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WPI Combined Heat and Power Feasibility

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Abstract

We explored the potential use of combined heat and power (CHP) on the main campus of Worcester Polytechnic Institute (WPI). CHP units have the potential to reduce electricity and heating costs, while simultaneously lowering greenhouse gas emissions. The team interviewed stakeholders to determine WPI energy goals, carried out a payback analysis for a CHP on campus, and estimated carbon waste savings. The team concluded that implementing a 2 MW Reciprocating CHP unit on campus would be economically and sustainably with an estimated savings of $ 22 million over 20 years with state incentives. Recommendations were also provided on integrating the machine into campus such as a location for the unit, as well as on capturing the thermal exhaust and using it for buildings on main campus such as the Rubin Campus Center and Salisbury Labs. This included calculating an estimated thermal load in order to achieve state incentive minimums making this unit economically beneficial and sustainable.

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1. Introduction

Energy production, including the generation of both electric and thermal energy is a large contributor to greenhouse gas (GHG) emissions in the United States (US) (Wiesser 2007). Colleges and universities across the country have been leaders in reducing GHG emissions by searching for innovative solutions to energy production. The US Department of Energy (DOE) has identified combined heat and power (CHP) as an “effective near-term energy option” that will reduce greenhouse gas emissions, while promoting energy efficiency and economic growth (Shipley, 2009). Using a single fuel source such as natural gas, CHP units create both thermal and electric energy by primarily generating one and then capturing the byproduct of the process to generate the other type of energy. The machines involved in this process are more environmentally friendly and cost effective than buying energy from the electric grid (DOE, 2013).

Currently, Worcester Polytechnic Institute (WPI) purchases electricity from a third-party source and spends roughly $200,000 on electricity costs monthly (WPI Facilities). The electric bills are high because they include not only the generation of electricity, but transmission, infrastructure, and maintenance as well. Additionally, by purchasing electricity, WPI does not have total control over its GHG emissions from electricity generation. Generating the electricity would give WPI control over how the emissions they contribute through their power source, as well as the ability to lower costs.

CHP units reduce energy costs, cut GHG emissions, and provide energy security, but to achieve this, numerous aspects of the unit need to be considered relative to its location (Wiesser, 2007). Different fuel sources for the prime mover, which is the type of generator, have different costs, carbon emissions, and efficiencies, which must all be taken into consideration. The unit must be sized properly for its given location so that total electrical and thermal efficiency is high.

Each CHP unit that is installed has unique requirements and specifications that need to be considered at different campuses. While there has been energy analysis in the past on WPI’s campus, this information is outdated because of the growth of campus; the electric capacity at WPI is constantly changing with the addition of both new buildings and more energy efficient technologies (WPI Facilities). In addition, there has been minimal research on the potential use of CHP as a means of creating electricity for WPI. There has never been an extensive study done exploring the use of CHP on WPI’s campus.

Our goal is to explore the potential use of CHP on the main campus of WPI. To accomplish this, the team first performed a series of interviews to collect data to identify the requirements for a potential CHP unit on the WPI campus. Using information from these interviews, we identified a system that would best fit on campus and calculated the potential cost savings of adding a machine. Finally, we calculated the carbon savings of implementing the machine. Based on these results, we created a series of recommendations for how to implement the system on campus and how the exhaust thermal energy could be used.

This report outlines relevant research, the series of actions executed, results, and recommendations. The background section highlights potential renewable energy sources on campus, CHP engine types, and WPI infrastructure. The methods section describes motivation for interviews, as well as how we calculated economic and greenhouse gas projections. Following methods, the results section outlines the important information received from our process. Finally, the paper concludes with our recommendations for WPI.

2 Background

Worcester Polytechnic Institute (WPI) originally created a micro grid to electrify the campus in the late 1800s and early 1900s (WPI Facilities). In the 1800s, most large-scale electricity users such as estates and campuses created micro grids at their facilities. At WPI, the grid was centrally located in the powerhouse, which created heat and electricity using two coal powered steam boilers and one steam turbine respectively. With the growth of campus over time, the original boilers were replaced with new boilers to accommodate increased energy and heating needs. In the meantime, the nation-wide electric grid was created, updated, and proven as a reliable means for electricity. Around 1950, WPI switched electricity consumption to the electric grid to accommodate the growth of campus without the need to continually upgrade the power house.

In this chapter, we discuss energy usage and combined heat and power (CHP). In Section 2.1, we explain the potential use of renewable energy sources and their potential on campus. In section 2.2, we expand specifically on CHP and prime movers. Finally, in 2.3, we discuss the infrastructure of WPI.

2.1 Energy Options

The recent emphasis on global warming has led to an increase in research and knowledge about greenhouse gas (GHG) emissions (Global Warming 2018). As a result, renewable energy and more eco-friendly sources such as solar, wind, geothermal, and CHP are transitioning to the forefront of energy creation. Each renewable energy resource works well in different unique environments depending on terrain, whether, or electrical needs. Sustainability on WPI’s campus is a part of the goal of this project; looking into different clean energy options is important.

Solar

Sunlight can be used to create solar energy when photons are absorbed by silicon solar panels and excite electrons creating the flow of electricity (Boxwell 2014). Solar energy is traditionally implemented in the form of solar panels either on the roofs of buildings or homes. This means that roofs need to be stable enough to support the weight of panels and have a large enough surface area to support the electric needs of its attached building.

There are three main types of solar panels: monocrystalline, polycrystalline, and thin film, each of which have their own pros and cons (Greenmatch, 2018). Monocrystalline panels are known to be the most efficient, usually ranging from 22-27%. Polycrystalline panels are usually less efficient due to the way the silicon is produced in bulk rather than individually and the effectiveness usually ranges from 15-22%. Lastly, there is are film panels, which are the cheapest version due to the ease of their production, but because of this, they also lack in efficiency, only ranging from 15-22%. Solar panels can be a good option for a campus, if given the space to produce enough energy.

Solar energy can be used to create electricity, heat water, as well as heat and cool buildings. As of January 2018, solar power ranged from $2.16 to $3.08 per watt (Solar Estimate, 2018). Solar panels are generally maintenance free, with little to no cost once they are installed. The typical cost for homeowners up front can seem reasonable, until the added installation fee, permitting, and inspection cost gets added on, which can be upwards of

$2,500 for a house-sized unit (Solar Estimate, 2018). The added costs, permitting, and inspection could delay the installation for over 6 months, which means solar panels generally have a large upfront cost.

Moreover, in New England, because of the weather, energy production from solar panels is not always reliable. Assuming Earth, at a season peak, receives a solar influx of approximately 1,000 W/m^2, and solar panels generally are 15-22% efficient, one can conservatively state that solar panels collect 150 W/m^2. This calculation assumes an ideal temperature of 25 degrees Celsius and a perfectly angled panel. Since WPI is in the Northeast, we must account for seasonal changes well below 25 degrees Celsius. Additionally, solar panels become 100% ineffective with more than 5 cm of snow on them, which can happen often during a New England winter.

WPI is in an urban environment in the center of New England, which limits the capability of solar power on campus. The only possible option for solar panels at WPI would be placing them on the roofs of buildings or above parking lots. However, there is not enough surface area to create enough electricity for peak loads. A solar panel that created 2 MW of electricity would need approximately half a square kilometer (two tenths of a square mile) (Gaughan, 2018).

Wind

Wind is a renewable energy source that can be captured through wind turbines and used to create electricity. Wind turbines are often placed in locations with ideal and consistent wind speeds. Electricity generation begins to be created at wind speeds around 8 mph and wind turbines usually max out their efficiency at around 30 mph. When speeds are greater than 50 mph wind power becomes less effective and turbines begin to shut down (Nottingham, date).

Wind turbines are generally large machines, each blade can be upwards of 180 feet long and they usually average more than 280 feet tall. Wind provides over 30% of electricity in 4 states; Iowa, Kansas, Oklahoma, and South Dakota. These states have many open areas where large wind farms can play a much bigger role in the electric grid than in Massachusetts. Wind energy prices have been on the decline in recent years as it is harvested more frequently; the prices for offshore wind turbines has dropped as low as $0.02/kwh (Energy Top 10).

Wind turbines require a large amount of space and many communities have ordinances regarding their use. Worcester is one of these communities, so wind turbines would not be feasible on or around WPI’s campus. The only option to implement wind turbines would be for WPI to buy land and develop their own wind farm elsewhere.

Geothermal

Geothermal energy is thermal energy stored beneath the Earth’s crust that can be harvested to create electricity, as well as, to heat or cool buildings. The first 10 feet of the Earth’s crust are a constant temperature. This constant temperature can be used to heat in the winter or it can be used to cool in the summer. Geothermal energy can produce hydrogen gas, which smells like sulfur and the fluids used have toxic material within it.

Geothermal energy is one of the world’s most reliant energy sources, as it is consistent. This energy can be used to meet the minimum base load for a power plant or an electric grid and take more load as needed. Geothermal can be used to cool buildings indirectly, generate electricity, or heat a building directly. There is over 100 GW of potential geothermal energy available to harvest across the globe. Currently, most of the geothermal energy being harvested in the US is in western states including California and Colorado (National Geographic, 2018).

Geothermal energy could be a good source to use at WPI because warming the water from the natural heat of the Earth would reduce the electricity that the campus currently uses. However, with WPI's current infrastructure, geothermal would not be easily integrated on campus. Like wind power, being in an urban environment restricts the available space for geothermal.

2.2 Combined Heat and Power

A combined heat and power (CHP) unit is a system that uses a single fuel source such as natural gas or coal to create both thermal and electric energy. It does this by primarily generating one source and then capturing the byproduct of the process to generate the other type of energy (Energy, 2013). Because the unit only uses one fuel source to create two types of energy, CHP units can reduce energy costs. This energy cost savings has led apartment complexes, as well as government buildings to begin installing CHP units (Matulka, 2013). In addition to the cost savings, CHP systems can provide power even when the external grid has shut down. In the wake of Hurricane Sandy in 2012, a hospital in Greenwich, CT lost power for about 7 seconds because of it had CHP unit, while the grid in the surrounding area remained offline for nearly a week. A CHP system is a reliable source for energy creation that can be used on WPI's campus.

There are two main engine cycles that can be used for a CHP unit, a topping and a bottoming cycle. In a topping cycle, a single fuel source is used to generate electricity, then waste heat is captured and converted into thermal energy. As can be seen in Figure 1, which represents a basic topping cycle, fuel goes into the engine to generate electricity, while hot exhaust gases are captured by a heat recovery unit to create steam or hot water.

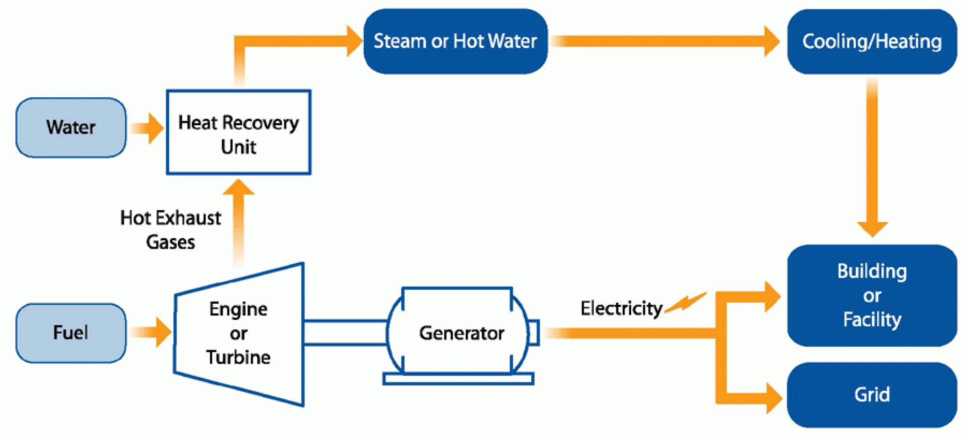

Figure 1: CHP Basic System, Topping Cycle (EPA, 2018)

In a bottoming cycle, the energy source combustion is used to generate heat for manufacturing processes with exhaust heat being captured and turned into electricity. Even though both topping cycles and bottoming cycles can be beneficial given the right criteria, the team focused on an engine with a topping cycle because the primary concern for WPI is to produce electricity.

There are five main types of prime movers that can be used in a topping cycle, including gas turbines, steam turbines, reciprocating engines, micro-turbines, and fuel cells. Each prime mover has advantages and disadvantages that are discussed below.

Gas Turbine

A gas turbine, mainly described by a Brayton Cycle, starts with compressing the inlet air raising its temperature, which is then further heated due to the fuel of the combustion chamber as seen in the left part of Figure 2. The mixture of hot air and combustion gas drive the power turbine, as seen in the middle of Figure 2, which produces enough energy or net power to provide shaft power to the mechanical process of running the compressor. A gas turbine is a good prime mover for providing both electrical and thermal needs for allocation (Energy, 2016).

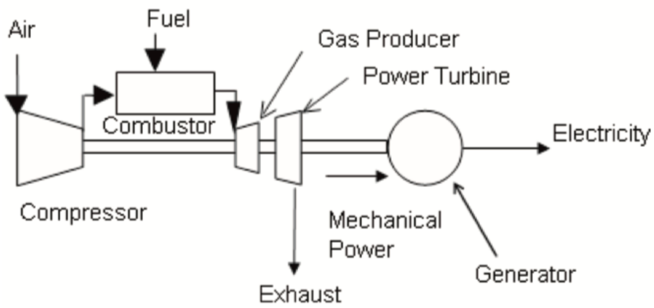

Figure 2: Simple Gas Turbine (Gas Turbine-Energy, 2016)

This system works best when the expansion turbine runs at the highest temperature while the compressor has an inlet flow temperature as low as possible because the power that is produced by the expansion turbine and used by the compressor is proportional to the absolute temperature. It has also been found that the system can have a better efficiency and specific power when there are higher temperature and pressure ratios. The range of efficiency for this prime mover varies based on its size and specific model and type, but it has been found to have a combined electrical and thermal efficiency of between 65% and 71% based on gas turbine averages throughout the United States (Energy, 2016).

However, prime movers involving turbines create a larger percentage of thermal energy than electrical energy. The average installation cost for these units ranges from $1,300 to $3,300 per kW. These units should be run at maximum power all the time, so the efficiency does not drop, and emissions remain low (Energy, 2016). A gas turbine could be a great fit as a CHP prime mover if given certain circumstances with a base electric load of 10MW and higher.

Steam Turbine

A steam turbine functions on a Rankine cycle where water under high pressure is heated to produce high pressure steam as seen in Figure 3. The high-pressure steam is expanded in a steam turbine where the steam energy is then converted into a mechanical power that drives the electrical generator. When looking to fill the CHP thermal requirement, the low-pressure steam that leaves the steam turbine is used as seen in state 4 on Figure 3. Finally, the condensed liquid is then returned to the pump making the cycle repeatable.

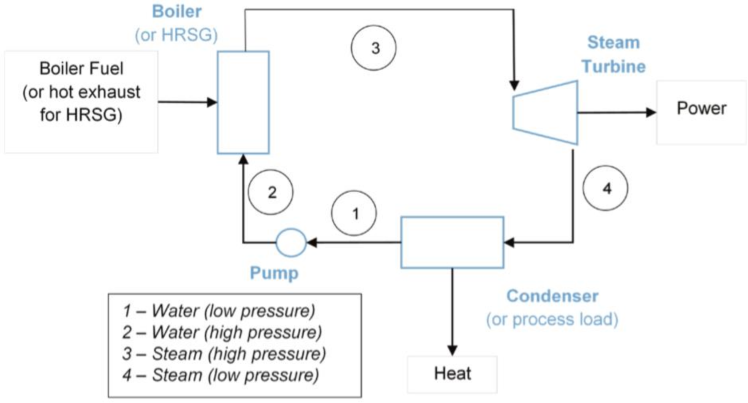

Figure 3: Simple Steam Turbine (Steam Turbine-Energy, 2016)

Steam turbines are categorized as either extraction or non-condensing. An extraction turbine has one or more openings that take out steam at some intermediate pressure and then use it in a CHP configuration that requires steam pressures higher than pressures available from back pressure steam turbines. A non-condensing steam turbine exhausts steam directly into an industrial or steam distribution system. Even though the efficiency is dependent on the size and exact company, the average prime mover efficiency for a steam turbine is about 80%. The electrical efficiency for these is a lot lower at an average of 6%, but this number can be tweaked to get a little higher in efficiency. The average price range for one of these units is about $670 to $1,100 per kW (Energy, 2016). Steam turbines are an appropriate fit for a location with a high thermal load.

Reciprocating Engine

Reciprocating engines are characterized by a rich or lean burn. There are two primary types of engines, a spark ignition and a compression ignition. A spark ignition start uses a spark plug to ignite a pre-mixed air fuel mixture. A compression ignition start compresses the air introduced into the cylinder creating an auto-ignition. Even though they have different starting processes, both engines have a similar four step process for power generation. As seen in Figure 4, they first have an intake stroke where there is an introduction of air or an air-fuel mixture into the cylinder. They next have a compression stroke where there is a compression of the air or an air-fuel mixture within the cylinder. Next, the power stroke begins to accelerate the piston due to the expansion of the hot and high-pressure combustion gases. Finally, there is an exhaust stroke where there is an expulsion of combustion products from the cylinder through the exhaust (Energy, 2016).

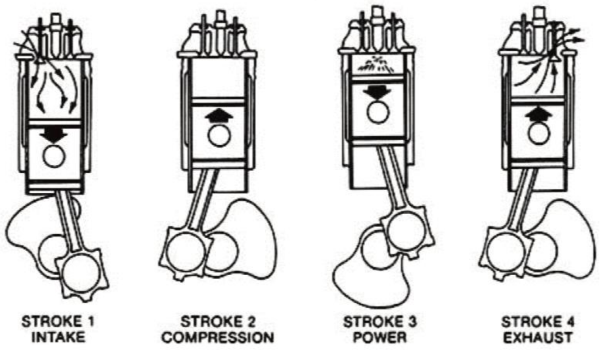

Figure 4: Reciprocating Engine 4 Stroke Start (Reciprocating Engine-Energy, 2016)

The overall combined efficiency is about 77% to 83% with an electric efficiency of about 36% and a thermal efficiency of 44%. However, the bigger the MW size, the more electrical efficiency is achieved while the thermal efficiency drops. The installation cost, not including future maintenance, is around $1,400 to $2,900 per kW (Energy, 2016). Reciprocating engines are a great fit for a location with a varying load while still requiring good electrical and thermal efficiencies.

Microturbine

A microturbine is a smaller combustion turbine ranging from about 30 to 330 kilowatts of power generation. The setup of a microturbine is very similar to that of a gas turbine where it operates on a Brayton Cycle. As seen in the bottom of Figure 5, air is compressed through the compressor, heated by fuel, and those mixed together drive the expansion turbine which pushes the inlet compressor and a drive shaft which is fastened to an electrical power generator.

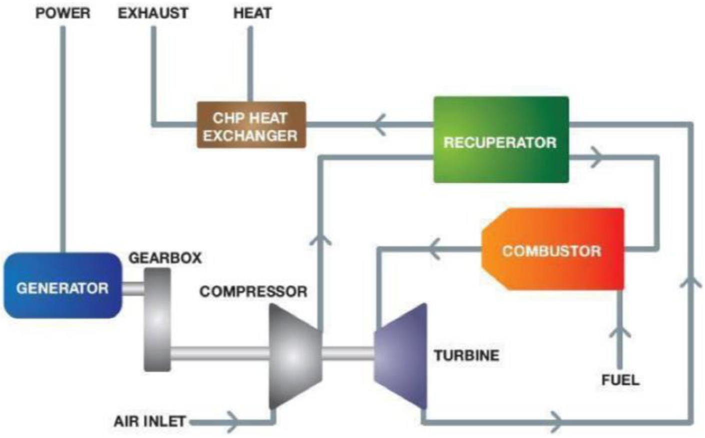

Figure 5: Simple Microturbine (Microturbine - Energy, 2016)

At the heart of a microturbine is the compressor-turbine or turbo-compressor, which is a single moving part in the shaft that has the potential for lowering maintenance needs and enhancing the overall reliability (Reciprocating Engine-Energy, 2016). The combined electrical and thermal efficiency of this unit is about 64% to 72%, but the average maximum size of a microturbine is limited to 330 kW while WPI needs a much higher electrical value. It has also been found through CHP companies such as Capstone that microturbines are not seen as reliable due to not operating as well anchoring the company. The 20-year plan of some of these units has shown that the maintenance costs, as well as the average life expectancy, are limiting optimism about this prime mover. The range for the price of this type of prime mover is about $2,500 to $3,200 per kW. Given the small electrical requirements of a microturbine, one of these units may be great for a small application like a home.

Fuel Cell

Fuel Cells are a newer technology that have high efficiencies while having low emissions. Most CHP units use a natural gas or biogas as power whereas the gas in a fuel cell is reformed into hydrogen. The hydrogen reacts creating electricity for the CHP unit. In Figure 6 below, hydrogen and oxygen are constantly fed to the anode and cathode where chemical reactions occur. These chemical reactions create ions and electrons leading to a direct current. Since fuel cells are a newer technology, their capital costs are higher, with parts needing replacements every five to six years. The current market is sharply steering away from these systems as they prove to be inefficient with numerous replacements of hydrogen cell beds (Energy, 2016).

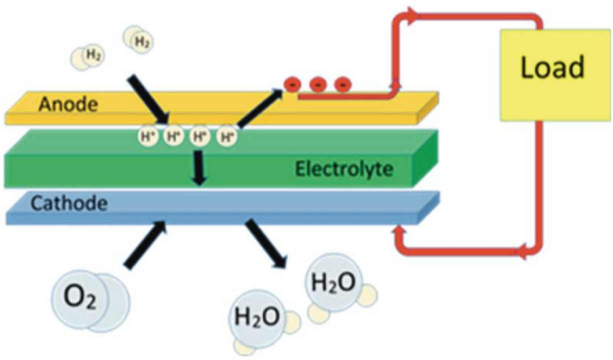

Figure 6: Simple Fuel Cell (Fuel Cell -Energy, 2016)

Hydrogen is not used in many other applications making it difficult to buy. Because of this, maintenance costs are high for fuel cells as the cell beds need to be replaced every 5 to 6 years. The location of this type of unit is also controversial. With Fuel Cell prime movers, there is also auxiliary equipment that is required with the prime mover unit. The fuel cell also has an overall efficiency of about 62% to 75%. An average starting price for fuel cell prime movers ranges from about $4,600 to $10,000 dollars per kW.

2.3 WPI Infrastructure

Since WPI opened in the mid-1800s, it has grown and outgrown the capacity of the main campus. In the past 30 years alone, numerous buildings have been added to campus including the Rubin Campus Center, the Sports and Recreation Center, the Bartlett Center, Fuller Laboratories, and Foisie Innovation Studio. In addition to buildings, the number of students on campus is constantly increasing with the goal of 40 students per year growth (Henry Fitzgerald). Because of this constant growth, the WPI Power Plant has been adapting constantly to meet the increasing needs of campus.

Electric

WPI receives electricity from National Grid, which is transported into campus through the main power plant. From the power plant, the electricity is then wired to buildings across main campus, which means there is one main meter that accounts for the electric use of the main campus. Fortunately, the power plant has upgraded hardware to track the electric usage for some specific buildings. The electric load comes from traditional uses such as lighting and outlets, but a large portion of use comes from the electric heating and cooling of campus buildings as well.

Natural Gas

Natural gas is both transported to the power plant and to individual buildings across campus. The gas transported to the power house is used to power the steam boilers, which are used to heat most of the campus. Steam is transported around campus using two separate loops, the east and the west loop. The east loop starts at the power plant and continues to Salisbury Labs where it then goes to buildings such as Fuller Laboratories and Atwater Kent. The west loop starts at the power plant as well and continues through Higgins Laboratories where it then goes to the Foisie Innovation Studio and separates at a t-joint to connect more buildings such as Sanford Riley and Morgan Halls. Gas that is transported to individual buildings is used for cooking and domestic hot water. The price of fuel compared to the price of power is known as the spark spread. In Massachusetts, the spark spread is over 4, meaning that the difference between the cost of fuel to power a CHP system producing power and heat versus grid power is four times cheaper (Eversource, 2018).

3.0 Methodology and Engineering Process

Our goal was to explore the potential use of combined heat and power (CHP) on the main campus at Worcester Polytechnic Institute (WPI). To accomplish this, the team identified the requirements for a CHP unit on campus via interviews. After determining requirements, we established the size and type of prime mover. Finally, we performed payback calculations and determined how much greenhouse gas WPI would save in pounds of carbon dioxide. We modelled our process based on *Engineering Design: A Materials and Processing Approach* (Dieter, 2000) by George E. Dieter, as well as, *Engineering Design Process* (Yousef, 2003) by Yousef Haik.

3.1 Identify Requirements

To determine the requirements of a CHP unit at WPI, we conducted interviews and collected data pertaining to the needs of campus. Each interviewee highlighted specific perspectives, specifications, and considerations to the process. Following the interviews, we carried out data analysis to determine heating and cooling requirements, as well as identified existing infrastructure on campus.

3.1.1 Interviews

At the beginning of our project, we carried out a series of interviews. These interviews served two purposes; the first was providing the team with background knowledge and the second was to determine requirements of a CHP unit on campus. Each interviewee had a unique perspective on the project and were able to provide different types of information. Based on our research prior to interviews, we identified infrastructure, size, cost, and emissions as critical considerations for this project. Table 1 lists the people who were interviewed and their titles.

Table 1: Informational Interviewees

Name (Title)	**Group Represented**
Bill Spratte (Director of Facilities Operations)	WPI Facilities
Bill Grudzinski (Chief Engineer)	WPI Facilities
Mark Macauley (VP of advanced CHP Systems)	ZHP Systems
Henry Fitzgerald (Trustee)	WPI Board of Trustees
Mark Gunnard (Chief Engineer)	Clark University

For background knowledge, we needed to determine the current infrastructure on campus because the potential system would need to be integrated into the preexisting system. To determine information on the electric infrastructure, we asked about meters, their locations, and what buildings were on the main campus meter. For thermal, we asked about the number of boilers, their types, fuel sources, current steam loops, and chilling units on campus.

Once we determined how campus was laid out, we needed to determine more specific requirements of the CHP system. First, we needed to determine the sizing requirements, so we asked WPI's chief engineer, Bill Grudzinski, about the current loads on campus, while we talked to the VP of Advanced CHP Systems at ZHP, Mark Macauley, about how system sizes related to incentive programs. Then we asked the Director of Facilities, Bill Spratte, and the Board of Trustees member, Henry Fitzgerald, questions about the cost of the system including payback time and maximum capital cost of implementing a system. Finally, we asked all interviewees about the carbon emissions of the system, including what the goals for campus were and how to reduce the emissions of the system.

3.1.2 Decision Matrix

Based on the interviews, we created a decision matrix to prioritize stakeholder requirements. This prioritization is achieved in a decision matrix by comparing each requirement to each other in a matrix format. The requirements were placed as headings for both the rows and columns, then each customer need is compared to every other. A score of 1 is given if the need in the column is considered of greater importance than the need in the row. If the opposite is true, the respective cell is marked with a score of -1. Two requirements that are of equal importance are given a score of 0. The sum score of each customer requirement is used to rank the requirements overall. The importance of each customer requirement in relation to one another, represented by the score ranging from -1 to 1, is determined based on the information acquired through the interviewing stakeholders. At the end of this activity, if done correctly, the customer requirements are prioritized based on which ones are more important for our final recommendation. At the end of this process, we created a list of requirements that need to be considered for the system ranked based on their importance. The item requirements were: Size (Physical), Size (Megawatts), Thermal Byproduct, Prime Mover Efficiency, Location, Cost, Noise, Unique Features, Greenhouse Gas Emissions. This process was first done by the team, then done individually with both Bill Grudzinski and Mark Macauley.

3.2 CHP at WPI

In this section, we explain the methods that we used to evaluate the best CHP option for WPI. Interviews were very helpful in giving us general information about campus, but we needed to do our own research and analysis for specific details. We determined average, maximum, and minimum electric loads for campus in megawatt hours (MWh). Following this, we also determined the heating and cooling loads of campus.

3.2.1 CHP Electrical Size for WPI

Facilities provided the team with the monthly electric bills from 2012 through September 2018 for all of campus. To choose the right CHP electric size for WPI, we had to sort through the data given and filter out all buildings not on the main meter. We then compiled all the data into one spreadsheet and organized it by month. Once the spreadsheet was created, we were then able to take the maximum and minimum values for each of the months to create a range. These bills were given in total kilowatts hours (kWh) per month, but we wanted to find the average megawatt's used per hour per month. To do this, we had to convert to megawatt hours (MWh), so we divided the given number by 1000, which was repeated for each month. A frequency graph was also created in MWh to depict the number of times a certain MWh usage was hit and to catalog the frequency with which the usage ranged between 1.6 and 2.6 MWh. Based on historical usage, the team made an informed decision on the proper electrical size of a CHP for campus.

3.2.2 CHP Prime Mover for WPI

For CHP units, there are numerous prime mover options including gas turbines, steam turbines, reciprocating engines, microturbines, and fuel cells. To choose the best fit for the WPI campus, we did research and completed a literature review to determine each system's strengths and weaknesses. We then went through each prime mover and determined how it would best fit on campus; some limiting factors include physical and electrical size.

3.2.3 Determining the Current Thermal Load at WPI

With CHP units, it is important to look at and understand not only the electric sizing of the unit, but also the thermal load. To do this, the team received the amount spent in natural gas per month between 2012 and September 2018 for the main campus and combined that data into one spreadsheet. Once we compiled the data for the main campus, we created a range in one million British Thermal Units (MMBtu) per month so we could see the maximum and minimums over the last 6 years. Using the chosen prime mover and electrical size, we linearly interpolated a useful thermal output based on a Department of Energy data sheet and a number in MMBtu/hr. which we converted to MMBtu/month (Department of Energy, 2016). We then compared that average thermal output to the thermal needs of WPI. This information was important to consider to properly use the thermal output for WPI to receive CHP incentives from the state.

3.3 Economic Analysis

After choosing a prime mover and engine size, we wanted to determine the economic impact this machine would have on campus. To do this, we had to calculate the installation costs, maintenance costs, fuel savings, and incentives that would apply to this machine.

Installation and Maintenance Cost

To estimate installation and maintenance, we used linear interpolation from the information given in Table 2.

Table 2: Reciprocating Engine Capital Costs (DOE, 2016)

System	1	2	3	4	5
Net Power (kW)	100	633	1141	3325	9341
Installation Cost ($/kW)	2900	2840	2370	1800	1430
Maintenance Cost ($/kWh)	.024	.021	.019	.016	.009

The coefficient of determination or r squared value of Net Power verse Installation Cost is .8166, so the data set is strong enough to roughly estimate installation cost at 2 MW through linear interpolation. 2 MW is equal to 2000 kW so, we interpolated between systems 3 and 4 because 2000 kW falls between 1141 kW and 3325 kw. The formula we used was:

$$y = y_1 + (x - x_1) * \frac{y_2 - y_1}{x_2 - x_1}$$

Where y_1 and x_1 come from system 3 in Table 2

And y_2 and x_2 come from system 4 in Table 2
And x = 2000 kW~ 2 MW

Like installation cost, we used the source from Table 2 to estimate maintenance costs. For Net Power versus Maintenance Costs, the coefficient of determination was 0.9381 so this data is strong enough to interpolate from. We repeated the same interpolation formula f above with the same assumptions except used Maintenance Costs instead of Installation Costs.

Mass CHP Incentive

Massachusetts offers incentive programs for CHP units because they can create less waste and lower carbon footprints than traditional energy creation. Specifically, the Commonwealth offers incentives based on overall efficiency of the unit. At minimum, a unit must be 60 % efficient to receive an incentive. Massachusetts CHP incentives range from $.075 to $.120 per kWh depending on unit size and efficiency (Mass Save, 2018). The formula we used to estimate the incentives is:

$kW \times hrs \times incentive\ rate$

$kW = 2000$ (based on the recommended size of the unit, see section 4.2.1)

$hrs = 8000$

$incentive\ rate = .075\ to\ .09$

Hours is assumed to be 8000 annually to account for maintenance.
Incentive rate is a range because overall efficiency is not certain.

In addition to initial capital incentives, Massachusetts participates in the Alternative Energy Portfolio Standard (APS) program, which provides incentives for alternative energy production. The current program currently averages $20 in credits per MWh. To calculate this annual saving, we used the formula:

$MW \times hrs \times \$20$

$MW = 2$

$hrs = 8000$

This incentive will be applied every year until the program ends.

Electrical Savings

To calculate the electrical savings for campus, we calculated the savings per kwh. Cost of fuel is given in $/MMBtu, so we first had to convert $/MMBtu into $/kwh. To do this, we used the following conversions:

1 MMBtu = 1000000 Btu
1 btu = .0002931 kwh

The cost of commercial natural gas in New England is currently $9.20 per MMBtu so we used that figure to determine the cost of creating electricity in the CHP (EIA, 2019). Currently, WPI pays $0.103 per kwh of energy so we subtracted the converted cost of fuel from this number to find the savings in $/kwh (WPI Facilities).

Simple Payback

Once we had calculated installation and maintenance costs, Massachusetts CHP incentives, and electrical savings, we summarized the information in a table. Based on the table, we used cumulative cash flow to determine the simple payback period.

3.4 GHG Emissions

To calculate greenhouse gas emissions, we compared our project to the Worcester County Jail CHP. We followed the steps shown in Table 3. The definitions of all variables are also included in Table 3. The first step was to calculate the CO2 emissions from an on-site thermal production. The equation used for this is: $C_T = F_T \times E_{FF}$ (WPI, 2016)**.** The variables are defined as follows:

C_T is the CO_2 emission from on on-site thermal production,

F_T is the thermal fuel savings in Btu

E_{FF} is the CO_2 emission factor (lbs of CO_2/MMBtu).

We use this equation to calculate the CHP's thermal output in Btu.

$The\ thermal\ futel\ saving\ is\ calculated\ as\ F_T = \frac{CHP_T}{\eta_T}, where\ CHP_T$ is the thermal output of the unit in Btu and η_T is the efficiency of the thermal equipment. E_{FF} can be found on the EPA's website (EPA, 2018).

Next, we calculated the CO_2 emissions from the electric grid. We use the following equation: $C_G = E_G \times E_{FG}$**,** where C_G is the CO_2 emissions from the electric grid (lbs. of CO_2), E_G is the displaced electric grid power from the CHP (kWh), and E_{FG} is the electric grid emissions within Massachusetts (lbs. CO_2/kWh). $E_G = \frac{CHP_E}{1-L_{T\&D}} CHP_E$ is the electric output of the CHP unit (kWh) and $L_{T\&D}$ is the loss of transmission and distribution (percent in decimal form) (EPA, 2018).

Table 3: Equations and definitions for greenhouse gas emission calculations

Step	Equations/Variables	Definition
1	$C_T = F_T \times E_{FF}$	
	C_T	CO_2 emissions from onsite thermal production.
	F_T	Thermal fuel savings
	E_{FF}	CO_2 emission factor
	$F_T = \frac{CHP_T}{\eta_T}$	
	CHP_T	Thermal output of the unit
	η_T	Thermal efficiency of the unit
2	$C_G = E_G \times E_{FG}$	
	C_G	CO_2 emissions from electric grid
	E_G	Amount of electricity that the CHP generates
	E_{FG}	Emissions from the electric grid in our area
	$E_G = \frac{CHP_E}{1 - L_{T\&D}}$	
	CHP_E	Electric output of the unit
	$L_{T\&D}$	Loss of transmission and distribution
3	$C_{CHP} = F_{CHP} * E_{FF}$	
	C_{CHP}	CO_2 emissions from CHP system
	F_{CHP}	Fuel used in the CHP unit
	E_{FF}	Fuel emission factor
	$F_{CHP} = \frac{CHP_E}{EE_{CHP}}$	
	CHP_E	Electric output of the CHP unit
	EE_{CHP}	Electric efficiency of the unit
4	$C_S = C_T + C_G - C_{CHP}$	

We calculated the CO_2emissions from CHP using $C_{CHP} = F_{CHP} * E_{FF}$, where C_{CHP} is the CO_2 emissions from the CHP system (lbs. CO_2), F_{CHP} is the fuel used in the CHP unit (Btu) and E_{FF} is the fuel emission factor (lbs CO_2/MBtu). We calculated F_{CHP} as

$F_{CHP} = \frac{CHP_E}{EE_{CHP}}$, where CHP_E is the electric output of the CHP unit (Btu) and EE_{CHP} is the electric efficiency of the system.

Finally, we calculated the carbon dioxide savings (in lbs.) using: $C_S = C_T + C_G - C_{CHP}$

4.0 Results

In this chapter, we present our findings from interviews, show how we came to our recommendations for facilities, and explain the projections for the future CHP unit. In the first section, we summarize our key findings from interviews and outline which features we looked for in a system. In the second section, we discuss how we analyzed and determined the proper system type for campus. Next, we analyze the economic savings that the system is expected to provide for campus. Finally, we calculate the carbon savings for campus.

4.1 Requirements

Interviews revealed specific requirements for the CHP system such as cost, size, and location. We were able to determine the requirements in two ways; first when interviewees directly mentioned them and second when interviewees indirectly revealed the need for them through their answers. All parties interviewed emphasized the importance of considering cost when researching an option. Since WPI is a research academic institution, capital projects that are not performed in labs, classrooms, or for research are often scrutinized closely for their potential cost benefit to campus. Mark Macauley informed the team that the Commonwealth of Massachusetts offers incentive programs for CHP that could potentially make the machine more affordable. For this he stated that we need to strongly consider both the electric and thermal loads and efficiencies to make the machine more economically appealing. Based on these loads, a prime mover and engine size had to be researched to determine if the machine would be efficient enough to meet the load requirements for campus, as well as incentives. These were the focus of our interviews, so we determined that they were the four most important requirements to consider.

Through interviews, studies, and analyses, we found many useful results for the potential of a CHP unit at WPI. From multiple sources, the most important piece of information is the megawatt sizing of the CHP. A designer can always oversize a unit, but one cannot undersize it. Keeping in mind that a CHP unit always needs to be running with at least a 60% efficiency; if not, incentives could be foregone, and the payback period extended. The most important factor is thus to properly size the CHP unit to receive all benefits, as well as save WPI money.

Three requirements that were not always directly mentioned were physical size, location, and noise of the unit. WPI has a small inner-city campus with not much space to maneuver around. Additionally, the power plant is surrounded on three sides with academic space and on the fourth with executive offices. This means that physically the machine needs to fit within the limited space or potentially be put in another place on campus with infrastructure to connect it to the power house. Location is important because adding additional infrastructure has the potential to drastically increase the cost of the project. Also, CHP units are loud and if the machine is going to be surrounded, noise reduction needs to be a consideration.

Finally, emissions and unique features were brought to our attention. When we visited the CHP unit at Clark University, their chief engineer Mark Gunnard mentioned black start and island mode. Black start means that a unit would be able to start itself without electricity and island mode would allow the unit to run even if local power was out. WPI is a residential campus and if the power were to go out for an extended period, these features would allow the CHP unit to keep campus online. CHP units can reduce GHG emissions if they are implemented with proper scrubbers, which Mark Macauley brought to our attention.

Decision Matrix

Once we determined the nine requirements, we executed three decision matrices to determine which requirements were the most important to consider. During the process, we conducted our own run through the decision matrix together. We also gave Bill Grudzinski and Mark Macauley, separately, an opportunity to complete the decision matrix so we could get a different perspective on the ranked list of requirements. Mark Macauley, coming from a background of installing over 300 CHP units, and Bill, being one of the customers and the chief engineer at WPI facilities, were able to give us different perspectives on the requirements. We explained the process of the decision matrix to them. We went through the same process as we did and let them talk through which ones would play more of a role on WPI's campus. After, we explained we did the same process and compared the lists to one another. The results are shown in Table 4.

Table 4: Decision Matrix Results

MQP Team	Bill Grudzinski	Mark Macauley
1. Size (Physical) 2. Size (Megawatts) 3. Thermal Byproduct 4. Prime Mover Efficiency 5. Location 6. Cost 7. Noise 8. Unique Features 9. Greenhouse Gas Emissions	1. Cost 2. Unique Features 3. Size (Physical) 4. Size (Megawatts), Location, Prime Mover Efficiency 5. Thermal Byproduct 6. Noise, Greenhouse Gas Emissions	1. Cost 2. Size (Megawatt), Location 3. Thermal Byproduct 4. Unique Features 5. Prime Mover Efficiency 6. Noise 7. Size (Physical) 8. Greenhouse Gas Emissions

It was interesting to compare our results as engineers to those who are customers and professionals within the business. Looking at cost specifically, the team had it ranked 6/9 compared to both Mark Macauley and Bill Grudzinski, who it ranked first. All three decision matrices had megawatt sizing in the top half of our lists. This shows it is important to really take into consideration the size, and thus with it, the thermal byproduct, of the CHP system.

4.2 Best CHP for WPI

Based on our interviews, data, and results found, the team was able to find the best electrical size, prime mover, and establish the current thermal load to understand the current thermal needs of the WPI campus.

4.2.1 Best CHP Electrical Size for WPI

Following interviews, the WPI Facilities Department gave the team access to electric data for campus. The data showed that over the past 6 years, electric loads had a wide range as seen in Figure 7

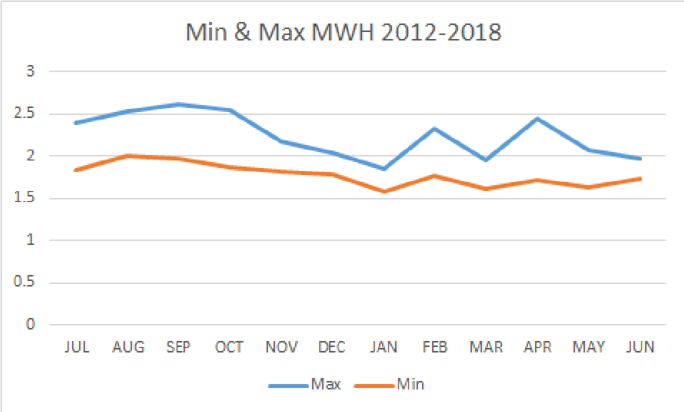

Figure 7: Maximum and Minimum Electric Usage

In this figure, the maximum and minimum electrical charges for the last 6 years are outlined. As shown in Figure 7, the minimum electrical usage is as low as about 1.6 MW and the maximum as high as about 2.6 MW. Even though Figure 7 provides a range for analysis, it was not specific enough as we did not want to oversize this CHP unit, leading to our Figure 8.

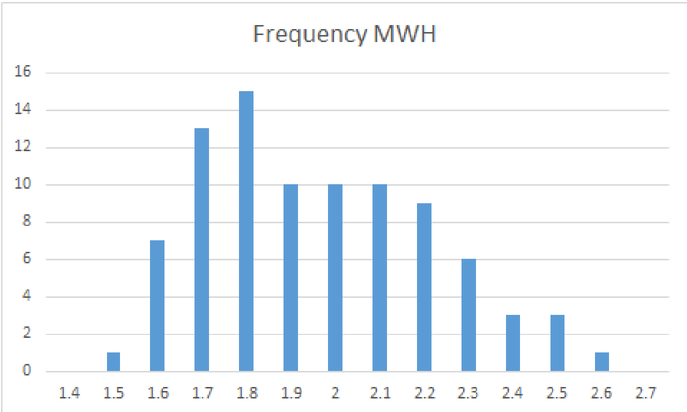

Figure 8: Frequency of MWH Electric Usage

Figure 8 shows that over the last 6 years, the most frequent megawatt per hour usage was 1.8 megawatts per hour, occurring total number of 15 months. We used this data to ensure that the CHP unit is properly sized.

When determining the proper size for campus at WPI, we considered average campus loads, potential growth of campus, and total overall efficiency. While 31 of the 72 months in Figure 8 do not use 2 MW of power, the facilities department can net-meter during these times. If WPI connects the unit to the main power grid, excess electricity can be sold back to the utility companies for surplus unit savings. During interviews each party mentioned the possible addition of a new building to campus and then WPI President Laurie Leshin also mentioned this building during a campus-wide meeting. With a potential new building being added to campus and campus expansion, we predict that electric loads will increase. Figure 8 shows that at least 50% of the time campus is currently using more than 2 MW of energy, so if loads increase, more often campus loads will be over 2 MW. Sizing up the machine would increase this thermal energy, which WPI would have a hard time utilizing. For all these reasons, we believe that a 2 MW CHP unit will be the best option for campus.

4.2.2 Best Prime Mover for WPI Application

After comparing each prime move with the others, as well as to the list of prioritized requirements, the reciprocating engine was proven to be the best fit for campus. Fuel cells use hydrogen to move their prime mover and these cell beds would need to be replaced every five years, which is incredibly costly. Additionally, because of the hydrogen fuel source, there is a lot of auxiliary equipment, which would need more space than current campus capacity allows. Our focus as an MQP team was to choose a CHP unit that would meet the electrical needs of campus. Steam turbines have an average electrical efficiency of about 6% while having an average thermal efficiency of 74%. With a two-megawatt unit, that much thermal would be impossible to capture on this campus while simultaneously not producing enough electricity (DOE, 2016). Gas turbines can be effective CHP units, but are more effective for a much larger megawatt electric need than what is required at WPI. When looking at the two efficiencies of the three remaining prime movers, it can be seen for that this size, the efficiencies are much better for the reciprocating engine than that of a gas turbine. The average electric efficiency is about 15% higher and the average thermal efficiency is about 4% higher for our estimated megawatt range (US DOE, 2016). Finally, when comparing the reciprocating engine to the microturbine, the reciprocating engine was more cost effective (Darrow et al. 2017). Since microturbines come in much smaller sizes, we would need to install upwards of 4 to meet WPI demands, whereas if we used a reciprocating engine, we would only need one. A single unit brings down both the installation and maintenance cost of the units. A reciprocating engine also has the ability where one can turn down the engine to run at half power instead of full power and still provide a proportional efficiency of both thermal and electric energy (Energy Solution Center, 2018).

4.2.3 Thermal Loads of WPI

The thermal load of campus was originally depicted in natural gas units, as natural gas used per month. Figure 9 shows the maximum and minimum amount of gas used each month between 2012 and September 2018 on the main campus. We can see that the range in the amount of thermal energy need to be considered when considering which CHP unit. The gray line shows the usable thermal energy that the engine generates, which was calculated from a 2016 Department of Energy Data Sheet.

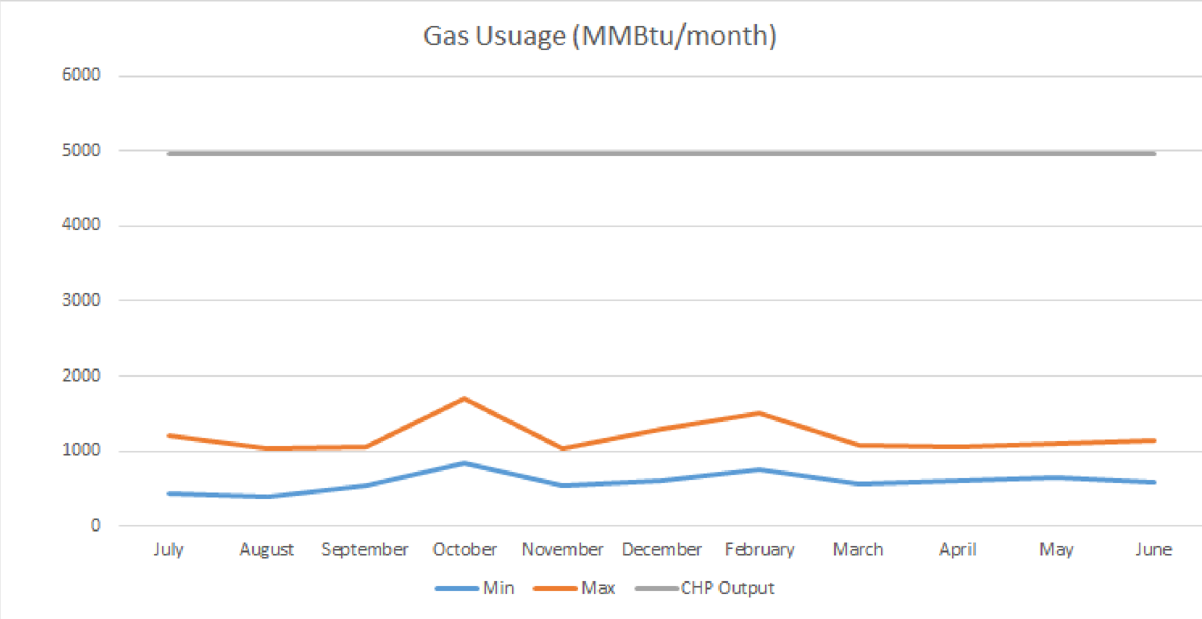

Figure 9: Thermal Usage on Campus

A 2 MW reciprocating unit creates about 5000 MMBtu/month, of thermal energy, which is a significantly larges amount that used right now on campus. We were able to find the useful amount of thermal energy for a reciprocating engine from Department of Energy data sheets where we got a number in MMBtu/hr. To compare that number to the WPI load, we converted it to MMBtu/month as seen in the graph above. Because the thermal given off the of the 2 MW reciprocating engine is so high, and the campus load is about fourth of that, the facilities department must find other ways to capture the heat. In order to do this, we estimated the hot water usage for the main dorm showers and the pool.

To estimate the pool heater size in BTU/hr. the department of energy suggests using the equation:

$$Pool\ Surface\ Area * Temperature\ Rise * 12$$

First, we had to estimate the surface area of the WPI pool, which is roughly the size of an Olympic pool. An Olympic pool is 82 feet by 164 feet, with a surface area of 13,448 square feet. Since the WPI pool is slightly smaller, we estimate the surface area to be about **13,000 square feet**. Next, to determine temperature rise, we estimated room temperature at 68 degrees and we know the pool sits at about 80 degrees Fahrenheit, so the temperature rise is **12 degrees Fahrenheit.** Finally, we executed the calculation:

$$13{,}000 * 12 * 12$$

The result was 1,872,000 BTU or 1.9 MMBTU/ hr., however, to be conservative, rounded the MMBTU down to 1.6 MMBTU/hr. Finally, we multiplied this number by 24 hours in a day and 30 days in a month to get **1100 MMBTU/month.**

The main campus generates a large need for domestic hot water from residents, the dining halls, and the pool. The average family of four uses about 19.5 MMBtu/year, which is about .406 MMBtu per person per month, from showering alone. If we take this number and multiply it by the number of students that live in Morgan, Daniels, and Riley (827 residents), during the school year, the dorms could use about **330 MMBtu per month**, camps are held for another 2 months in the summer, which could use a portion of this heat.

Finally, there is an average **900 BTU/month average**. Adding all of these together, we sustained a total of **2330 MMBtu/month**, however, this number could be even higher as we did not account hot water usage of the POD and CC, other dorm needs such as sinks, and heat exchangers for the chilling loop to still maintain a high efficiency of the unit.

As a result, if thermal is around **2300 MMBtu/month** that would bring overall efficiency to 60%, which is enough to qualify for incentives.

4.3 Economic Analysis

In this section, we will discuss the installation and maintenance costs, possible incentives for CHP, and payback period of the unit. This will allow WPI to see the benefits economically on campus, as they continue to save money while the CHP unit is in commission.

Installation and Maintenance Cost

By calculating installation cost, we can estimate the initial capital costs associated with implementing a CHP unit. After plugging in the numbers from Table 2 into the equation from section 3.3:

$$y = 2370 + (2000 - 1141) * \frac{1800 - 2370}{3325 - 1141}$$

Installation Cost was calculated to be $2,145.81 per kW. The initial capital cost is calculated by multiplying $2,145.81 by 2000, the total kW of the CHP unit, which results in a total capital cost of $4,291,620.

Like installation cost, we used the equation and Table 2 from section 3.3:

$$y = .019 + (2000 - 1141) * \frac{.016 - .019}{3325 - 1141}$$

Maintenance Cost was calculated to be $ 0.018 per kWh, which we rounded to $0.02 because generally costs are slightly inflated in the north east and the data was pulled from national averages. In total annual maintenance costs $320,000.

Mass CHP Incentive

The Massachusetts capital incentive is based on the expected overall efficiency of the CHP unit. Depending on the investment WPI makes into infrastructure that can capture and utilize thermal energy, we expect incentives to range on the lower end from $.075 to $.09 per kWh.

$$lower\ incentive = 2000 * 8000 * .075$$
$$higher\ incentive = 2000 * 8000 * .09$$

Where 2000 is kW and 8000 represents hrs./yr. accounting for maintenance.

So, we estimate the incentives to range from $1,200,000 to $1,440,000

Simple Payback and Lifetime Savings

WPI will receive incentives depending on the total overall efficiency of the CHP unit. The total efficiency needs to be at least 60% in order to receive a $.075/kW capital incentive, and as that number increases, the capital incentive will increase. However, we don't foresee

WPI being able to capture enough thermal energy currently to receive the full $.120/kW incentive. In Tables 5, 6, and 7, we show payback calculations for a low capital incentive at $ .075/ kW with an annual APS incentive, $ .09/ kW with an annual APS incentive, and no incentives respectively.

Table 5: Low Capital Incentive Payback

Year	**Installation and Maintenance ($)**	**Electrical Savings ($)**	**Incentives ($)**	**Total Cumulative Savings ($)**
0	-4,291,620	-	1,200,000	-3,091,620
1	-320,000	1,256,184	320,000	-1,835,436
2	-320,000	1,256,184	320,000	-579,252
3	-320,000	1,256,184	320,000	676,932

The low capital incentive payback period is 2.46 years and the lifetime savings would be approximately $ 22,032,060.

Table 6: Medium Capital Incentive Payback

Year	**Installation and Maintenance ($)**	**Electrical Savings ($)**	**Incentives ($)**	**Total Cumulative Savings ($)**
0	-4,291,620	-	1,440,000	-2,851,620
1	-320,000	1,256,184	320,000	-1,585,436
2	-320,000	1,256,184	320,000	-339,252
3	-320,000	1,256,184	320,000	916,932

The medium capital incentive payback period is 2.27 years and the lifetime savings would be approximately $ 22,272,060.

Table 7: No Incentive Payback

Year	**Installation and Maintenance ($)**	**Electrical Savings ($)**	**Incentives ($)**	**Total Cumulative Savings ($)**
0	-4,291,620	-	-	-4,291,620
1	-320,000	1,256,184	-	3,355,436
2	-320,000	1,256,184	-	-2,419,252
3	-320,000	1,256,184	-	-1,483,068
4	-320,000	1,256,184	-	-546,884
5	-320,000	1,256,184	-	389,300

The no incentive payback period is 4.58 years and the lifetime savings would be approximately $14,432,060.

With no incentives, the payback period is almost double both the options with incentives. Additionally, the total simple lifetime savings is about $8,000,000 less than both options with incentives. Because of this, we would strongly suggest that WPI allocate resources to capture enough thermal energy to get to at least 60 % total efficiency, which would qualify campus for a $.075/kWh incentive. However, the difference between the low and medium capital incentives is only .19 of a year or about 2.28 months. This shows that it is fiscally responsible to invest in enough infrastructure to receive low incentives but striving for higher incentives may not necessarily be cost effective.

4.4 Greenhouse Gases

Table 8 provides a step by step explanation of how greenhouse gas emissions were calculated. It was determined that installing a 2 MW CHP unit on WPI's main campus would save approximately 960 pounds of carbon dioxide per hour compared to using electricity from the grid. The excel spreadsheet shown in Table 8 highlights the savings in a step by step guide.

Table 8: Equations and definitions for greenhouse gas emission calculations

Step	**Equations/ Variables**	**Definition**	**Value**	**Units**
1	$\boldsymbol{C_T = F_T \times E_{FF}}$			
	C_T	CO_2 emissions from onsite thermal production	1919.72	lbs.
	F_T	Thermal fuel savings	16421957.04	Btu
	E_{FF}	CO_2 emission factor	.0001169	lbs./Btu
	$F_T = \frac{CHP_T}{\eta_T}$			
	CHP_T	Thermal output of the unit	6880800	Btu
	η_T	Thermal efficiency of the unit	.419	% (decimal form)
Step 1 show the calculation for the **CO2** emissions from our current system				
2	$\boldsymbol{C_G = E_G \times E_{FG}}$			
	C_G	CO_2 emissions from electric grid	1168.88	lbs.
	E_G	Amount of electricity that the CHP generates	2094.02	kWh
	E_{FG}	Emissions from the electric grid in our area	.5582	lbs./ kWh
	$E_G = \frac{CHP_E}{1 - L_{T\&D}}$			
	CHP_E	Electric output of the unit	200	kWh
	$L_{T\&D}$	Loss of transmission and distribution	.0449	% (decimal form)

Step	Equations/ Variables	Definition	Value	Units
Step 2 shows the calculation for the **CO2** emissions that are made from the electric grid based on our area				
3	$\boldsymbol{C_{CHP} = F_{CHP} * E_{FF}}$			
	C_{CHP}	CO_2 emissions from CHP system	682400	Btu
	F_{CHP}	Fuel used in the CHP unit	18197333.33	Btu
	E_{FF}	Fuel emission factor	.0001169	lbs./ Btu
	$F_{CHP} = \frac{CHP_E}{EE_{CHP}}$			
	CHP_E	Electric output of the CHP unit	682400	Btu
	EE_{CHP}	Electric efficiency of the unit	.375	% (decimal form)
Step 3 shows the calculations for the **CO2** emissions that would be made from a 2 MW reciprocating CHP engine				
4	$\boldsymbol{C_S = C_T + C_G - C_{CHP}}$		961.34	lbs./ hr.
Step 4 shows the calculations for **CO2** WPI could save if they converted to a reciprocating CHP unit				

For all values relating to a specific CHP unit, we utilized EPA sources to determine average values for these inputs. For all values relating to the electric grid, we used eGRID summary tables from 2016 to find the Massachusetts numbers (EPA, 2018). Massachusetts is part of the Northeast region on the map (EPA, 2018). This will end up saving thousands of pounds of carbon dioxide each year, helping to reduce the greenhouse gases being emitted into the atmosphere.

5.0 Conclusion, Recommendations and Reflections

Our goal for this project was to explore the potential use of combined heat and power (CHP) on the campus at WPI. We identified a 2 MW reciprocating engine as the most appropriate CHP unit to be implemented. Based on our calculations, WPI will be able to save about $1.2 million per year in electric cost and over 900 pounds per hour of greenhouse gas emissions. In the following recommendations section, we will make suggestions for capturing thermal energy, earning Massachusetts CHP incentives, and integrating the unit onto campus. This chapter also contains our reflection design and teamwork processes throughout the project.

5.1 System Recommendations

We developed several recommendations for WPI regarding the installation of the proposed CHP system. These recommendations are guidelines and considerations for the leadership of WPI as they design a CHP unit for campus.

Massachusetts Incentives

There are two main incentives offered by the federal government that a CHP at WPI could qualify for, the installation incentive and APS incentive. First, the installation incentive could potentially pay for up to $0.12 per kW of the machine, so we strongly suggest WPI work to receive this entire incentive by creating a plan to collect all exhaust heat. Capturing a large majority of the exhaust heat would make the unit more efficient overall, which is what the DOE emphasizes in these projects. Additionally, the APS credit currently averages $20 per MWh, so campus should apply for this as well. Both incentives would drive the costs of the machine down.

Thermal Energy

Without adding extra infrastructure, the CHP will not capture enough heat to qualify for Massachusetts state incentives. We recommend that WPI spend additional time considering the possible options for capturing the waste heat from the CHP including domestic hot water, heating buildings with steam, heating the pool, and chilling loops. The CHP unit will emit an extra 4,000 MMBtu per month.

The main campus generates a large need for domestic hot water from residents, the dining halls, and the pool. The average family of four uses about 19.5 MMBtu/year, which is about .406 MMBtu per person per month, from showering alone. If we take this number and multiply it by the number of students that live in Morgan, Daniels, and Riley (827 residents), during the school year, the dorms could use about 330 MMBtu year, camps are held for another 2 months in the summer, which could use a portion of this heat. In addition to showering in the dorms, the dining halls have a need for domestic hot water for cooking. Although residence halls could use most of the excess heat, there are not always residents using them, so another option for capturing waste heat is the pool. The WPI pool has over 660,000 gallons of water that need to be kept between 78- and 82-degrees Fahrenheit. Once the domestic hot water infrastructure is set up for the various locations such as the Campus Center, the Sports and Recreation Center, and the main dorms, WPI would no longer need to pay for the heating of water for uses in the pool, showers, and dining halls.

Additionally, the exhaust heat could be used to power chillers around campus. WPI has an abundance of sensitive technology on campus that needs to stay at cool temperatures throughout the summer to work effectively. In the summer months, when students are not on campus, a chiller could take on the portion of the load that would normally go to the dorms. The chillers would remove the heat from the hot water through a vapor compressor. The colder water can then circulate into buildings that have technology within them to keep them cool throughout the entire year. Buildings on WPI's main campus that should be included in the chilling loop include Fuller, Kaven, Higgins Labs, and Washburn Shops. While adding all this infrastructure would impact capital costs and the payback period, gas savings in terms of heating water and cooling buildings could add more to savings.

Mechanical Considerations

With the consideration of a CHP unit on campus, other mechanical issues such as the noise level and the distance from the powerhouse need to be considered. The main concern with placing the CHP unit in or near the powerplant would be loss of classroom and academic space. With proper insulation and noise cancelling material, noise would be a non-factor as WPI is in the city of Worcester and it could be considered as almost a small background noise. However, WPI will need to allocate enough resources to properly insulate the unit. The biggest mechanical consideration for the CHP unit is the actual location of the machine. If it were to be placed in the WPI Power Plant, it would be cheaper and a lot easier to connect to the system to the powerplant than if the unit were placed elsewhere on campus. If it were placed in the new building being proposed for campus, there would be added infrastructure to the unit such as plumbing from that building to the power plant, driving up the capital cost of the unit.

5.2 Reflections

While the main topic of our project was to determine the feasibility of a CHP unit on the campus at WPI, the goals of a Major Qualifying Project (MQP) extend well beyond the project. Throughout the course of our experience, we were challenged to design our own engineering process, while working effectively as a team. This section of the paper will outline our reflections on what we learned throughout the course of our project.

Design Process

The main goal of our project was a feasibility study, so determining requirements and constraints of both campus and CHP units was our main task. Our first step in this process was background knowledge acquisition through literature review. As a team, we had to gather a proper background of WPI's electrical and heating infrastructure. This information could not be found in textbooks, but had to be acquired through interviews with the WPI Facilities departments. While we were developing our understanding of WPI infrastructure, we needed to research the different types of CHP units including their benefits and disadvantages. This research gave us a sufficient background for the project, but did not specifically highlight many constraints, so we next needed to speak with stakeholders.

We performed a series of informal interviews with the stakeholders listed in Table 1 to gauge their perspectives on a CHP unit. Each stakeholder had unique backgrounds from WPI Trustee with experience in large capital decisions, to a Clark's Chief Engineer with knowledge on operating a CHP unit. These interviews highlighted to us the nine major constraints, which can be found in section 4.1. First, there was the economic constraint of initial cost versus payback period, which could be a deal breaker. Then there were physical constraints such as size and location of the machine. However, no one constraint could be considered without the context of other constraints. If we exclusively focused on electrical size of the machine, we would not have understood the importance of considering the thermal exhaust. Moreover, we could recommend that the machine be plopped right into the powerhouse, but that would not consider its physical size, or the infrastructural needs of the system. Understanding all constraints and concerns of the unit allowed us to create the best recommendations for campus.

Teamwork

As a team, we all have different strengths, weaknesses, experiences, and goals. Working on a long-term project with three different individuals challenged us to be understanding, direct, and communicative. Charles is the technical expert on our team, his love for research and drive to solve problems propelled us through the stressful moments. Rosie is well spoken and used this skill to mediate group conversations ensuring we always worked in a positive direction. Daly is a hard worker and was always willing to grind through sections when school became particularly busy for the group. Each group member's individual talents lead us to work like a well-oiled machine.

While the team had many strengths, we also had to learn lessons throughout the course of the project. There were specific moments where one groupmate or another would be having a bad day or week. During these moments, the people aspect of group work had to kick in; the group needed to realize that sometimes project-work had to take the backseat. We learned that a team cannot operate at full capacity if all members aren't thriving, so on bad days, we would cut each other slack. Throughout the course of the project each member had lows, but the strengths of the others carried us through the end.

6.0 Appendix

Appendix A: Interview Protocol

Interview Protocol

Introduction: Good morning/ afternoon. Our names are ________. *Thank you for taking the time to meet with us today. We requested to meet with you to gather more information towards the background of our MQP project. For our MQP, we are working with the WPI Facilities department to create recommendations for transitioning WPI off the electric grid. For our project, we will be identifying technology and creating recommendations for how to implement it on campus.*

Example Questions:

- What type of solutions can be added to help lower GHG emissions?
- What have you looked at for capturing thermal energy?
- Have you invested other options in more unique ways of capturing the thermal load and using it in a way that might not have been initially thought.

If a CHP unit were to be put in, would we want to have a maintenance contract or hire an engineer to take care of the unit.

Conclusion: *Thank you for taking the time to meet with us today. With the information you shared with us, we are going to be able to fully optimize the potential for a CHP unit at WPI.*

If we have any follow up questions, would it be okay to email them to you?

Thanks again.

7.0 Work Cited

5 Things to Know About Geothermal Power. (n.d.). Retrieved from https://www.energy.gov/eere/articles/5-things-know-about-geothermal-power

Boxwell, M. (2014). Is solar energy right for you? Some solar energy basics from the author of the solar electricity handbook.(Cover story). Natural Life.

British Wind Energy Association. (2005). Wind Turbine Technology. https://www.nottingham.ac.uk/renewableenergyproject/documents/windturbinetechnology.pdf

Carello, Fay, Ghion, Smith. (2016). Integration of a CHP Unit into the Worcester County Jail. https://web.wpi.edu/Pubs/E-project/Available/E-project-032216-174653/unrestricted/Integration_of_a_CHP_Unit_into_the_Worcester_County_Jail.pdf

Combined Heat and Power (CHP) A Guide to Submitting CHP Applications for Incentives in Massachusetts(Rep.). (2018). Boston, MA: Mass Save.

Darrow, Ken, et al. Catalog of CHP Technologies. Environmental Protection Agency, 2017, Catalog of CHP Technologies, www.epa.gov/sites/production/files/2015-07/documents/catalog_of_chp_technologies.pdf.

Energy Required for Water Heating. (n.d.). Retrieved from https://www.e-education.psu.edu/egee102/node/2003

Gaughan, R. (2019, January 10). How Much Land Is Needed for Wind Turbines? Retrieved from https://sciencing.com/much-land-needed-wind-turbines-12304634.html

Geothermal Energy Information and Facts. (2009, October 19). Retrieved from https://www.nationalgeographic.com/environment/global-warming/geothermal-energy/

How Efficient Are Solar Panels? (n.d.). Retrieved from https://www.greenmatch.co.uk/blog/2014/11/how-efficient-are-solar-panels

Joskow, P. (2011). Comparing the costs of intermittent and dispatchable electricity generating technologies.(Author abstract). American Economic Review, 101(3), 238–241. https://doi.org/10.1257/aer.101.3.238

Luther, R. (2018, September 21). 4. CHP Technologies. Retrieved from https://understandingchp.com/chp-applications-guide/4-chp-technologies/

Mass Save. (2016) Combined Heat and Power (CHP) A Guide to Submitting CHP Applications for Incentives in Massachusetts. https://www.masssave.com/-/media/Files/PDFs/Business/GuidetoSubmittingCHPApplications_06012016.pdf?la=en&hash=CF3CC5086F1985CEA210BB8153257A4E094A1521

Measurements for an Olympic Size Swimming Pool. (n.d.). Retrieved from https://www.livestrong.com/article/350103-measurements-for-an-olympic-size-swimming-pool/

Meehan, C. (2018, November 14). Are solar panels leading America to a zero marginal cost society? Retrieved from https://www.solar-estimate.org/news/2018-03-08-how-are-solar-panels-changing-america

Otis P. (2016). CHP Industrial Bottoming and Topping Cycle with Energy Information Administration Survey Data Results. https://www.eia.gov/workingpapers/pdf/chp-Industrial_81415.pdf

Top 10 Things You Didn't Know About Combined Heat and Power. (n.d.). Retrieved from https://www.energy.gov/articles/top-10-things-you-didn-t-know-about-combined-heat-and-power

Top 10 Things You Didn't Know About Wind Power. (n.d.). Retrieved from https://www.energy.gov/eere/wind/articles/top-10-things-you-didnt-know-about-wind-power

US Department of Energy. (2016). *Combined Heat and Power Technology Fact Sheet Series-Fuel Cell.* https://www.energy.gov/sites/prod/files/2016/09/f33/CHP-Fuel%20Cell.pdf

US Department of Energy. (2016). *Combined Heat and Power Technology Fact Sheet Series-Gas Turbine. https://www.energy.gov/sites/prod/files/2016/09/f33/CHP-Gas%20Turbine.pdf*

US Department of Energy. (2016). *Combined Heat and Power Technology Fact Sheet Series-Microturbine. https://www.energy.gov/sites/prod/files/2016/09/f33/CHP-Microturbines_0.pdf*

US Department of Energy. (2016). *Combined Heat and Power Technology Fact Sheet Series-Reciprocating Engine. https://www.energy.gov/sites/prod/files/2016/09/f33/CHP-Recip%20Engines.pdf*

US Department of Energy. (2016). *Combined Heat and Power Technology Fact Sheet Series-Steam Engine. https://www.energy.gov/sites/prod/files/2016/09/f33/CHP-Steam%20Turbine.pdf*

US Department of Energy. (2018). eGrid Summary Tables. https://www.epa.gov/sites/production/files/2018-02/documents/egrid2016_summarytables.pdf

US Department of Energy. (2018). What is CHP? https://www.epa.gov/chp/what-chp