green waste including sticks, leaves, and grass clippings, all of which can be turned into biofuel with an HTL reactor. For this reason, an interview was scheduled where questions pertaining to what types of green waste were collected, where it is currently disposed of, and how much green waste was collected on a yearly basis was asked. A complete list of these questions can be found in **Appendix C.**

Determining Reactor Specifications

To completely understand the feasibility of implementing a reactor on WPI's campus, an encompassing description including size, cost, benefits, and challenges a reactor would pose would be needed. This transitioned to leaders in companies that specialize in HTL technology such as Pacific Northwest National Laboratory, Genifuel, and Mainstream Engineering being contacted. Since these companies specialize in the design of these reactors, the estimates obtained could provide the experts adequate figures in producing an estimate for WPI. Additionally, it was important to interview a wide variety of experts to gain a more diverse understanding of these reactors and their needs.

The first representative our team met with was a senior engineer at Mainstream Engineering who holds a PhD in Chemical Engineering. The second representative our team met with was James Oyler, the president of Genifuel, who holds a bachelor's degree in Electrical Engineering and power generation, and a master's degree in Economics. When interviewing each of these representatives, the information on the amount of food waste our campus produced and how much could be collected for use in this reactor was presented. With the information on food and green waste, the experts were asked the size of the proposed reactor on WPI's campus, how this reactor could be powered and the amount of energy this reactor could produce. These questions were directly related to the overall question of would this help WPI cut its carbon footprint. Additional questions were asked regarding the cost of the proposed reactor, amount of noise produced by reactors, and operation needs such as the amount of people needed to run it. These questions were used to develop an understanding of what resources WPI would need to allocate to this proposed reactor. After all of the initial questions were asked, any comments or concerns on streamlining the process of implementing such a reactor, and how they believed this process would work were asked of the experts. A complete list of questions can be found in **Appendix C.**

Public Outreach

Once information concerning the overview of the proposed reactor estimate was collected, the next action was to garner WPI community members' outlook on implementation of the reactor on campus. Investigating community members' outlook was necessary, as a hydrothermal liquefaction reactor on campus could cause changes to community members' regular lives. Thus, it was of the utmost importance to gauge the opinion of students, staff, and faculty members that could be affected. To reach as many current WPI community members as possible, a Qualtrics survey was utilized. In order to break down the WPI community, the survey had three main categories: students, staff, and faculty. The survey was constructed with a broader section for all groups. Within this section, the questions were broad and meant to collect information regarding general support for such an idea. Some of these questions concerned how important it was to pursue green initiatives, how much support there would be if the reactor would be an eyesore, and if it would cause smells or unwanted noise. These were important questions to ask to every community member because all people would be affected similarly in these areas if a reactor were to be implemented.

After asking these broad questions, our team moved into the grouped questions. Our team specifically asked students questions on how they felt about our plan if it were to increase tuition. Asking students about tuition increases was important to ask because introducing an expensive plan that could fall on their shoulders would make them a crucial stakeholder in this implementation. Thus, their opinion would be crucial in a feasibility study. In addition to questions about cost, it was important to ask students a question about how important it was to apply to colleges with green initiatives. Student opinion on campuses with green initiatives was an important question to ask as they had recently applied to college and represented future generations of WPI students. If a large portion of students said this mattered, administration may be concerned with improving WPI's image as a destination of innovation.

The survey also focuses on the staff separately, as the implementation of the reactor may change some of their duties, especially within facilities. Additionally, the school may have to hire additional employees to work with the reactor. This in turn may affect some of the managers and possible employees with work due to training new members. Faculty members were also surveyed as they may have key insights into the notion of this reactor playing an educational role within their respective programs. The importance of this question was due to the fact they would be highly affected if there was a possibility of new research or academic options. A complete list of our survey questions for students, staff, and faculty can be found in **Appendix D.**

Findings

Introduction

From our research, the team was able to develop a clear picture on the social state of implementing a hydrothermal liquefaction reactor on campus. Our team researched the social state of implementing an HTL reactor using a series of interviews, surveys, and conversations with multiple individuals at WPI's campus and various industry leading experts. These actions led to the following results from our study:

- The total amount of waste on campus which could be used for the HTL reactor was approximated to be 75 tons of food waste and 20 tons of green waste annually.
- The cost of the reactor was given an $1-2 million price tag excluding government subsidies. Taking this into account could bring the effective price down to as low as $750,000.
- Over 75 percent of WPI's community believes green initiatives that reduce our carbon footprint should be explored. Additionally, about 50 percent of the students surveyed would support an increase to fees upwards of 50 dollars to implement a green initiative.
- Educational value of this reactor was cited as a major contributing factor to WPI campus's support from both students and staff.

To explore these findings more in depth, this section will focus on the specifics learned from speaking with the various individuals and deductions the team made to further our study. The exploration will be guided by distinct segments highlighting each major finding.
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Determining Waste on Campus

Through various interviews, the amount of viable feed, which could be allotted to this proposed reactor, was 75 tons of food waste and 20 tons of green waste. This information gave grounds for further research and investigation into the production, capabilities, and restrictions of a HTL reactor.

The first interview of the set was conducted with the head of facilities at WPI. When questioned on what kind of green waste was collected, we were told that WPI does not collect substantial amounts of waste, other than during fall clean up and then a smaller amount for spring cleanup, where they collect around 200 cubic yards of leaves and sticks. When asked how this waste is disposed of, he mentioned that there is an on campus location where nearly all of the leaves are taken. In the rare case of overflow, the excess waste is taken to a composting facility in Leominster, MA. When focusing on the changes that the reactor may create, in particular questions regarding the final resting place of the leaves was addressed. The individual said a change of this magnitude would be fairly easy, as this just requires a change in the dumping location. In addition to these questions, it was suggested that during some years, the facilities department needs to clean up old mulch, and that instead, this could potentially be collected to help operate our reactor. After divulging the figure of about 200 cubic yards of green waste a year, an accurate translation from volume to mass was needed. A conservative estimate, given the 200 cubic yards of leaves and sticks weighs about 20 tons (Walker, 2012).

When conducting the second interview with Mr. Kraskouskas, the main goal was to obtain an estimate of how much food waste we could get, identify where that food goes, and identify what steps were being taken to mitigate food waste. When interviewing him, we also asked him to consider numbers from a normal academic year, with no covid guidelines in place. Mr. Kraskouskas presented information on all of the campus dining facilities, which includes the Morgan Dining Hall, Campus Center Food Court, Dunkin Donuts, Goats Head, and Library Cafe. Between all of these, there is approximately 500 pounds of food waste a day for 10 months of the year. This figure translates to roughly 75 tons a year. Currently, all of this food waste is picked up by a local pig farm called Tyde Brook. Mr. Kraskouskas described the relationship that WPI has with Tyde Brook as mutually beneficial. WPI benefits because Massachusetts law requires anyone producing over 1000lbs a week of waste to either donate the food or pay to send it to a landfill. Tyde Brook benefits because they get about 3500 pounds of food waste per week that they can convert to pig feed for free.

If the relationship with Tyde Brook was severed, WPI would have to find alternative ways to deal with its food waste. In particular, the proposed HTL reactor could sustain WPI's food waste. If severed, and no HTL is in place, WPI would have to completely overhaul its current recycling practices, and would have to pay to send it to the trash. In addition to the responses above, the practice of separating food waste from trash is in place at two of the dining locations on campus. WPI could implement more food recycling locations and effectively raise the available food waste for the proposed HTL reactor.

Expert Interactions and Findings

Through interviews with three different hydrothermal liquefaction reactor companies, the team found that the cost of a reactor would be $1-2 million excluding government subsidies. When considering government subsidies, the effective price would be as low as $750,000. The net annual running cost would be approximately $100,000, with a large portion of the cost being tied to the labor of maintenance to operate the reactor. Experts concluded that the reactor poses a large educational value, as Chemical Engineers, Mechanical Engineers, Computer Scientists, and other engineering students may reap the benefits of the reactor's complex systems.

When looking to find an appropriate estimate on the cost of the proposed reactor, two distinct companies were asked. Mainstream Engineering, which currently focuses on making transportable pyrolysis reactors, and operates a larger HTL reactor in Florida, producing a ton of biofuel a day. The Mainstream Engineer, a senior Chemical Engineer, provided information detailing the development of a smaller scale HTL reactor. Another company, Genifuel, has worked to develop technology to convert food waste, and other organic materials such as animal waste, into biofuel by using various types of hydrothermal systems. Both companies said the reactor could produce either biogas or biocrude oil. Although the biogas reactor would incorporate some type of generator to convert the biogas into electricity.

The Mainstream engineer noted that the oil produced would still need to be refined prior to being burned in furnaces or in vehicles on campus. In relation to the fuel production, they noted that the most efficient form is biocrude oil due to it requiring less energy than the making of biogas as the reactor runs at a lower temperature. They mentioned that when choosing between a biogas or biodiesel reactor, the uses of the products must be considered. James Oyler, the president of Genifuel, described that a biocrude reactor would be slightly more profitable than a gas producing reactor, but it may not produce a higher revenue. Essentially, the net cost would be almost identical, and he mentioned that the biogas reactor may be a better option as everything would be completed at WPI. If implemented, WPI could claim partial carbon neutrality in addition to qualifying for additional government subsidies.

The representative from Mainstream engineering concluded that the reactor would be around the size of a shipping container or two. It could also be stored in a modified shipping container that would allow it to be outside. The machine would still require electricity, water and natural gas, which approximate to 3.7 MJ/h of electricity, about 42 lb/h of water, and about 61.4 MJ/h in natural gas. The natural gas could be supplemented with some of the char that our reactor will make. Mr. Oyler, suggested that the reactor could be housed in a 500 square foot building, which would need to be built, or be placed into an existing building with this much empty space. Additionally, the power outputs suggested are approximated to be 135.6 MJ/h in the form of biocrude oil and 565 MW/h a year produced by the electrical generation.

Mainstream Engineering priced the cost of the reactor to be $1-2million for initial implementation and anywhere from $200-$500 thousand annually. A majority of the annual cost being associated with the labor of maintenance in operation. When speaking about the daily operation, the representative explained that this reactor would require a trained individual that would be needed to monitor and operate this reactor at all times. Furthermore, a reactor needs another expert to oversee and maintain the reactor. The annual maintenance required would be periodic cleaning of the reactor and replacements of the catalysts. The maintenance was included in the annual cost estimate given by Mainstream Engineering. Mr. Oyler introduced the initial cost of nearly 1 million dollars with no government subsidies. With subsidies, the predicted price would be in the ballpark of 750 thousand dollars. Moreover, this machine could be run by students and faculty, with a member of our facilities team overseeing the whole operation and always on call. This machine is mostly automated and can run without around the clock supervision. With these figures, he estimated this machine would lose around 100 thousand dollars a year.

When asked about the academic value to this machine, Mr. Oyler stated this machine would be a great academic and research tool for the school. Researchers could run experiments on this reactor with different catalysts. He also noted that using this machine as an academic tool would reduce costs of implementation because students and faculty would be overseeing it a large portion of the time when in use. Experts informed the team that multiple depths of engineering and the sciences may be applied for educational benefit.

Exploring Public Outlook

Our survey was answered by 131 students, 47 faculty, and 64 staff for a total of 242 responses. The first important thing that we learned was that 77 percent of respondents thought that it was very or extremely important that "WPI pursues green initiatives to reduce their carbon footprint" (**Figure 3**). Knowing that a strong majority of WPI's community wants the school to pursue green initiatives exploration into what people thought about the specifics of our proposed project.

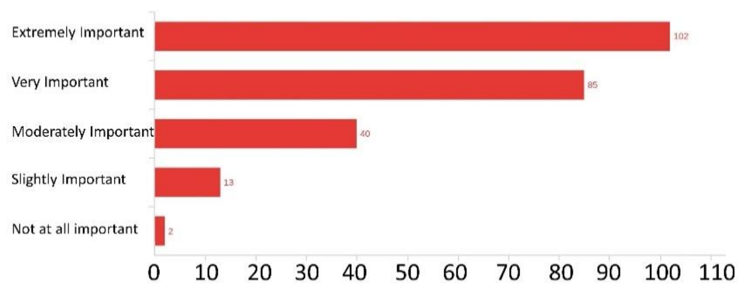

Figure 3: How important to you is it that WPI pursues green initiatives to reduce their carbon footprint?

The next facet of the survey which was recorded was how different people currently dispose of their food waste. **Figure 4** shows responses by students only, and is broken down by where students live. Out of the 63 students that live in apartments, 68 percent of them throw their food waste in the trash. The same percentage of those living in Greek/sport houses (larger apartment buildings with 20-40 residents) also throw their food in the trash. Sixty two percent of students who live in on campus dorms reported that they throw their food waste out at designated food bins.

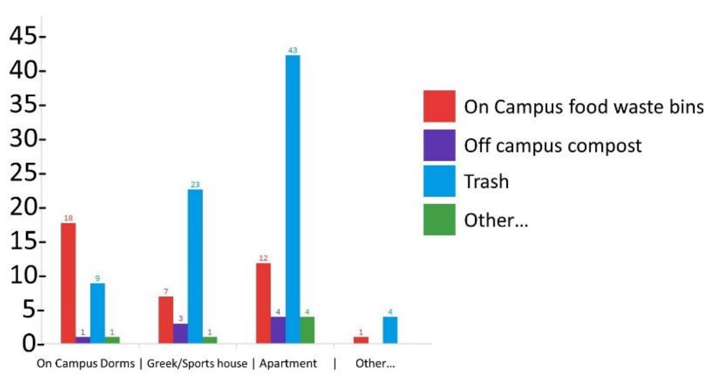

Figure 4: How do you currently dispose of food waste?

When the respondents were asked how likely they were to dispose of their food waste at designated bins on campus, there was a broad range of answers. The largest portion, 87 percent of people said they would be somewhat or extremely likely to take the time to recycle their food. The breakdown based on student, faculty, and staff can be seen in **Figure 5**. Some of the main reasons people said they would be unlikely to donate include: already composting at home, unwillingness to bring food from home to the campus, lack of convenience and time, and fear of odor/rodents.

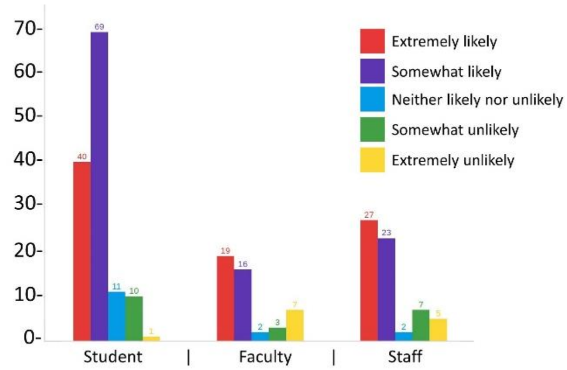

Figure 5: How likely are you to dispose of your food waste at designated disposal areas so that they can be recycled into biofuel?

After learning more about campus's overall thoughts on green initiatives, exploration into the specifics of our project goals was investigated. Where 84 percent of respondents said they would support the idea to implement a food waste conversion system at WPI a lot or a great deal. The exact numbers can be seen in **Figure 6**.

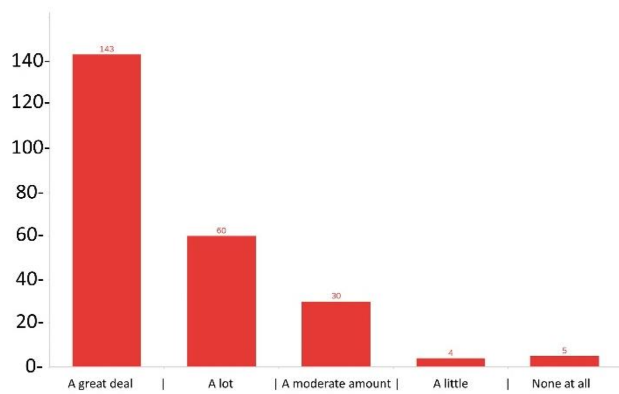

Figure 6: How much do you support the idea that WPI should implement a food waste conversion system to convert unused food waste into biofuel?

As seen in **Figure 7**, all of the respondents supported the idea either the same or more if it held some sort of educational benefits for students and professors. Additionally, support was taken away if the project would create a smell around campus.

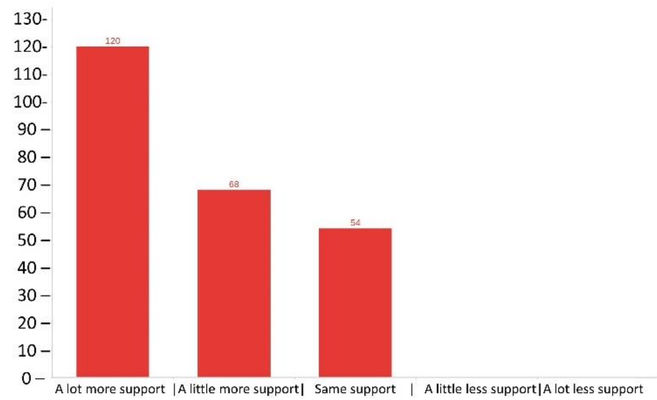

Figure 7: How much do you support this idea if students and professors could use this system for educational value?

Information regarding whether students would support the project if it raised tuition was investigated. To develop an understanding on the amount of money the students would feel comfortable paying for, within an increase in tuition or fees was asked. This concluded with 31 percent of students saying they would not support any increase in tuition or fees. Whilst, 47 percent of students said they would support at least 50 dollars in an increase in tuition. The full breakdown of these results is in **Figure 8.** The investigation also wished to determine the amount of time respondents would spend per day to prepare and separate their food for donation at on-campus food bins. It was found that 48 percent of the respondents said they would spend at least 6 minutes doing this *task.*

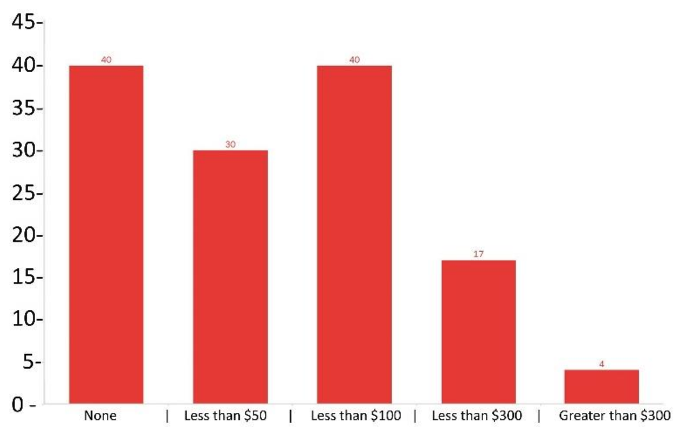

Figure 8: If this project were to increase tuition (or fees) how much would you support?

An additional 125 people said they would spend 0 - 5 minutes doing this, but this was a poorly designed question because we cannot separate the people who wanted to say zero from the people who wanted to commit 1-5 minutes per day. The full breakdown by students, faculty, and staff can be seen in **Figure 9.**

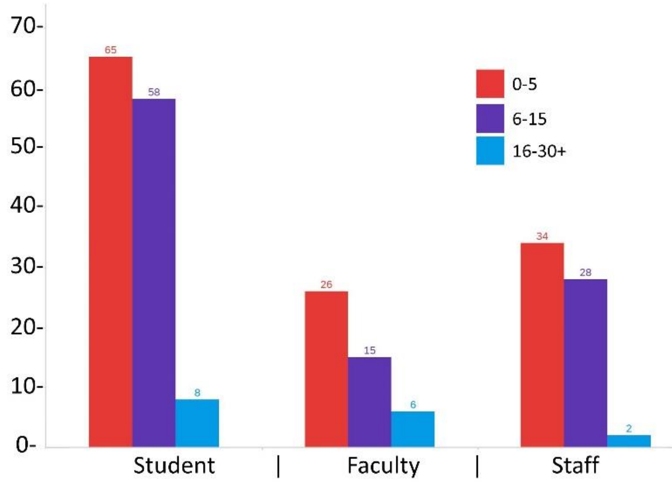

Figure 9: How many minutes per day are you willing to spend to dispose of your food waste from home at a WPI designated bin if you knew that it could generate biofuel to run WPI vehicles?

Some other notable results include that 46 percent of students didn't factor in their potential school's green initiatives when picking a college. 24 percent of students said that this was a slight factor. As for faculty and staff, 43 percent of them said that working at a school that invests in green initiatives is extremely important. The full breakdown of this information can be seen in **Figure 10** and **11**.

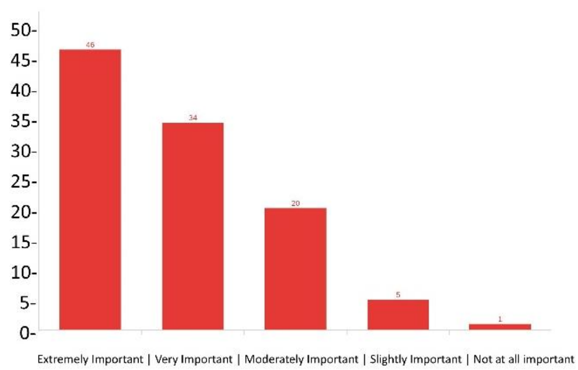

Figure 10: How important to you is it to work at a school that invests in green initiatives

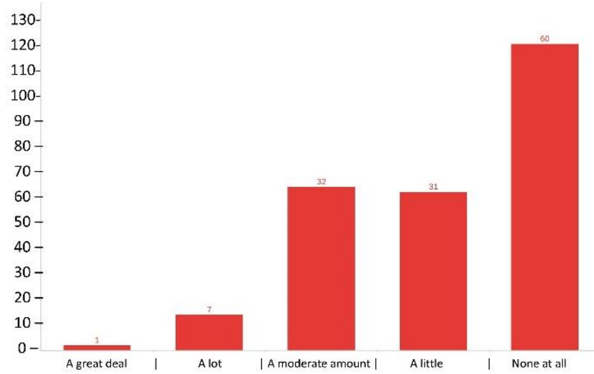

Figure 11: When picking a college, how much of a factor was the potential school's green initiatives?

Discussion

This section looks to analyze the data presented in the results section and discuss what advantages and disadvantages implementing an HTL reactor would have at WPI. To do so, we will have to look at what sized reactor is necessary, what form of energy could be made, what type of educational value could be provided, and how a machine like this could be funded. Additionally, in this chapter we will discuss how future projects could build off of the information collected within this report.

If all the food waste and green waste that WPI produced could be collected, there would be around 75 tons of food waste and 20 tons of green waste. When disclosing this information to experts from Mainstream Engineering and Genifuel, crucial information on the specifications of these reactors was obtained. First, we learned that this reactor would cost anywhere from 1 to 2 million dollars. These prices do not take into account any government subsidies. Mr. Oyler from Genifuel was confident that WPI could easily receive some sort of subsidy for building this reactor. Furthermore, there was recently a grant given for a similar type of reactor for 2 million dollars (Holbrook, 2021). For this reason, we feel that the initial price is reasonable for this type of project.

The next tangible figure obtained was the yearly maintenance and operating costs of the machine. The representative from Mainstream had a slightly larger estimate than the Genifuel representative. Mainstream did not take into account the selling of any products in the form of biocrude oil or in the form of electricity produced with gas. This produced an estimate with yearly costs around $200,000-500,000. The representative from Genifuel took into account that WPI could sell some of the electricity produced to the grid, or some of the biocrude oil to a refinery for money. When factored in, the Genifuel representative estimated we would lose just under 100 thousand dollars a year. This loss was a more tangible number to work with, since it took into account selling the energy we produce. To come up with this 100 thousand dollars a year, our team thought of implementing a “Green Tax". According to our survey, almost half of the students said they would support an increase of at least $50 dollars to tuition or fees in order to fund this project. With a conervative number of 4500 undergrads each paying $25, the school could generate an additional $112,500 per year.

Our survey data further suggests that there is campus wide support for such a project. Our survey found that 77 percent of respondents thought that it was very or extremely important that “WPI pursues green initiatives to reduce their carbon footprint.” These respondents included faculty, staff, and students. Thus, finding that the reactor could produce 135.6 MJ/h in the form of biocrude oil or 565 MW/h a year produced by the electrical generation clearly shows this project would help WPI reduce its carbon footprint.

The support for green initiatives also translates into students taking their own time to help. Our survey data found that 87% of people said they would be somewhat or extremely likely to take the time to recycle their food. WPI would likely have a steady supply of food from students if the reactor was implemented. Adding to this data, all of the HTL experts cited that this reactor would provide many educational opportunities. When surveyed, students overwhelmingly said they would support this idea if it introduced academic opportunities, with almost 78 percent saying that their support would increase by “a lot more” or “a little more” compared to no academic use. Lastly, over 84 percent of respondents said they support this plan of implementation. This suggests that WPI would have campus support for such a project. The only noted downside to a project of this magnitude, is the possibility of a smell around campus. However, the HTL experts assured us that smell would not be an issue. In addition to this, we also found the reactor could be housed in a 500 square foot building which is slightly larger than the size of a truck trailer, thus it would not be an eyesore or take up much space on campus.

One of the biggest shortcomings of this project however, is the relationship WPI currently has with Tyde Brook Pig Farm. Right now there is a very mutually beneficial relationship between Chartwells Dining services and the pig farm, as described by Mr. Kraskouskas. Chartwells donates all of its food waste to the farm, which saves the farmers money on food, and allows WPI to avoid waste disposal costs. For our current implementation plan, we would need to either cut ties with Tyde Brook Pig Farm, or find an alternative food source from some of the local restaurants or other schools.

One important factor is that according to the EPA's Food Recovery Hierarchy, organizations should prioritize sending their food waste to create animal feed before using it to generate energy. If WPI cut ties with Tyde Brook, then the farm would need to purchase animal feed. Creating animal feed uses land, water, and energy, so it is better to use existing food than making it. However, it is possible that if WPI cut ties with Tyde Brook that they could quickly find another local school, college, or organization to take its place. We reached out to Tyde Brook to ask how dependent they were on WPI and what would happen if WPI decided to stop donating their food, but unfortunately they were unavailable to interview.

Despite this, using the campus' food waste to create energy is still an environmentally friendly process. Furthermore, if this project can create educational benefits, then perhaps it makes sense to divert the food from Tyde Brook and use it for this project. One factor we had been thinking about throughout the project was if WPI decided it wanted to scale this project and get more food, how could it do so? One solution that may need more exploration is getting food from local restaurants and grocery stores. According to Massachusetts law, businesses must pay a tax if they throw away more than 1000 pounds per week. WPI could take over the food waste management for these businesses and use it to fuel the reactor, and produce more energy.

Another idea is to collect food waste from more students on campus. Currently, the food waste only comes from students who eat at the dining halls, but WPI could set up waste collection bins all around campus or in the community so that more people could contribute. From our survey data, 68 percent of students that live in apartments near campus throw their food waste in the trash. The same percentage of students who live in Greek or sports houses also throw their food waste in the trash. WPI could implement a collection system that is easy to use and convenient in the local community to encourage students to donate food waste. We also know that 48 percent of the students, faculty, and staff who took our survey would be willing to set aside at least 6 minutes per day to dispose of their food waste at WPI specific food waste bins. Thus, we believe that there is a possibility for WPI to maintain their relationship with Tyde Brook, and still implement this project. It would also be beneficial for a future project to weigh the pros and cons of donating the food to Tyde Brook on an environmental standpoint, and discovering new methods of collecting food waste.

For the rest of this discussion, we will assume that WPI has the necessary 75 tons of food waste needed to maintain the specifications of the reactor that was suggested to us. Looking at this project from an educational lens increases the number of benefits. Mr. Oyler was the first individual to point out that professors at WPI could modify and customize the reactor in order to conduct research and run experiments. Beyond that, chemists can learn from the composition and reaction going on inside the reactor. The reactor also has the potential to get first-hand experience in learning fluid mechanics and studying how slurries flow. Automation, signal processing, and controls could all be an interesting topic of exploration for electrical engineers. Math majors could make models of the process and expected yields with different amounts of inputs. Systems engineers could find the most efficient method of delivering the food waste to the reactor site. Lastly, software engineers could look at how the machine runs and develop new applications to make it easier to use. The possibilities are plentiful.

There are also a number of community benefits that could arise from a project like this. After taking our survey, Anne Ogilvie, Director for Team Learning in the Integrative & Global Studies department at WPI, reached out to the team and offered feedback and ideas. Anne pointed out that "public engagement is an extremely important component of sustainability, and so it would be excellent if the facility could not just benefit WPI, but our neighbors as well." She asked if other schools and organizations could also take part in donating their food waste. She also asked if this project could be a learning opportunity for local schools. Getting pre-K to 12 students learning about what happens to our food waste is important to spread awareness to the food waste problem in the United States.

Thus, implementing an HTL reactor on WPI's campus would only serve to benefit the campus. It would help reduce WPI's carbon footprint, provide new academic opportunities, and allow WPI to continue being a model campus. After the completion of this report, there is still work to be done before a reactor can be implemented. A different IQP group should investigate alternative food sources, or the willingness of Tyde Brook Farm to find an alternative feedstock for their pigs. Finding alternative food sources, supplemented with WPI's waste could potentially allow for a larger and more efficient reactor, for example, 750 tons of food waste annually had a profitable model, and could also help nearby businesses cut their food waste. Future projects should also look into how a grant could be obtained to initially purchase this reactor, and should work to push higher level administration to plan with companies such as Genifuel and Mainstream Engineering to get a better understanding of pricing. Lastly, it would be beneficial of another project to investigate a different method of changing bio waste into energy. This project only focused on HTL reactors, and it is possible there are more efficient and cost effective alternatives.

Conclusions and Recommendations

Introduction

This feasibility study examined WPI implementing a hydrothermal liquefaction reactor and community support to reduce its campus waste and carbon footprint. We found that the WPI community supports this project and may reduce its waste through individual onus of correct disposal of waste and funding of green initiatives. Implementation of an HTL reactor is a feasible possibility for WPI to recycle its campus waste, reduce its carbon footprint, and become more sustainable. Additionally, the HTL reactor provides educational and professional opportunities for students and faculty. WPI may broaden its green reach by extending its waste reduction to the local Worcester community.

Conclusions

Implementation of the hydrothermal liquefaction reactor requires a building, funding, operators, logistical systems, and yearly maintenance. The reactor would be housed in a 500 sq. foot metal container, similar to a shipping container. Estimated upfront costs are between $1-2 million and as low as $750,000 with government subsidies or grants. It requires one individual to be knowledgeable about operating the reactor and be on call to handle any problems. A logistical plan will be used to transport food and green waste from collection sites to the reactor storage. Estimates suggest an HTL reactor here at WPI would lose $100,000 a year.

The reactor cost may be reduced through government subsidies, grants, and/or tuition increase. For example, a similar project recently received a grant for $2 million dollars (Holbrook, 2021), and about half of the surveyed undergraduate students support an increase in tuition or fees of at least $50. With a $25 tuition increase and an estimate of 4500 undergraduates, $112,500 could annually be portioned to the reactor costs, covering annual maintenance.

WPI can increase its food waste collection and reduction through WPI Greek and off-campus housing, local restaurants, and grocery stores. With the added waste, the reactor will increase its energy output and capital production. Furthermore, the reactor will reduce the waste and carbon footprint of the Worcester community.

An HTL reactor provides WPI with educational and professional opportunities. A reactor would be an on-campus example of the WPI mission of theory in practice for the engineering departments and will give students experience with an operating reactor.

Recommendations

We have found that there are many benefits to implementing an HTL reactor at WPI. Beyond the environmental benefits of putting food waste to use, this reactor would open up valuable opportunities for students to put theory in practice that could later be applied to their careers. Since HTL is a growing industry, students who continue to pursue this field would be going into a career with a bright outlook. Students' experiences with this reactor during their education can be applied to their job search even if they do not continue to work with these reactors.

Obtaining grants and investigating government subsidies are ways in which the price of the reactor can be greatly reduced. A future IQP team should look into obtaining these grants. In addition to this, forming a relationship with one of these companies may not only help reduce the price of one of these machines, but may also create career opportunities for WPI students who have gained experience using these reactors.

Proposing this idea to administrators, and other WPI community members could help garner support from students which is already high. Moreover, if WPI wanted to pass the yearly operating costs to undergraduates, they could create a "green tax" of $25 which according to our surveyed students, will not have much pushback.

Because of all the benefits involved, and the many opportunities WPI has to reduce the price of the reactor, our team highly recommends WPI puts such a project under serious consideration and that future IQP and MQP groups investigate key questions surrounding the implementation of this reactor.

However, the decision need not be narrowed down to whether or not to implement such a reactor. WPI could conduct another project which investigates more processes to reduce food waste, such as anaerobic digestion or pyrolysis, as alternatives to an HTL reactor. If building something on campus is not desirable, a future project could investigate whether sending food waste off to a local company to process is feasible. These alternatives could offer similar educational benefits, while also giving food waste a better use.

If WPI would like to seriously consider the next steps in implementing the reactor, then looking into which company to work with would be an important next step. In our project, Genifuel and Mainstream Engineering were helpful, and stated that they are capable of building such a reactor, so we would suggest that WPI put those two companies under consideration. Considering where to place the building would similarly be an important decision. Our surveys suggest that the possibility of an odor generated by the food waste stored at the reactor could be a bother to students and staff. Fortunately, both of the experts we interviewed said this would not be an issue.

In summary, if WPI was to build this HTL reactor, they would reduce their carbon emissions by offsetting their energy needs with biofuel, create valuable educational opportunities for students and faculty, and could expand this project to involve and benefit other Worcester community members in order to be a model for pursuing sustainability goal.

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Appendix A: Chartwells Interview Questions

All questions concern a normal fiscal year at WPI, assuming no COVID-19 alterations as they may drastically change dining operations for a brief time period

- We read what an IQP in 2019 researched about the food waste management system at that time. Has anything changed since. What are some of the most meaningful impacts when it comes to managing food waste.
    - Have any suggested programs been implemented to your knowledge (collecting food waste from dorms for example)
- How much waste do we produce a year (in tons) between the dining halls on campus?
    - Where does this waste go and how is it sorted?
    - How do you track this waste?
    - How consistent is the waste/are there times in the year with little waste? Max waste? Do you have records for this?
    - What dining locations are you responsible for on campus? (Dunkin? Goat's Head?)
- Currently what does Chartwell's waste policy look like?
    - How are current waste products separated?
        - For example would vegetables be recycled differently than meats?
        - How do nonfood materials, such as napkins, get separated from other food waste products?
- Do you have an idea on what the campus dining waste profile looks like currently?
    - For example how much of our waste consists of fruits and vegetables, and how much consists of meats and other forms of waste?
    - Do you record any of this?
- What is the current procedure for ensuring there is only food waste in the designated bins.
    - How hard would it be to change our current recycling system to further separate things like napkins from other forms of biowaste?
    - Would your team be willing to make these changes?
        - We understand that a good portion of our food waste is donated to Tyde Brook Pig Farm. Could you elaborate on the process from WPI to the Farm? How much waste gets sent there?
- Is there a way we could get old data from previous years on the amount of food waste produced?
- Do you know of any contacts that could have more information on the specifics of our waste profile and recycling policies? (Only if needed)

Appendix B: Facilities Interview Questions

Concerning the normal year (without covid), our team would like to develop a better understanding of the techniques and the ways in which WPI deals with its yard waste

- Concerning the amount of green waste WPI produces annually, do you have an estimate or ball park figure?
    - What is done with this green waste?
    - What is the largest green waste item that you produce throughout the year?
        - What other items are included in this green waste?
- What is the process of disposing of this green waste?
    - Does all of the green waste get collected? If not why?
    - Is green waste production consistent throughout the year?
        - If not, what times of the year have the most and least green waste?
- How difficult would it be to start collecting green waste in a centralized location on campus?
    - Do you think your facilities team would have a hesitation or negative feeling towards this notion?

Appendix C: Expert Interview Questions

Given the amount of fuel available, 200 cubic yards of green waste, and approximately 75 tons of food waste annually, we have questions regarding the feasibility of a hydrothermal liquefaction reactor. Additionally, over the summer (2 months per year), the waste isn't separated so the consistency of fuel may drop.

- How much crude oil could be made from solid biowaste?
- How much refined oil could be made from the crude oil produced?
- How much is a gallon of biofuel and refined oil?
- What is the potential for the reactor to recoup on investment?
- Given the annual inputs, what size reactor would you recommend?
    - How much energy can we produce with this reactor?
- What is the initial cost to build a reactor and what are the operating/maintenance costs?
- Is there any smell/noise we should know about? If so, what are the methods used to regulate this?
- What is your recommendation for storing the reactor? If it needs to be stored indoors, where do most customers keep it?
- How many technicians does it take to operate the different potential reactors.
    - Do they need certain certifications and how difficult does it take to get these?
- How does the reactor run and what utilities does it need?
- What kind of material can we put in this machine, can we throw big objects in or will they need to be ground down?
- How reliable are these reactors? How often does the machine break down and what do you recommend customers do when this happens?
- For two months in the summer, dining services do not separate their trash and food waste. Instead, everything is mixed together and is sent to incineration. What should the school do during these two months? Should we continue to send this to the incineration or can the reactor handle the extra waste (napkins and plastic)?
- What academic value, if any, could having this reactor on our campus provide to students?
- What is the output of the reactor? What can this biofuel be used for as is? Does it need to get refined in order to get used?
    - On average, how much biofuel will the reactor generate?
- Do you have any suggestions on how we can implement bioenergy on campus?

Appendix D: Survey Details

In this appendix section, all questions for the teams survey are included. This encompasses the general, student, staff, and administration sections. The survey was prompted with this introduction:

> The purpose of our IQP is to investigate the feasibility of implementing a system that converts food and green waste to energy. As a result, WPI could reduce its carbon footprint. The plan would be to build a small reactor the size of a classroom either on the outskirts of campus or off campus. All the food waste that WPI collects will be fed to this reactor which will convert it either to bio-oil or bio-gas, both of which are natural alternatives to crude oil and natural gas.

General section - in this section, the purpose was to garner feelings towards broad green initiatives, and the potential consequences and benefits of the proposed hydrothermal liquefaction Reactor on campus:

- Are you a:
  - Student
  - Faculty
  - Staff
- How important to you is it that WPI pursues green initiatives to reduce their carbon footprint?
  - Extremely Important
  - Very Important
  - Moderately Important
  - Slightly Important
  - Not at all Important
- How do you currently dispose of your food waste?
  - On campus food waste bins
  - Off campus compost
  - Trash
  - Other…
  - If "other" please explain
- In order to create more bio-oil and further reduce carbon emissions, we had an idea to set up food waste bins around campus so that off campus students, faculty, and staff could all divert their food waste from the trash. How many minutes per day are you willing to spend to dispose of your food waste from home at a WPI designated bin if you knew that it could generate biofuel to run WPI vehicles?
  - 0 - 5
  - 6 -15
  - 16 - 30+
- How likely are you to dispose of your food waste at designated disposal areas so that they can be recycled into biofuel?
  - Extremely likely
  - Somewhat likely
  - Neither likely nor unlikely

- Somewhat unlikely
- Extremely unlikely
- If you are not likely to do so, why?

- How much do you support the idea that WPI should implement a food waste conversion system to convert unused food waste into biofuel in order to run some of the vehicles on campus? Assume no changes to tuition cost, fees, student life, noise, and any other factors.
    - A great deal
    - A lot
    - A moderate amount
    - A little
    - None at all
- How much do you support this idea if students and professors could use this system for educational value?
    - A lot more support
    - A little more support
    - Same support
    - A little less support
    - A lot less support
- How much would you support the idea if it created noise on the outskirts of campus?
    - A lot more support
    - A little more support
    - Same support
    - A little less support
    - A lot less support
- How much would you support the idea if it created a smell on the outskirts of campus?
    - A lot more support
    - A little more support
    - Same support
    - A little less support
    - A lot less support

Student Section - in this section our team wanted to gather more information about the student population and their thoughts on tuition increases, in addition to other factors:

- When picking a college, how much of a factor was the potential school's green initiatives?
    - A great deal
    - A lot
    - A moderate amount
    - A little
    - None at all
- If this project were to increase tuition (or fees) how much would you support?
    - None
    - Less than $50
    - Less than $100
    - Less than $300
    - Greater than $300
- What is your expected YOG
    - 2021
    - 2022
    - 2023

    - 2024
    - 2025
- What is your major?
    - Open ended
- If covid was not a factor, where would you live?
    - On campus dorms
    - Greek/sports house
    - Apartment
    - Other

Faculty/Staff Section - in this section we wanted to develop a better understanding of different members of WPI's faculty felt towards green initiatives. If a member said they were apart of facilities department, the survey continued:

- How important to you is it to work at a school that invests in green initiatives?
    - Extremely important
    - Very important
    - Moderately important
    - Slightly important
    - Not at all important
- What department do you work in?
    - Open ended
- Do you work in the facilities department?
    - No
    - Yes
        - How much do you support this idea if the department might have to hire additional employees?
            - A great deal
            - A lot
            - A moderate amount
            - A little
            - None at all
        - How much do you support this idea if you might have more responsibilities?
            - A great deal
            - A lot
            - A moderate amount
            - A little
            - None at all

Appendix E: Further Academic Research

This appendix contains further research and information learned through our various interviews with industry experts.

The representative said that this reactor would output biocrude oil. When asked about the storage of our product, our representative explained that our biocrude oil could be stored for a long time, however, it would require being mixed with ethanol or potentially frozen to keep it stable. In addition to the storage of the oil, our representative explained that this oil is still not refined enough to be burned in an engine without going through another refinement process, which would not be cost effective. Nevertheless, our representative said that by mixing this crude oil with diesel oil could be usable in some engines, and potentially some furnaces.

When Mainstream was asked how much energy this reactor could produce with the given waste amounts, our representative explained that we would be processing about 21.7lb/hr of dry waste and about 146.4 lb/h of wet slurry into the reactor, and that assuming a 20 minute residence time, the reactor would need to be 8.8gal(33.2L) large. He explained that running this machine for 24 hours a day would produce approximately 135.6MJ/h in the form of biocrude oil. These figures were calculated using a very conservative estimate of a 30 minute resonance time. Mr. Oyler also described a process where the resonance time could be reduced to 20 or even 10 minutes. This would make the machine more efficient and also capable of processing more waste. In addition to lowering the resonance time, Mr. Oyler said that uses of certain catalysts could also help the machine to run more efficiently.

Additionally, if the reactor were used to produce biocrude, it would be capable of producing 139 gallons a day, which is nearly three barrels of oil. Mr. Oyler explained that this oil would need to be refined before it could be used in any engines, but informed us he didn't see this as a draw back because the bio crude oil could be stored for 2 weeks, in which time there would have been enough produced to take a full truckload to a nearby refinery. It was also noted that due to the high temperature and pressure needed, safety is critical to an HTL reactos implementation. The potential reactor also should not produce too many noises or unwanted smells.

When asked about which electrical generator should be used, Mr. Oyler said this would be a pretty small generator of nearly 14 hp, and that this machine would cost 10 thousand dollars. When asked how long this machine would run, Mr. Oyler told us we could expect it to run nearly 300 days of the year and be closed for a short period of time for regular maintenance. This temporary shutdown was also due to the fact WPI doesn't collect resources in the summer so the feedstock dwindles.