Integration of a CHP Unit into the Worcester County Jail

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Abstract

This project analyzed the feasibility of using the heat generated by a West Boylston Municipal Lighting Plant (WBMLP) owned and operated combined heat and power (CHP) unit to provide domestic water heating for the Worcester County Jail (WCJ). After a site visit and analysis of data gathered by a flow meter installed in the boiler room of the WCJ, the team determined the jail's domestic water heating load and decided on an appropriate CHP unit size to meet this demand (two 75 kW units). After numerous calculations, it was found that the project was financially and environmentally feasible. The team also reviewed permitting requirements and compiled a list of incentive programs that the WBMLP should apply for; as well as a guideline on how to apply for these incentives. The project also provides the following: a detailed visualization of the proposed CHP units and how they will be placed in relation to the jail's boiler room, an estimated budget for the CHP unit installation which includes financial returns, and a construction schedule to be used in planning the logistics for the integration of the CHP units.

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Acknowledgements

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We would also like to express our gratitude to our project sponsor, **West Boylston Municipal Lighting Plant**, and **Jonathan Fitch**, for providing information, advice, and inspiration to the group.

1.0 Introduction

Despite efforts from the government and the energy industry to mitigate air pollutant and greenhouse gas (GHG) emissions, carbon dioxide (CO_2) emissions have increased by 32% in the past decade (IEA, 2016). Fortunately, scientific and technological advances in recent years have increased the efficiency and availability and decreased the cost of alternative energy (non-conventional energy sources to generate electrical power) technologies, thus making these advances more attractive.

State and local agencies are looking for cost-effective ways to carry out vital upgrades in their prisons and detention centers. Lowering energy usage and transferring the savings to other valuable areas is one way in which improvements can happen. To this end, correctional facilities become accountable to reduce energy consumption. The West Boylston Municipal Lighting Plant located in West Boylston, Massachusetts, is very much aware of the need to serve the customers of West Boylston with the most reliable and economical power possible. They are striving to develop more alternative power resources to lessen the dependency on fossil fuels. With these two focuses in mind, WBMLP and the Worcester County Jail have joined together to reduce energy consumption use within the correctional facility. This move aims to reduce energy usage and reduce the carbon footprint of the jail with the installation of a combined heat and power unit.

Combined heat and power, also known as cogeneration, is the simultaneous production of electricity and heat from a single fuel source, such as natural gas. CHP is more efficient and requires less fuel to deliver a given energy output than separate heat and power systems. This high efficiency translates into lower operating costs and increased reliability as a result of the CHP unit recapturing and harnessing the waste heat. With the collaboration of the WBMLP and the Worcester County Jail, the project seeks to prepare a detailed analysis of the potential benefits of installing a CHP unit to fuel the energy consumption needs of both the correctional facility and the ratepayers of West Boylston.

In order to implement this project, WBMLP partnered with Worcester Polytechnic Institute (WPI) to develop and conduct an overall analysis of the proposed installation. To achieve this goal, it was necessary to work closely with the General Manager of the WBMLP, Jonathan Fitch, and Professor Brian Savilonis at WPI. The complexity of this project requires framing in the following way: a literature review and necessary background needed to understand the reasons for undertaking such an endeavor, a description of the results, and an outline of recommendations for continuing the work done by this team.

2.0 Background

2.1 Site Description and Stakeholders

2.1 a. Site Description

The project site is the Worcester County Jail and House of Correction, located at 5 Paul X Tivnan Drive in West Boylston, MA. The jail is operated by the Worcester County Sheriff's office and houses adult males who are pre-trial detainees or have been sentenced to a maximum of two and a half years. The jail is designed to hold approximately 800 inmates, but the average census in 2006 was 1,400 (Becker, 2008). On a recent visit in September of 2015, the census was approximately 1,200 inmates, still severely overcrowded. There also are a maximum of 100 workers (guards, primarily) in the prison at any one time.

The jail is comprised of several buildings that provide housing for inmates. The Main Jail House opened in 1973 and houses maximum and medium security inmates. It has 5 housing units: A-1, A-2, Maximum B, Maximum C, and Medium C. Inmates are also housed in the gymnasium when there are not enough cells in regular housing. The upper tier of A-1 has 16 single-bunked cells that are used for inmates on suicide watch. The lower tier of A-1 and both tiers of A-2 have 16 cells that are used for disciplinary and administrative segregation. The Modular Complex houses medium security inmates in five housing units with double-bunked cells. The Minimum Security Facility houses minimum security inmates in a dormitory style setting. Finally, the Annex is dormitory style housing for inmates on work release (Becker, 2008).

More specifically, the focus of this project is in the Worcester County Jail's boiler room. It is located in a separate building from the main prison complex (located by an arrow in Figure 2.1 a). Minimal security procedures are needed to enter this part of the jail, but it is still behind one barbed wire fence, and the inmates can clearly see it from the gymnasium facilities. The boiler room houses the components needed for space heating in the winter months and domestic hot water year round. These include: 2 Raypak units for domestic water heating, 3 boilers that are turned on in October to supply space heating for the jail, and 3 storage tanks that hold the hot water until it is transported for use in the facilities. A drawing of the boiler rooms components and layout is shown in Figure 2.1 b.

Figure 2.1 a: Worcester County Jail Site and Boiler Room Location (FOX25, 2012)

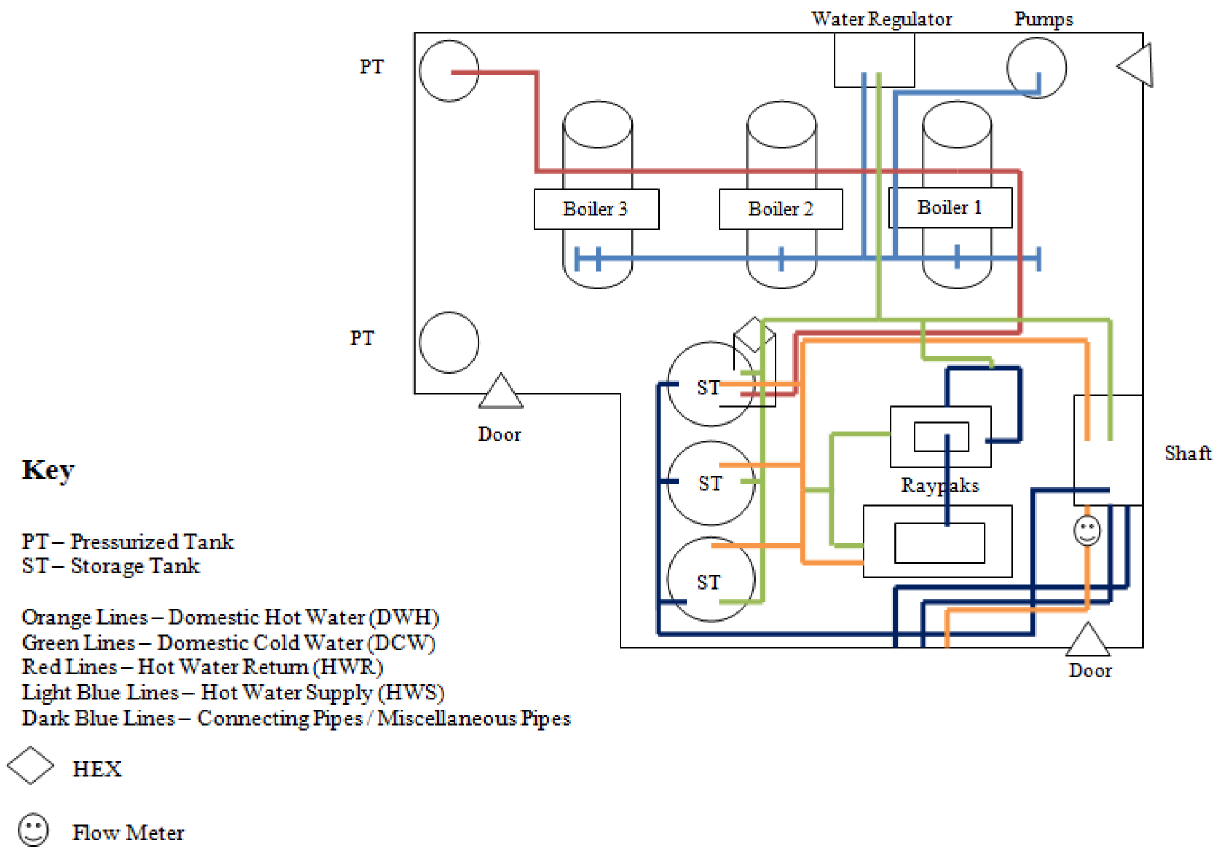

Figure 2.1 b: Layout of Boiler Room in Jail

2.1 b. Stakeholder Information

The stakeholder of the project is the West Boylston Municipal Lighting Plant. It is a municipal corporation, which is defined as a city, town, village or borough that has governmental powers and is capable of conducting business with public and private sectors (Farlex, 2015). WBMLP has provided citizens and businesses of West Boylston, MA with dependable electric power for over a century. It gives the town many benefits such as:

1. Better dependability, reliability, and economical pricing for electrical service
2. WBMLP is owned by the citizens of West Boylston, which creates a customer relationship not experienced by big-business electric utility companies
3. They are able to negotiate and buy long term power supplies from a diverse and balanced ranged of resources. This results in better rates for customer's homes and business.

4. Repair crews and maintenances are located within the town and can repair outages and electrical problems within minutes

WBMLP also strives to develop more alternative power resources to lessen their dependency on fossil fuels (WBMLP, 2015). They continue to grow their customer base and plan to be more and more involved in renew able energy projects where they provide electric power effectively and economically.

WBMLP's willingness to be involved in energy and their desire to always provide the lowest possible customer electricity rates is the driving factor for their involvement in this project. The CHP units will help maintain low electricity rates and provide resilient local generation to this customer. It also diversifies the energy supply portfolio and attracts additional customers.

2.2 CHP Basics

Over the last few decades, technological advancements have made huge impacts on society in a substantial way. However, the increase in technology also requires an increase in demand for energy supplies (fossil fuels) to account for all the required power, which causes the cost of the fossil fuels to rise, and has forced both consumers and nations to look for ways to reduce their energy consumption.

As of now, most thermal power plants reach power efficiencies up to 25-35% (65-75% of energy is lost as heat). The lost energy is considered waste heat and is usually discharged into the environment. In order to utilize this abundance of lost energy, companies have started implementing cogeneration plants. Cogeneration plants use a single fuel source (in most cases, natural gas) to generate both electrical and thermal energy (Intelligen, 2015). Due to the combined heat and power generation, the average cogeneration plant will have a total energy capture of greater than 80%.

Power efficiency is defined as the useful power output divided by the total power consumed (EPA, 2013). In this paper, power efficiency is used interchangeably with overall efficiency and cycle efficiency. The terms electrical efficiency and heating efficiency refer to the efficiencies of the electrical parts and heating parts of cogeneration, respectively. The details of how cogeneration plants work, the different types of cogeneration plants, and both environmental and economical impacts of cogeneration plants will be further explained in the following paragraphs.

2.2 a. General Information

Combined heat and power, also known as cogeneration, is the simultaneous production of electricity and heat from a single fuel source, such as natural gas (EPA, 2013). CHP is not a single technology, but an integrated energy system that can be modified depending upon the needs of the energy and user (EPA, 2013). There are multiple components that are a part of this integrated energy system. These include, the prime mover (or heat engine), the generator, the heat recovery system, and the electrical interconnection system (C2ES, 2015). An example of how a typical CHP system operates is shown in Figure 2.2 a.

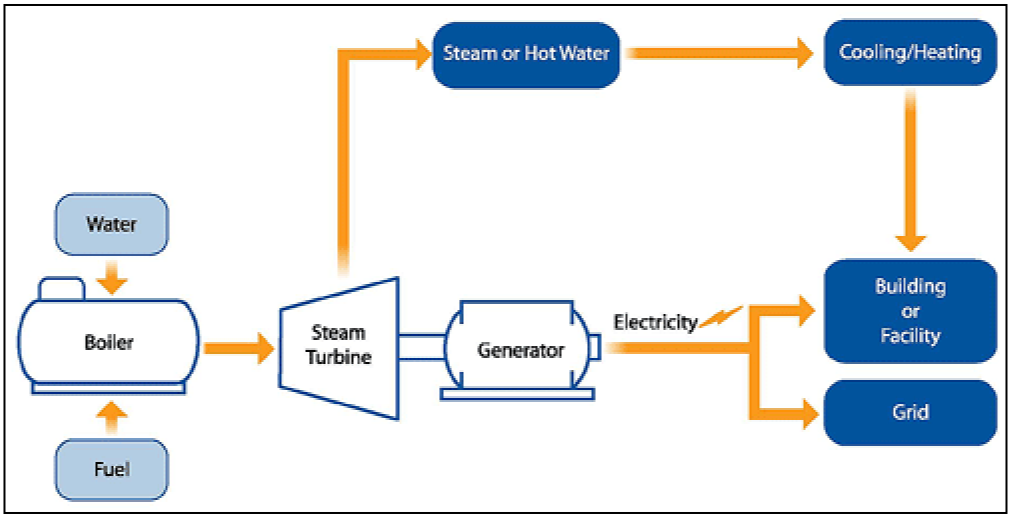

Figure 2.2 a: A Simple CHP System (Davvar Energy, 2011)

The type of CHP unit is usually dependent on the prime mover being used, i.e. a reciprocating engine, steam or gas turbine, micro-turbine, etc. (The different types of prime movers will be explained in detail in Section 2.2 b). Although these CHP units may have different prime movers, the way they work is very similar. The Topping Cycle is the most common thermodynamic cycle used in CHP units according to the '*Energy Efficiency Guide for Industry in Asia'* (United Nations, 2006). There is also a Bottoming Cycle; however, it is not going to be considered for this project because it does not make sense in this application.

In a Topping Cycle, the fuel that is being burned is first used to create useful power; usually electrical. The mechanical energy produced from the prime mover can also be used to power internal components of the unit such as compressors, pumps, and fans. The heat recovery system in the unit allows for waste heat to be converted into thermal energy to be used for space/domestic heating or other applications. The different types of Topping Cycle CHP units will be further explained in Section 2.2 b.

CHP requires less fuel to produce a given energy output than separate heat and power systems. The higher energy capture translates into lower operating costs, increased reliability and power quality, reduced grid congestion (no distribution charges), and avoided distribution losses. This produces building operators and other industries with high-energy efficacy, profitability, independence, and in some cases they can become energy suppliers themselves (C2ES, 2015).

Economically, cogeneration plants can be very valuable when used correctly. A typical natural gas power plant requires almost the same cost of maintenance and production as a cogeneration plant. However, the cogeneration plant takes energy that would have been wasted and uses it as thermal energy to provide heating for buildings. This recovered energy can also be utilized in other ways. If a chiller is introduced in the cogeneration cycle, then the unit can supply cool air for space cooling. This not only saves wasted energy; it also increases production, which means more income for the power plant. CHP units must run continuously to gain maximum efficiency (NYC Buildings, 2010). If the amount of time the unit is being run is optimized, then the production rate will increase. When CHP units are continuously turned off and on, they lose efficiency. Due to this, CHP units are not typically used as back-up power supplies or in situations where the required power/heating loads are inconsistent (C2ES, 2015).

There are numerous aspects that factor into the cost of a cogeneration plant. The size of the plant, the desired power outcome, and the labor necessary to construct and work the plant are just a few facets that contribute to the cost. Due to this, it is hard to determine the economic impact of a cogeneration plant (Princeton, 1983). However, based on a study from Princeton, it is noted that:

> "Comparisons of capital and O&M costs and labor requirements for equivalent amounts of central station and cogeneration capacity indicate that cogeneration has the potential to reduce the cost of supplying electric power while increasing the number of jobs associated with electricity generation (Princeton 1983)."

Although cogeneration plants are economically viable, as shown in the costs spreadsheets produced by the team in Section 3.7, their environmental impact may cause an issue. Power plants are usually in remote locations away from the public. However, in order to use the thermal waste energy, the CHP plant must be close to the building(s) it is heating/cooling. This will locate greenhouse gases near populated areas versus power plants which are typically located remotely. Therefore, the plant will have to accommodate pollution cleanup costs (EPA, 2013). Depending on the size of the plant and how much pollution it gives off, the economic benefit that cogeneration plants usually have may diminish. However, researchers have concluded that the amount of CO_2, NOx, and other pollutants given off by cogeneration plants is less than most current power plants by about 30% (includes electric and heat). Also, the growing emphasis on greenhouse gas reduction has enhanced the attractiveness of natural gas for power plant fuel, since it has CO_2 emissions that are 58.6 % less than that of coal and 30 % less than that of oil (the percentage of CO_2 reductions is even lower when being used for overall power and heat) (EPA, 2013). For that reason, natural gas cogeneration power plants do offer an environmental incentive, in addition to its economical benefits.

2.2 b. Comparison of Cogeneration Plants with Combined Cycle Plants

Another option that has been used to increase efficiency in power generation is the combined cycle plant. This plant consists of a gas turbine that is used to produce electricity. The high temperature exhaust heat is then recovered using a heat recovery steam generator, which creates steam and then sends it to a steam generator that produces more electricity. Typically, the combined cycle generates 50% more electricity than the simple cycle plant (EPA, 2013). Compared to cogeneration plants, the combined cycle does generate more electricity, but it needs another plant and fuel source to generate heat. Cogeneration generates both electricity and heat from a single fuel source. In this section, cogeneration is compared with the combined cycle to show why cogeneration is a more viable option for WBMLP.

There are many benefits to utilizing cogeneration. The greatest advantages are that they have high efficiency and low carbon emissions. On average, cogeneration units have an efficiency rating of roughly 80%, whereas combined cycle plants have an efficiency rating of almost 60%. Though the cogeneration plant generates only about 30% electricity compared to the combined cycle plants' 60%, the other 50% of energy generated is heat. Due to this, cogeneration reduces carbon emissions by up to 30% compared to a combined cycle. Other greenhouse gases are also reduced with the use of cogeneration. Since heat generation is not always in demand, the heat that is generated can be used to drive an absorption chiller for space cooling (EPA, 2013). An additional advantage to implementing cogeneration plants is that there is no need to build new power plant sites; CHP units can be placed in existing industrial or commercial sites. Due to the on-site application, there is less energy loss in the transmission and distribution of electricity (EPA, 2013).

2.2 c. Types of CHP Systems

As previously mentioned, CHP units are highly beneficial in many situations. There are two types of CHP units, the Topping Cycle and the Bottoming Cycle. The Bottoming Cycle is the less common of the two types and it is the process that uses fuel combustion to generate heat for manufacturing purposes. The exhaust heat is then captured to produce electricity. The Topping Cycle units are much more common and they use fuel to generate electricity or mechanical energy. The waste heat is then captured and converted into thermal energy (C2ES, 2015). There are 5 main sub-types under the Topping Cycle CHP units. These include: (1) Gas Turbine, (2) Steam Turbine, (3) Reciprocating Engine, (4) Micro-Turbine, and (5) Fuel Cells. The main aspects of each sub-type Topping Cycle CHP unit are described below.

CHP units incorporating Gas Turbines tend to be reliable and can sustain high heating loads. Gas Turbines use natural gas in a combustion process to turn the blades in the turbine to spin an electric generator. The CHP unit then captures heat from the exhaust to generate thermal energy that can be used for heating or cooling applications. A diagram showing how a Gas Turbine CHP unit works is shown in Figure 2.2 b, which represents a Brayton Cycle. A Brayton cycle is a type of thermodynamic cycle where atmospheric air is compressed, heated, and then expanded to produce power. However, there are two different types of Brayton Cycles; the Open Cycle (more common in CHP) and the Closed Cycle.

The Open Brayton Cycle works by air going through a diffuser to a combustion chamber that is kept at constant pressure. The diffuser decreases the velocity of the air so that it is at an appropriate speed to enter the combustion chamber. In the combustion chamber, there is a pressure drop of about 1.2% (United Nations, 2006). Combustion then takes place between the fuel (usually natural gas) and the excess air. The exhaust gases exit the chamber at relatively high temperatures. This is actually the hottest point of the cycle. The hotter the exhaust gas leaving the combustor is, the more efficient the unit is. The high pressure and temperature exhaust gases then enter the gas turbine to drive both the compressor and the generator (power producing element in the CHP unit). The exit temperature of the exhaust gases from the turbine is then high enough to be used in a heat recovery system (450°C to 600°C). This is used by a heat recovery boiler that either is a single pressure or double pressure type unit. The steam that the boiler produces can then be used for heating purposes (EPA, 2013).

On the other hand, Closed Brayton Cycles use a working fluid (helium or air) that is circulated continuously in a cycle. It is heated in a heat exchanger before being used by the turbine. Then it is cooled upon leaving the turbine to generate thermal heat. Usually Gas Turbine CHP units are found on big sites, as they typically have capacities between 500 kW and 250 MW (C2ES, 2015).

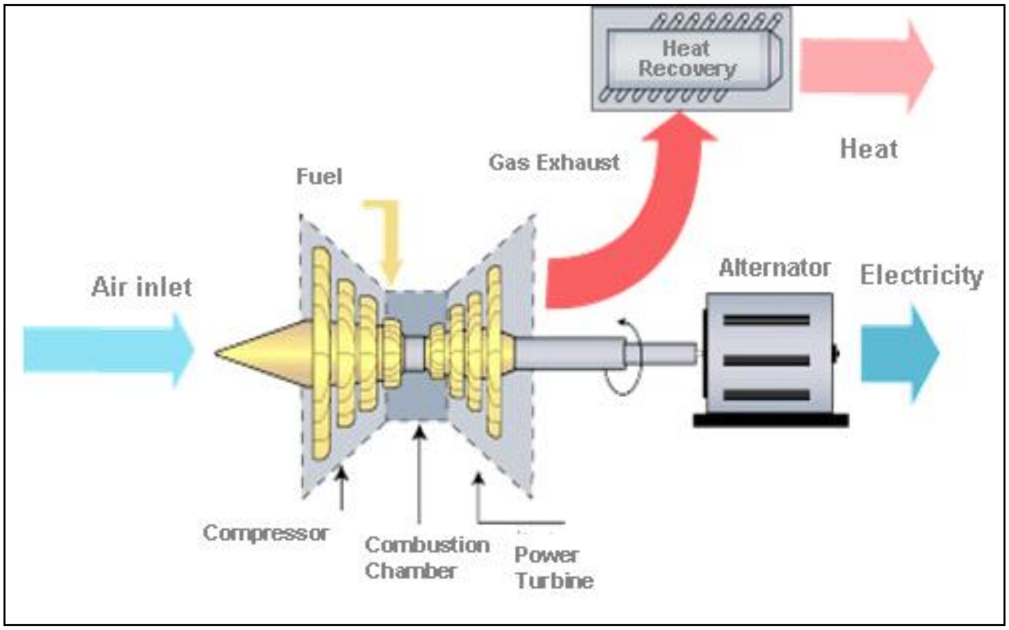

Figure 2.2 b: Diagram Showing How a Gas Turbine CHP Unit Operates (Veolia Alternative Energy, 2015)

The Steam Turbine CHP unit is unique because it can use a variety of different fuels including natural gas, solid waste, coal, and wood. They work by combusting fuel in a boiler. This heats up water and creates high-pressure steam that then turns a turbine to generate electricity. The low-pressure steam that leaves the turbine can then be used to capture thermal energy (C2ES, 2015).

Steam turbines follow a Rankine thermodynamic cycle. This cycle uses a heat source (typically a boiler) to convert water to high pressure steam. Water is first pumped to a certain pressure, typically a medium to high range. It is then heated to the corresponding temperature, where the water is boiled and becomes steam. This steam is expanded to a lower pressure by a multi-stage turbine and is sent either to a distribution system or to a condenser to be re-cycled. There are two types of steam turbines, the back pressure steam turbine and the extraction-condensing steam turbine. The back pressure steam turbine has steam exit the turbine at a pressure at least equal to atmospheric pressure. In general, the extraction-condensing steam turbine typically has a higher capital cost and a lower efficiency then the back-pressure turbine; therefore, it will not be written about in detail.

Steam Turbine CHP units typically have capacities between 50 kW and 250 MW, and are typically found on medium to large scaled sites, especially ones with high thermal loads (C2ES, 2015). A diagram of a typical Steam Turbine CHP system is shown in Figure 2.2 c.

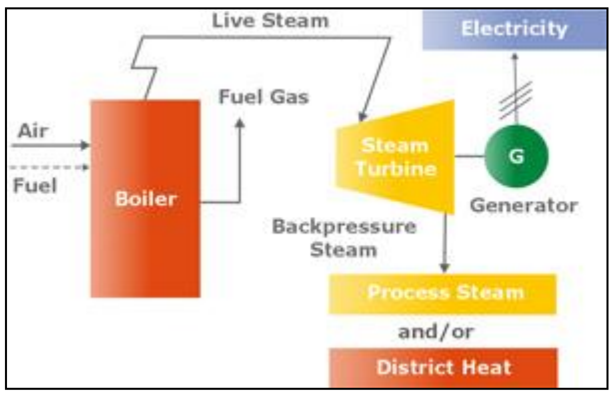

Figure 2.2 c: Steam Turbine CHP System Diagram (HROTE, 2012)

Reciprocating Internal Combustion Engines are the most widespread units for power generation in terms of the numbers of units utilized. However, because of their small size, these units only produce about 2% of the total United States' CHP capacity. The most common type of reciprocating engine used for CHP systems is the Spark Ignition Engine. It is very similar to gas-powered automobile engines, but they typically run on natural gas. A major benefit of Reciprocating Engine CHP units is that multiple units can be used at a site location to better improve the system capacity and enhance overall capacity. They also can maintain high efficiencies, even when they are not operating under maximum load. The reciprocating engine is typically used for capacities under 5 MW (C2ES, 2015). A Reciprocating Engine CHP system is shown in Figure 2.2 d.

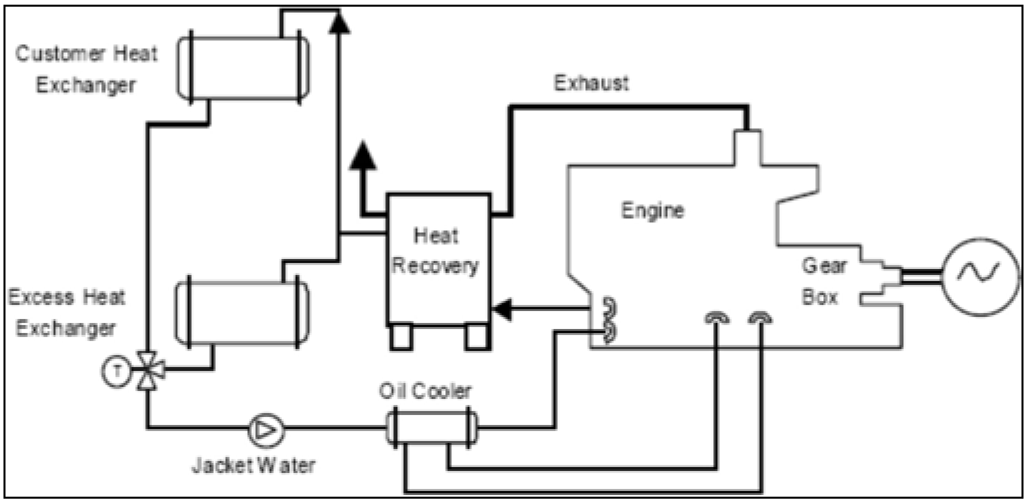

Figure 2.2 d: Reciprocating Engine CHP system (Mid-Atlantic CHP TAP, 2015)

Micro-Turbines are very small and compact. They generally reach output capacities of only 30-300 kW. A combustion process is used to spin a turbine to generate electricity. A heat exchanger then captures heat from the exhaust to be used for many building purposes (C2ES, 2015). A Micro-Turbine CHP configuration is depicted below in Figure 2.2 e. Due to their rather small output capacities; Micro-Turbines are rarely used in commercial endeavors. However, they can be beneficial due to their ability to utilize a variety of fuels. Thus, many are utilized in land and marine transportation systems, such as cruise ships (ESC, 2015).

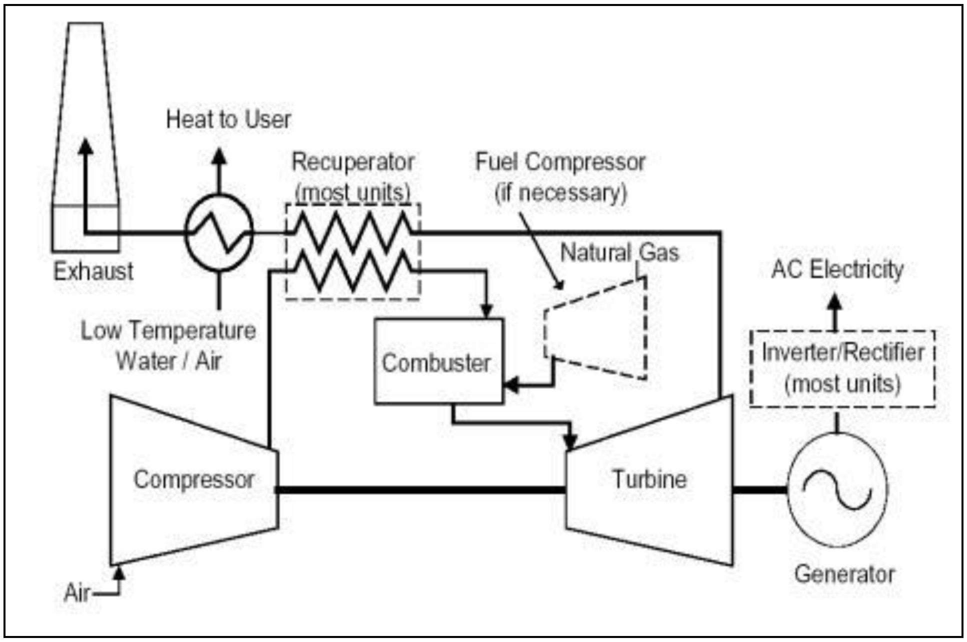

Figure 2.2 e: Micro-Turbine CHP system depiction (ESC, 2015)

Fuel Cells are a promising technology that has the potential to become very useful in the power sector. Fuel Cells have high electrical efficiencies (up to 60%) and very low emissions. Fuel cells use a battery-like chemical reaction process to convert the chemical energy of hydrogen into water and electricity. The hydrogen is generally obtained through the use of hydrocarbon fuels such as natural gas, coal, and methanol. Due to the early stages in the technology, these units typically have high capital costs and low reliability. Nevertheless, Fuel Cell CHP units offer benefits like creating little noise when running and having modular designs (C2ES, 2015). A Fuel Cell CHP system is portrayed in Figure 2.2 f.

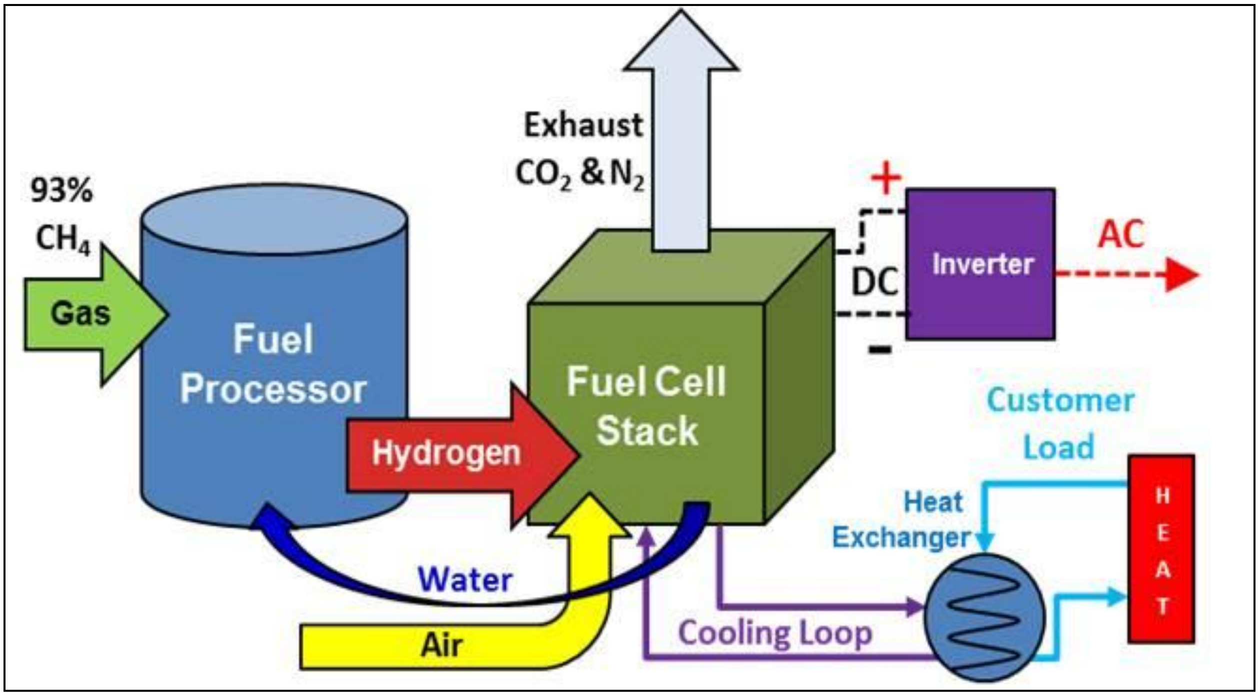

Figure 2.2 f: Fuel Cell CHP System (ESC, 2015)

2.2 d. Worldwide Growth of CHPs

The number of CHP units generating power in the world is constantly increasing. Cogeneration is responsible for 325,000 MW of electricity, more than 8% of the world's electricity generating capacity (Worldwatch Institute, 2013). In 2008, 9% of the United States' electricity-generating capacity came from cogeneration. Cogeneration is becoming more widely implemented because its' overall efficiency of 75%, considering both electricity and heat generation, is higher than the overall efficiency of conventional generation (51%) (EPA, 2013). This greatly reduces the end-users utility related operating costs. It can also reduce greenhouse gas emissions from electricity generation and hot water production by up to 50% (Tecogen, 2015). Another reason for the increasing use of cogeneration is that most countries have incentives in place that are available to those who produce less pollution from power generation.

To illustrate the expanding role of cogeneration in today's society, three cases are presented below. Due to the fact that the CHP unit in this project will be retrofitted to the boiler room in the Worcester County Jail, each case describes a correctional facility that has successfully installed and benefited from CHP units.

Santa Rita Jail

Santa Rita Jail is located in Dublin, California and houses 4,000 inmates. It consumes more energy than any other county government building in the United States. When opting to use cogeneration, the jail's goal was to reduce peak electricity demand and improve security and reliability of power at the jail. In May of 2006, Santa Rita Jail installed a Fuel Cell CHP unit that had a life expectancy of 25 years (shown in Figure 2.2 g). The CHP unit generates 50% of the jail's electricity needs and 18% of the jail's heating needs. The jail was able to reduce its NOx emissions by 98.5% compared to standard power plants (Alameda County, 2013).

Figure 2.2 g: Picture of Fuel Cell CHP unit implemented at Santa Rita Jail (Alameda County, 2013)

Lackawanna County Prison

Lackawanna County Prison is located in Scranton, Pennsylvania and houses 1,200 inmates. They upgraded their power structure by replacing a 400 kW standby generator with a 600 kW generator and a 225 kW Aegis PowerSync cogeneration system. The Aegis PowerSync system is shown below in Figure 2.2 h. The cogeneration system addresses the prison's need for standby power and supplements domestic hot water heating on site (Aegis, 2015).

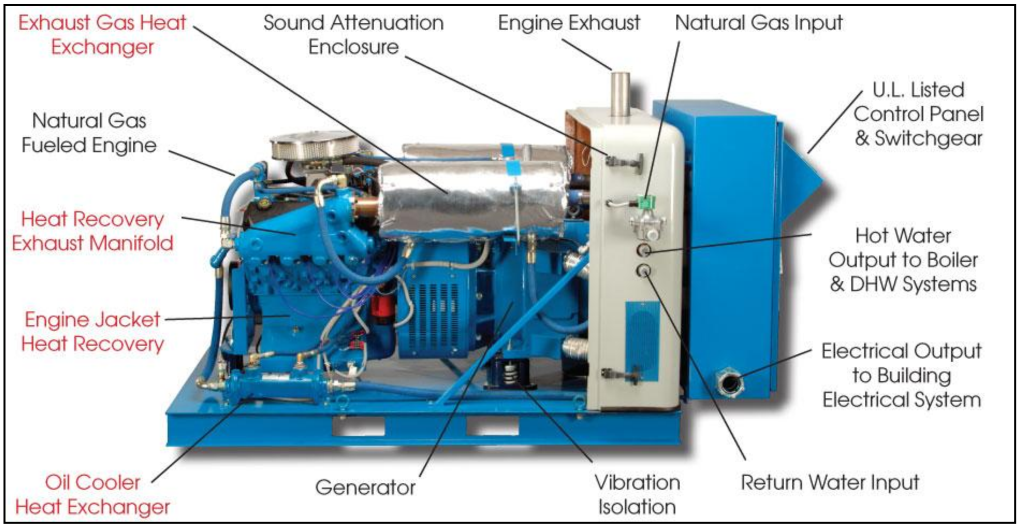

Figure 2.2 h: Aegis PowerSync Cogeneration System (Aegis, 2015)

Laurel Highlands Prison

Laurel Highlands Prison is located in Somerset, Pennsylvania. They installed a cogeneration unit that generates electricity and produces steam using methane gas. This methane gas came from the nearby Mostoller Landfill. The cogeneration unit eliminated the need for the prison to use coal-fired boilers. The excess electricity produced by the plant is sold back to the power grid. This helps create continuous revenue for the prison and helps offset project costs (PR Newswire, 2012).

2.3 Obstacles and Regulations on Implementing CHP Units

2.3 a. Obstacles to CHP Implementation

For all the benefits that Cogeneration systems bring, there are obstacles to further development and deployment. These barriers include: Capital Constraints, Utility Interconnection, and Environmental Permitting Regulations.

CHP systems are large investments that could potentially have initial costs into the millions of dollars (EPA, 2013). Firms may be unwilling to undertake such a venture even if there are positive returns and opportunities to save money in the long run. Business uncertainty also is a critical barrier to implementation (C2ES, 2015). A project involving CHP units may take several years of operation to reach the break-even point and start becoming profitable. If the investors are not confident that the company will continue operations at the same facility after a number of years, it may not want to contribute the high upfront costs. Figure 2.3 a shows a breakdown of the costs of a large CHP system (an example, not necessarily the size that is going to be proposed). The two most important aspects of the figure are that the total installed cost is $1,800,000 and the simple payback for the system is 6.3 years.

Understanding Economics of CHP Systems (EPA, 2013)	
Max Electrical Demand (MED)	2,500 kW
Total Electric Consumption (TEC1)	16,000,000 kWh
Total Electric Cost (TEC2)	$1,280,000
Total Natural Gas Consumption (TNGC1)	1,000,000 therms
Total Natural Gas Cost (TNGC2)	$700,000
Operating Schedule (OS)	8,760 hours
Avg Hourly Electrical Demand (TEC1/OS)	1,826 kW
Avg Price of Purchased Electricity (TEC2/TEC1)	$0.080/kWh
Average Hourly Natural Gas Consumption (TNGC1/OS)	114 therms/hr = 11,400,000 Btu/hr
Average Price of Natural Gas (TNGC2/TNGC1)	$0.70/therms = $7.0/MMBtu
Sizing CHP System	
If we size the CHP system to 60% of the maximum electric demand (1,500 kW), we can recover 6,750,000 Btu/hr (6.75 MMBtu/hr), which is 74 % of the total heat load	

Annual Energy Generation	
Annual Electic Generation (1,500 kW*(OS))	13,140,000 kWh
Annual Thermal Generation (6.75 MMBtu*(OS))	59,130 MMBtu
Annual Fuel Consumed (AFC)	154,858 MMBtu
Annual Energy Revenue	
Electric Revenue ((TEC2/TEC1)*(1,500 kW*(OS)))	$1,051,200
Thermal Revenue ((6.75 MMBtu*(OS))/(80%))*(TNGC2/TNGC1)	$517,388
Annual Energy Expenses	
Fuel Expenses (AFC*(TNGC2/TNGC1))	$1,084,005
O & M Costs ((1,500 kW*(OS))*($0.011/kWh)	$144,540
Standby Charge ($3/kW installed * 1,500 kW * 12 months)	$54,000
Total Revenue (Electric Revenue + Thermal Revenue)	$1,568,588
Total Expenses (Fuel + O & M + Standby)	$1,282,545
Total Savings (Total Revenue - Total Expenses)	$286,043
Installed Costs (1,500 kW * $1,200/kW)	$1,800,000
Simple Payback (Installed Costs/Total Savings)	6.3 years

Figure 2.3 a: Economics of a Large CHP System

Cogeneration systems are only economically viable when they can reliably and safely interconnect with the existing grid (C2ES, 2015). Interconnection standards and specifications vary regionally and nationally. This lack of uniformity regarding CHP systems makes it very difficult for manufacturers to mass-produce modular components (In the case of this project, WBMLP has a standard interconnection agreement for all distributed generation including CHP. Since they are directly involved, the interconnection is much simplified and less expensive). Many CHP systems have to be customized and the prices can become expensive, which hinders the ability of CHP technology to grow.

Cogeneration technology involves generating both heat and electricity onsite. This type of combination may cause an increase in a facility's onsite air emissions even if the total emissions associated with the facility's heat and electrical consumption are decreased. Environmental permitting regulations that are currently in place do not recognize the overall emissions reduction benefit due to the increase of onsite air emissions (C2ES, 2015). In order to reduce the onsite air emissions and allow the CHP system to be implemented, it is necessary to install pollution control equipment, like thermal oxidizers, during construction or retrofit the system to improve environmental outcomes. This carries a high upfront cost and may discourage installation.

2.3 b. CHP Regulations

There are many rules and regulations regarding CHP systems and their implementation. The details that need to be followed in order to obtain approval of CHP technologies can cause much confusion. That is why many states have endorsed providing siting and permitting requirements guidelines to help potential installers of cogeneration systems. The following paragraph summarizes some of what needs to be accomplished in order to obtain approval for permitting a CHP system.

The process of permitting a CHP system takes 3-12 months and includes many approvals and steps that need to take place before installation. Some of them include: approval from the electric and natural gas utility companies, an assessment of the CHP system by the Planning Department, a review completed by the Building Department, and approval from the Department of Environmental Protection regarding air quality. All of these agencies work together to ensure that the CHP project complies with local ordinances (noise, general planning and zoning, land use, and aesthetics), standards and codes (safety, piping, electrical, and structural), and air emission requirements (NO_X, CO, and particulate standards) (EPA, 2013).

An example of one such agency working with CHP installers to ease approval procedures is the Massachusetts Department of Environmental Protection (MassDEP). In March of 2008, the MassDEP proposed regulations “to encourage the installation of CHP systems” because CHP systems “will reduce greenhouse gas and other emissions, reduce fossil fuel usage and enable cost savings.” The regulations establish “a methodology that enables the applicant to adjust the emission limitation for a CHP system and take into account emissions that will not be created by omitting a conventional separate system (e.g. boiler) to generate the same thermal output (Harvard, 2013).”

2.4 Incentives for Implementing CHP Units

CHP systems can help businesses and institutions reduce energy costs, increase energy efficiency, enhance business competitiveness, and support energy infrastructure, all while offering environmental and climate change benefits. In recognition of these benefits, states and the Federal government have created financial incentives that create a favorable environment for CHP (EPA, 2013).

In a letter to the Worcester County Jail, the sponsor, Jonathan Fitch of WBMLP, was interested in establishing this CHP project as a renewable resource under the Massachusetts Alternative Energy Portfolio Standard (APS). Along with APS, the Massachusetts' CHP Program initiative offers incentives for CHP projects. Both are state incentive programs and are explained in the following sections.

2.4 a. Massachusetts APS

The APS was established on January 1st, 2009. It offers an incentive for installing eligible alternative energy systems, which are not renewable. It requires 5 % of the state's electrical load to be met by eligible technologies, which includes CHP systems (MassDOER, 2011).

Specifically, in regards to CHP units, a "Massachusetts APS-qualified CHP Unit should receive NEPOOL GIS certificates with APS Alternative Generation Attributes (termed Alternative Energy Certificates, abbreviated AECs) to the extent that the Unit is optimally-designed in relation to its electrical and thermal loads, uses excellent technology, and is well operated maintained and operated (MassDOER, 2011)."

2.4 b. Massachusetts' CHP Program

As a result of the Massachusetts Green Communities Act of 2008, CHP projects became eligible for incentives. The Massachusetts' Combined Heat and Power Program (CHP) initiative is one such program set up to help facilitate the incentive process on CHP units (MassSave, 2014). Like APS, the application process is lengthy and often times confusing, so MassSave created "A Guide to Submitting CHP Applications for Incentives in Massachusetts." It includes descriptions on available incentives, the application process, requirements for post-installation assessments, and regulatory evaluations. Complying with the recommendations of the Guide will increase the likelihood that a CHP project is eligible for incentives from Massachusetts' Program Administrators (PAs). A summary of the "Guide to Submitting CHP Applications for Incentives in Massachusetts" is included to describe the necessary components of an incentive application.

Thermal load is the key for having a successful CHP unit. CHP projects require passing the Benefit Cost Ratio (BCR) test, which demands rigorous examinations. A thriving CHP project typically utilizes nearly all of the thermal energy being produced by the system and involves the use of a prime-mover (reciprocating engine generator, gas turbine, fuel cell, etc.). Care should be taken not to propose an oversized system. An oversized system will cost more to install than a properly sized system and will result in a reduced number of equivalent full load operating hours compared to a correctly sized system (MassSave, 2014). Figure 2.4 a shows different CHP types, feasibility considerations, and whether it would go over well in an application. Reciprocating engines, gas turbines, and back pressure steam turbines are all eligible for CHP funding. Also, a CHP system can use any type of fuel.

PRIME-MOVER	PROSPECT	REMARKS
Reciprocating engine generator	More likely	Requires gas, i.e. natural, propane or landfill or #2-fuel oil. Highest electric conversion efficiency; lower installed cost; higher maintenance cost. Life expectancy is greater for larger units.
Gas turbine generator	Less likely	Requires gas, i.e. natural, propane, landfill or #2-fuel oil. Higher installed cost but lower maintenance cost. Booster compressor increases parasitic load which reduces net CHP kWh production. Potential use of a duct burner for increased thermal efficiency and thermal production.
Microturbine generator	Less likely	Requires gas, i.e. natural, propane or landfill. Booster compressor increases parasitic load which reduces net CHP kWh production; higher installed cost but lower maintenance cost.
Back pressure (BP) steam turbine	Most likely	Applicable only in high pressure steam systems. Steam systems using pressure reducing valves with significant flow and pressure drop should consider BP turbines. Lowest installed cost as boiler is usually in place. No or minor emissions permit required. Lower maintenance cost.
Fuel cell	Least likely	Requires gas, i.e. natural, propane or landfill. Least efficient; low grade waste heat is available; high equipment cost

Figure 2.4 a: Summary of Different CHP Systems and Likelihood of Being Approved (MassSave, 2014)

The qualifying criterion for incentives is extremely important. In order to receive incentives under this program, a CHP system must directly produce electricity. Also, the proposed CHP system has to have a minimum 60 % annual combined electric and thermal efficiency to qualify for Federal Tax Credits and Federal Grants.

A. Electrical Efficiency = $kW_{nameplate}$ X 3,412 BTU/kWh / Fuel Input $(Btu/Hr)_{HHV}$
B. Thermal Efficiency = Btu/hr useful thermal energy / Fuel Input $(Btu/Hr)_{HHV}$
C. Combined Efficiency = A + B

In addition to these two requirements, a benefit/cost analysis is needed that includes: the power (kW) output of the CHP system, annual net kWh generated, installed cost of the equipment, ongoing annual maintenance costs, quantity of fuel and type of fuel being fired in the CHP system, and timing of the power production (such as winter/summer and peak versus off-peak). Incentive funding mandates that the lifetime benefits exceed the lifetime costs as well (MassSave, 2014).

There are 3 tiers of incentives that depend on the size of the CHP project and other project attributes, such as system efficiency. Tier 1 includes an incentive for a CHP project up to 150 kW worth $750/kW. It requires that the total incentive payments may not exceed 50 % of the total project cost and that the CHP system sizing does not exceed the building requirements. Tier 2 has the same prerequisites as Tier 1, but also includes that the annual estimated efficiency shall be greater than 60 %. If a project is deemed to fall into this tier, the incentive is worth up to $1,000/kW. Tier 3 has an incentive worth up to $1,200/kW and requires an annual estimated efficiency of the CHP plant greater than 65 % (MassSave, 2014).

The CHP incentive application process is best facilitated when there is early engagement with the Incentive Program Administrator. Communication should be started in the early stages of development of a CHP project. This enables early feedback. It should also be confirmed that the electric utility circuit is compatible with a CHP project (WBMLP’s electrical circuit is compatible and interconnection will work). For systems firing natural gas, confirmation should be received from the gas account executive that sufficient gas volume and pressure is available to supply a facility’s total gas requirements for the proposed system (In terms of the scope of this project, Eversource is the current delivery provider and another firm provides the gas commodity). A typical CHP application process is shown in Figure 2.4 b.

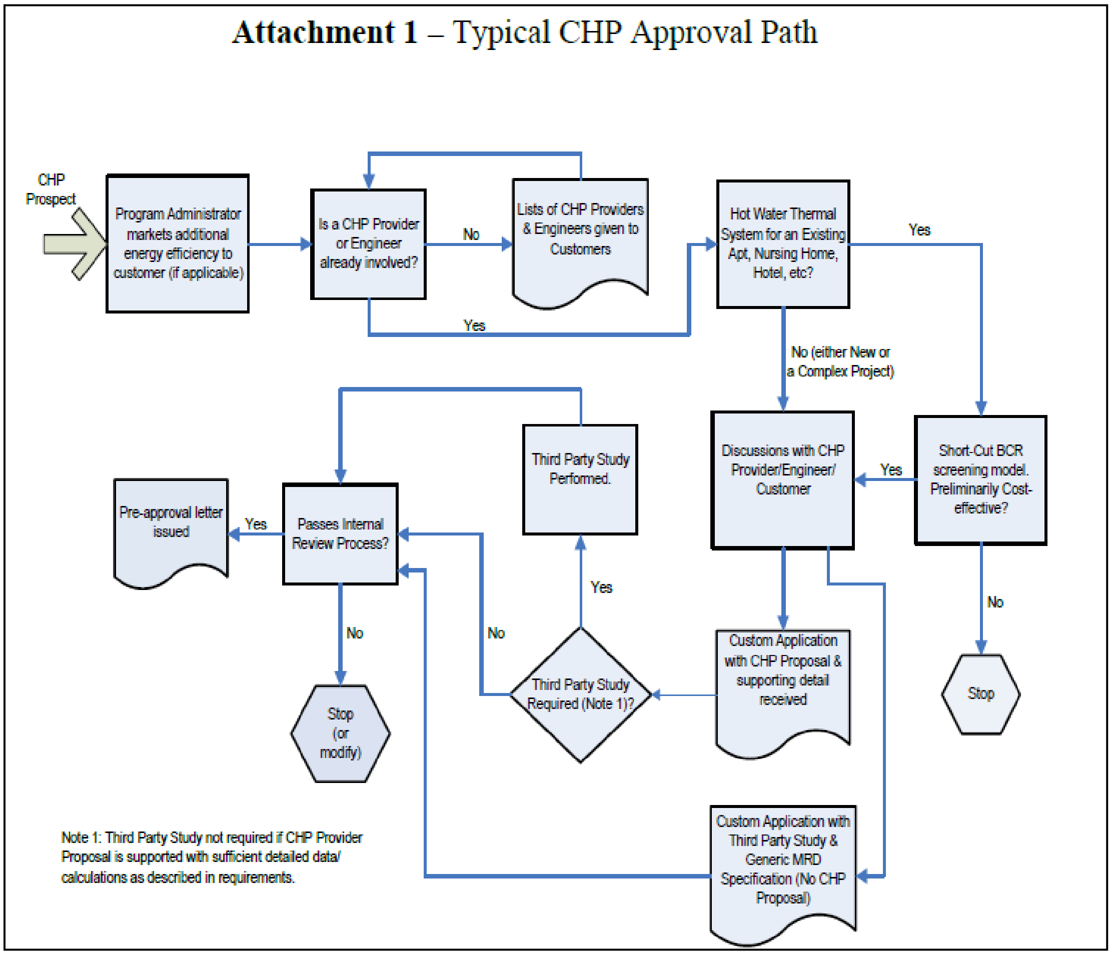

Figure 2.4 b: Typical CHP Application Process (MassSave, 2014)

2.5 Carbon Dioxide Emission Reduction Resulting from CHP Installation

When evaluating the feasibility of a cogeneration unit, the emission of greenhouse gases is one of the factors that need to be considered. Carbon dioxide is the primary greenhouse gas emitted through human activities. In 2013, it accounted for 82% of all U.S. greenhouse gas emissions (EPA, 2013). The generation of electricity accounts for 37% of the U.S.'s carbon dioxide emissions (EPA, 2013). The cogeneration units being considered will burn fossil fuels, leading to the emission of carbon dioxide. However, the carbon dioxide emitted by the cogeneration unit at the Worcester County Jail will be lower than the carbon dioxide emitted during conventional generation (separate generation of electricity and heat). This difference in the amount of carbon dioxide emitted needs to be calculated and it will affect the following:

- Whether or not the installation of the CHP unit will be approved by permitting bodies
- Whether or not WBMLP will be able to take advantage of incentives put in place by governmental and environmental agencies.

The above mentioned factors will affect the payback period of the CHP unit and as such, will also affect whether or not the CHP unit gets installed at the Worcester County Jail.

2.6 Integrating a CHP System into the Worcester County Jail

When choosing a CHP unit for the Worcester County Jail, the HVAC (Heating, Ventilating and Air Conditioning) system must be carefully evaluated with the aim of choosing a CHP unit that fits the current HVAC system. The CHP unit chosen should be the one that requires the least number of adjustments to the current HVAC system, as this will help WBMLP reduce project costs. This section will define HVAC systems and will display the components of the Worcester County Jail's HVAC system that need to be considered when selecting a CHP unit.

Cogeneration is the use of a CHP unit to simultaneously produce useful heat and electricity (EPA, 2013). To maximize the benefits of cogeneration, CHP units should be selected based on the heating load or the application of demand. In the case of the Worcester County Jail, the demand that needs to be met is the provision of domestic hot water (since it a demand that occurs year round).

HVAC systems deliver processed air or water at a preset flow rate, pressure, and quantity to maintain desired conditions within a facility. HVAC systems also control temperature, humidity, particulate levels, and room distribution patterns (Paoli, 2012). Typical components of an HVAC system include fans, ductwork, heat exchangers, life safety devices, terminal devices, filters, hazard containment devices, and duct insulation. Listed below, and accompanied by pictures, are components of the Worcester County Jail's HVAC system that have been determined essential in the process of selecting a compatible CHP unit.

Raypak Units

Quantity: 2

Model number: WH9-1532BL

Maximum allowable water pressure: 160 psi

Maximum allowable Btu/hr input: 1,530,000

Recovery Rating: 1576 gallons/hr

Size: 32.625 inches (length) x 41.25 inches (height) x 79.875 inches (width)

Figure 2.6 a: Picture of Raypak Units in Worcester County Jail (Fay, 2015)

The unit shown above is a natural gas powered water heater suitable for (potable) heating and space heating. It requires a minimum of 24 inches unobstructed clearance in front of the unit for servicing.

Reco Storage Tank

Quantity: 3

Model number: 29374

Maximum allowable working pressure: 150 psi

Minimum design metal temperature: -20^{o}F

Size: 52.5 inches in diameter, 111 inches in height

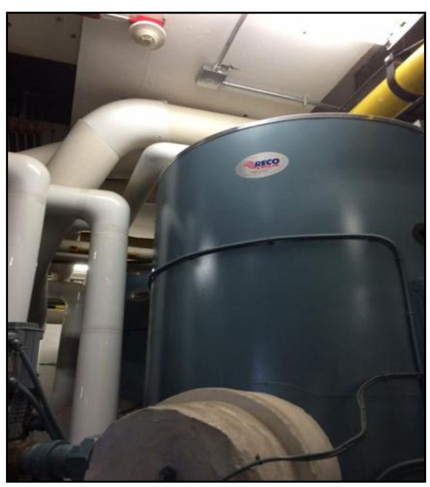

Figure 2.6 b: Picture of Reco Storage Tank in Worcester County Jail (Fay, 2015)

In the following WBMLP Expectations and Results section, topics discussed in the Background will be considered when sizing a suitable CHP unit and applying for incentives.

3.0 WBMLP Expectations and Results

The Methodology and Results section of this project have been combined to limit redundancy and to ease reading. The following section describes expectations that the sponsor, WBMLP, had for the project. There are 8 tasks that were deemed necessary to complete. The reasons for completing each task are given first and then the results follow. The expectations for this project were:

1. Site Visits to evaluate HVAC equipment and see potential space for the CHP unit
2. Evaluate Environmental Benefits
3. Use sensors/thermistors/flow meters to evaluate heating load profiles and energy consumption
4. Create a detailed visualization of the proposed CHP unit (SolidWorks)
5. Review permitting requirements for installing CHP units
6. Review potential incentives that can be received
7. Create a budget for the CHP unit installation which includes financial returns
8. Create a schedule for integration of the CHP unit

3.1 Site Visits to evaluate HVAC equipment and see potential space for the CHP unit

Early on in the project, the team decided it was necessary to visit the Worcester County Jail, the site where the CHP unit would be placed. In late September, the team scheduled a visit to the jail with Jonathan Fitch of WBMLP and his colleague, Bart Bales, a certified engineer. The head of maintenance at the jail, Mark Gabriel, led the tour of the facilities. The reasons for going on a site visit and the results of the visit are explained below.

Reasons for going on a Site Visit

- This would allow everyone to see what the jail is currently using for heat generation and plan out the integration of a CHP unit into the existing systems.
- Learn as much as possible about the jail's current boiler room setup
- See what systems supplied the various heating loads to the jail
  - Jonathan Fitch had installed a flow meter in the boiler room prior to the scheduled visit. The flow meter gave data that was used to calculate the heating loads supplied to the jail for domestic water heating.
- Determining a potential site for the CHP unit
  - The unit has to be in the vicinity of the boiler room, so that it can be attached to the water supply.
- Good learning opportunity for the team
  - Bart Bales is a certified engineer and he was a very valuable resource for the team. He provided further explanation and analysis of the components of the boiler room.

Post-Visit Summary

Upon entering the boiler room, the team directly examined the units that the jail currently uses to generate heat. The jail uses 2 Raypak units, 3 (Cleaver Brooks) boilers, and 3 storage tanks. The Raypak units are used year-round for domestic hot water heating. On the other hand, the boilers are only used for space heating. They are turned on in the fall/winter seasons, starting October 15th. The storage tanks are used to store the hot water generated from both systems at a temperature of 120°F. There were many pictures taken of the boiler room and its components throughout the visit, some of which can be seen below. There were also many supply/return pipes in the facility and it was discovered that there was no diagram describing the paths of these pipes. It was determined that a pipe diagram would be drawn up and that can be seen below as well.

Figure 3.1 a: Picture of the Boiler from the Worcester County Jail (Fay, 2015)

Figure 3.1 b: Picture of the Raypak Units (Fay, 2015)

Figure 3.1 c: Picture of the Storage Tanks (Fay, 2015)

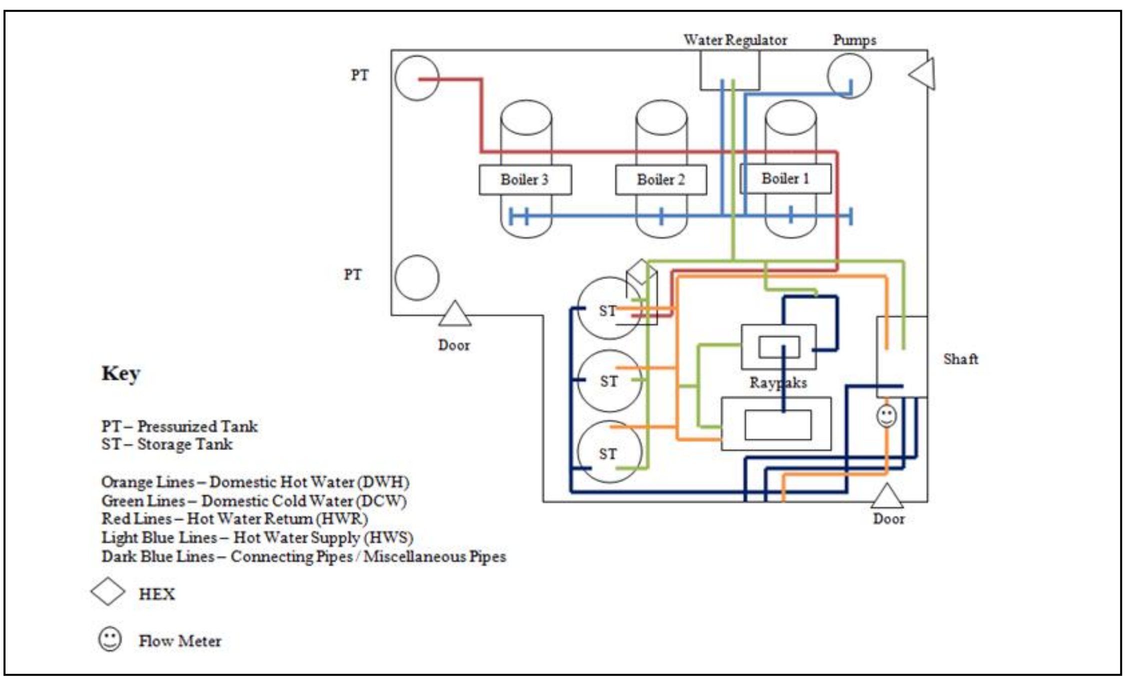

Figure 3.1 d: Pipe Diagram/Layout of the Boiler Room (Fay, 2015)

Once the team had taken a sufficient amount of pictures, and viewed the layout of the boiler room, the individual components were examined in more detail. The information on the nameplates of the boilers, storage tanks, and Raypak units (serial number, Btu/hour, recovery rating, etc.) were recorded. This was done to ensure that all information on the machines could be obtained and multiple trips back to the jail to check ratings were not necessary.

Before departing the jail, the team needed as much information on the heating load of the jail as possible. Mark Gabriel was there to assist in acquiring certain information. The jail uses domestic hot water mostly in the showers and in the kitchen. Showers are run every day at 8 am and 10 pm, and the kitchens are open from 2 am to 7 pm. Rough estimates were given of the following:

- Number of inmates eating per meal
- Dishwasher usage over the course of a day
- Meal hours
- Utensil and plate usage
- Gallons of hot water used per meal

One of the more important assumptions to analyzing the heating loads was that the kitchen uses about 1000 gallons of hot water per meal. Due to there being 3 meals a day, the total assumed hot water supply per day in the kitchen is roughly 3000 gallons.

Siting of the CHP unit

One of the deliverables for this project that WBMLP asked for was to come up with potential sites at the jail for the CHP unit. Two main concerns were relevant when determining the site for the CHP unit: accessibility and space efficiency. There were two locations that were deemed potential spaces for the CHP unit. One was inside the boiler room, underneath an air vent, and the other spot was against a sidewall outside of the boiler room facility.

- <u>Accessibility</u>
    - Important to consider because CHP units tend to be small (a 75 kW Tecogen unit is 7’ 2” L x 3’ 8” W x 3’ 10”H) and modular. This allows for upgrades

and any other additions to be potentially added on to the unit. Therefore, it is important to have enough room around the unit for it to be accessible.

  - Accessibility is also important because there needs to be enough room around the unit to provide any maintenance if there are malfunctions.

- Space Efficiency
  - Cannot be in the way of other operating units (boilers, tanks, etc.)

Benefits/Weaknesses to having the CHP unit inside the boiler room

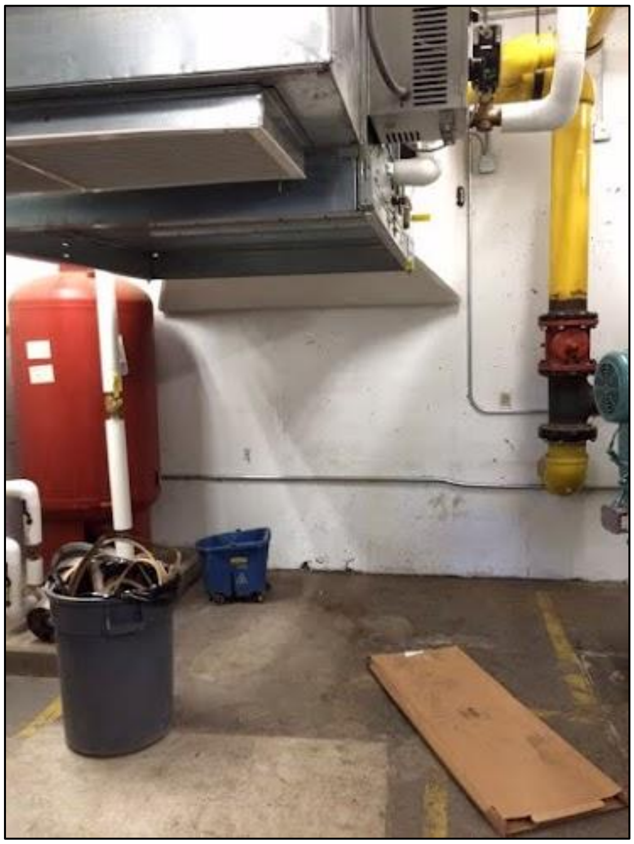

Figure 3.1 e: Potential Space inside Boiler Room for CHP unit (Fay, 2015)

- Benefits
  - It allows for all power/heat generation equipment to be in the same room, which can be beneficial for spacious purposes as well as for maintenance.
- Weaknesses

- There is not enough area inside the boiler room for the size of a CHP unit that the jail will need.
- This site also is in front of one of the boilers. Adding a CHP unit to this spot will cause issues with opening/closing the boiler.

Benefits/Weaknesses to having the CHP unit outside the boiler room facility

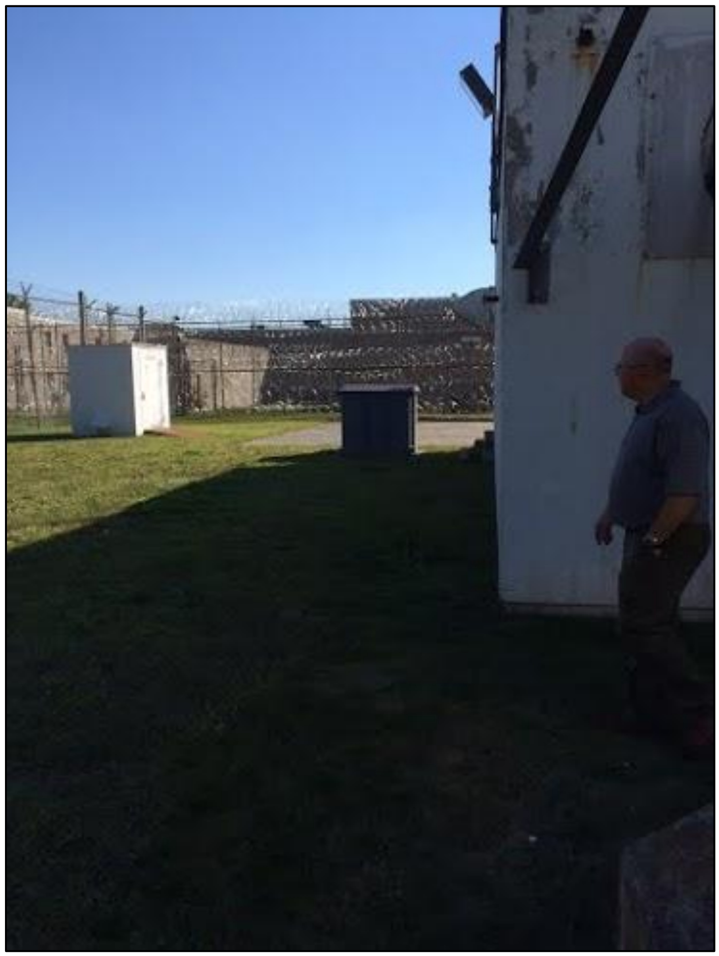

Figure 3.1 f: Potential Space outside Boiler Room Facility for CHP unit (Fay, 2015)

- Benefits
  - Open area with plenty of space and it is directly next to the boiler room facility
  - Full accessibility
  - Completely mobile from this site

    - It is not disrupting any other equipment by being there
- Weaknesses
    - Inside the boiler room would be ideal because all equipment can be confined to the same space. However, it is not a large enough concern to become a deciding factor.

Due to the above factors, the best option for placing the CHP unit is outside, next to the facility. The main reasoning behind this is space. The unit cannot block any access to other equipment in the room. The intended area meant for the unit inside the boiler room is too close to one of the boilers, and therefore cannot go in that area. There are no other viable options inside the boiler room to put the unit, so the only option left is outside the building.

3.2 Evaluate Environmental Benefits

Carbon Savings

Outlined below is the process that was used to calculate the total carbon dioxide savings (pounds). In other words, it is the carbon dioxide that will not be emitted if a cogeneration unit is installed at the Worcester County Jail (EPA, 2015).

1. The first step is to calculate the CO_2 emissions from displaced on-site thermal production. This can be done using the equation below:

$$C_T = F_T * EF_F$$

C_T is the CO_2 emissions from displaced on-site thermal production (lbs CO_2), F_T is the thermal fuel savings (Btu), and EF_F is the fuel specific CO_2 emission factor (lbs CO_2 / MBtu).

a) F_T can be calculated as:

$$F_T = CHP_T / \eta_T$$

CHP_T is the CHP system's thermal output (Btu) and η_T is the estimated efficiency of the thermal equipment (percentage in decimal form). η_T is the thermal efficiency of the Raypak units (84%) currently being used at the Worcester County Jail.

b) A value for the EF_F of natural gas can be found in Table 1 of the Environmental Protection Agency's website (EPA, 2015).

2. The second step is to calculate the CO_2 emissions from displaced grid electricity. Below is the equation used to evaluate this:

$$C_G = E_G * EF_G$$

C_G is the CO_2 emissions from displaced grid electricity (lbs CO_2), E_G is the displaced grid electricity from the CHP (kWh), and EF_G is the grid electricity emissions factor (lbs CO_2 /kWh) for the appropriate sub-region.

a) E_G can be calculated as:

$$E_G = CHP_E / (1 – L_{T\&D})$$

CHP_E is the CHP system electricity output (kWh) and $L_{T\&D}$ is the loss from transmission and distribution (percentage in decimal form). The $L_{T\&D}$ was selected from Table 9 of the eGRID summary tables, where the estimated transmission and distribution loss for each of the five U.S. interconnect power grids are listed (EPA, 2015). Massachusetts is part of the Eastern Region.

b) An appropriate value for EF_G can be selected using eGRID as well (EPA 2015).

3. The third step is to calculate the CO_2 emissions from the CHP system. This can be calculated using the equation below:

$$C_{CHP} = F_{CHP} * EF_F$$

C_{CHP} is the CO_2 emissions from the CHP system (lbs CO_2), F_{CHP} is the fuel used by the CHP system (Btu), and EF_F is the fuel specific emissions factor (lbs CO_2 / MBtu). A value for EF_F should have been selected in Step 1 b).

a) F_{CHP} can be calculated as:

$$F_{CHP} = CHP_E / EE_{CHP}$$

CHP_E is the CHP system electricity output (Btu). It is not usual to convert electricity output to Btu but the reason we do this is because it makes it easier to multiply F_{CHP} with EF_F and get a value in pound of CO_2.EE_{CHP} is the electrical efficiency of the CHP system.

4. The final step is to calculate C_S, the total carbon dioxide emission savings (pounds) using the equation below:

$$C_S = (C_T + C_G) - C_{CHP}$$

A spreadsheet was created to calculate the CO_2 emission savings (in pounds per hour) that result from switching from conventional heating and electricity to using a CHP system. A screenshot of the spreadsheet can be seen below:

Table 3.2 a: Screenshot of Carbon Savings Calculation

	A	B	C	D	E	F
1	**Step 1**	CHP sub T (Btu)	η_T	F sub T (Btu)	EF sub F (lbs CO_2 / MBtu)	**C sub T (lbs)**
2		978000	0.84	1164285.714	116.9	136.105
3						
4						
5	**Step 2**	CHP sub E (kWh)	$L_{T\&D}$	E sub G (kWh)	EF sub G (lbs CO_2 /kWh)	**C sub G (lbs)**
6		150	0.0917	165.143675	0.60178	99.38016074
7						
8						
9						
10						
11						
12	**Step 3**	CHP sub E (kWh)	EE sub CHP	F sub CHP (Btu)	EF sub F (lbs CO_2 / MBtu)	**C sub CHP (lbs)**
13		150	0.3	1706000	116.9	199.4314
14						
15						
16	**Step 4**			**C sub S (lbs)/ hour**		
17				36		

In the spreadsheet depicted above, once the cells in green are filled out, the CO_2 emission savings in pounds per hour can be calculated. The cells in green are:

- The CHP system's thermal output (Btu),
- The CHP system's electrical output (kWh)
- The CHP system's electrical efficiency

It was determined that installing a 150 kW CHP system at the Worcester County Jail would result in CO_2 emission savings of 36 pounds per hour. The formulas and values used for the CO_2 emission savings calculation are outlined below:

<u>Step 1:</u>

F_T = thermal fuel savings per hour (Btu) = CHP_T / η_T

CHP_T = CHP system's hourly thermal output = 978,000 Btu

η_T = efficiency of the thermal equipment (Raypak units) = 0.84

EF_F = fuel specific CO_2 emission factor = $1.169*10^{-4}$ lbs CO_2/ Btu

C_T = CO_2 emissions from displaced on-site thermal production (lbs CO_2)

$= F_T * EF_F = (CHP_T / \eta_T) * EF_F = (978{,}000 / 0.84) * 1.169*10^{-4}$

= 136.1 lbs

<u>Step 2:</u>

E_G = E_G is the displaced grid electricity from the CHP (kWh) = $CHP_E / (1 – L_{T\&D})$

CHP_E = CHP system electricity output = 150 kWh

$L_{T\&D}$ = portion lost from transmission and distribution = 0.0917

(EPA, 2015)

EF_G = grid electricity emissions factor for the appropriate sub region = 0.60178 lbs CO_2 /kWh (EPA, 2015)

C_G = CO_2 emissions from displaced grid electricity (lbs CO_2)

$= E_G * EF_G = (CHP_E / (1 – L_{T\&D})) * EF_G = (150 / (1 - 0.0917)) * 0.60178$

= 99.38 lbs

<u>Step 3:</u>

F_{CHP} = fuel used by the CHP system (Btu) = CHP_E / EE_{CHP}

CHP_E = CHP system electricity output (Btu) = 150 kWh * 3412 = 511,800 Btu

EE_{CHP} = Electrical efficiency of the CHP system (varies based on specific CHP system) = 0.3

EF_F = fuel specific CO_2 emission factor (lbs CO_2/ Btu) = $1.169*10^{-4}$

C_{CHP} = CO_2 emissions from the CHP system (lbs CO_2)

= F_{CHP} * EF_F = (CHP_E / EE_{CHP}) * EF_F = (511,800 / 0.3) * $1.169*10^{-4}$

= 199.4 lbs

<u>Step 4:</u>

C_S = total carbon dioxide emission savings (lbs/ hour)

= C_T + C_G – C_{CHP} = 136.105 + 99.38 – 199.43

= 36 lbs/hour

3.3 Use sensors/thermistors/flow meters to evaluate heating load profiles and energy consumption

When deciding on the size of a CHP unit, the heating load that will be supplied by the CHP unit must be considered. In order to determine this heating load (domestic water heating), a Fuji Portaflow Ultrasonic Flow Meter was installed in the boiler room at the Worcester County Jail. This flow meter measures and records velocity (ft/s), flow rate (gal/min), and temperatures of water before and after going through the water heater (°F). The monthly load for domestic water heating was calculated, in therms/month, based on data from the flow meter. This value was then compared to heating load data from the jail's gas bills. The steps taken to calculate the domestic water-heating load are outlined below.

1. A British thermal unit (Btu) is the energy required to raise 1 lb of water from 60°F to 61°F at sea level; 1 gallon of water weighs 8.33 lbs. Cold water and hot water temperatures are measured every minute by the flow meter. A value for change in temperature was calculated for each data point and an average value from this data was used as Delta T.

   Delta T = 50°F

2. Heating a gallon of water requires:

   1 Btu/(lbs*°F)*8.33lbs*50°F = 417 Btu (assuming 100% efficiency)

3. The efficiency for the Raypak heaters used at the jail is 84%. Therefore, it takes:

   417 Btu/ .84 = 496 Btu to heat a gallon of water

4. 1 therm = 100,000 Btu

   496 Btu = 0.00496 therms

5. The team has 7 days of data from August and 9 days of data from September. Included in these data is the flow rate (gallons/min) recorded every minute during

these days. These data was used to calculate a total volume (gallons), which was then divided by the number of days, and multiplied by 31 to find an equivalent gallons/month value. This value was 1,010,001 gallons/month.

6. The equivalent gallons/month value was multiplied by 0.00496 therms (amount required to heat 1 gallon) to find a value for therms/month. This value was 5,010 therms/month. This value was then compared to the actual number of therms provided to the Worcester County Jail from August 2013 and August 2014. The actual number of therms was gathered from a copy of the Worcester County Jail's natural gas heating account from Eversource. The calculated value for domestic water heating load was within 10.8% of the data from August 2013 and within 10.9% of the data from August 2014. This helps verify that the flow meter is gathering accurate data.

CHP Unit Sizing from Fuel/Hot Water Usage Data Comparisons

The heating load calculations developed were used to determine the size of the CHP unit. To determine the size, the following parameters were very useful in having a more successful feasibility study (Renac, 2015):

- Peak and average demand (kW)
- Load factor (ratio between average and peak demand, in %)
- Annual energy consumption (kWh/year)
- Load demand duration curves (graphs) covering different periods (presented in Figure 3.3 a)

All of these parameters were obtained through data collection and calculations. A flow meter recorded the heating loads used for supplying domestic hot water. With this data, the team was able to calculate the above parameters. However, the project is time sensitive and the flow meter cannot run for a year, so some assumptions were made from the actual recorded data.

Correct sizing of a CHP system is very important. Although CHP units typically save money and lower CO_2 emissions; if sized incorrectly, these units can actually waste money and power. In almost all circumstances, in order to get the most out of a CHP unit, it must be continuously running. According to Renac, there are 3 main CHP unit sizing options:

1. Sizing based on minimum internal thermal and electric loads
2. Sizing based on thermal load and selling excess electrical output
3. Sizing to maximize electric production

The second sizing criteria was followed because it is similar to what WBMLP has outlined as their plans for the CHP unit. Therefore, the team made all thermal load calculations, as mentioned in the previous paragraph, to determine all thermal load parameters. Once these parameters were calculated, a CHP unit was decided on that generates a thermal capacity equivalent to that of the jail's needs.

CHP Unit Sizing Analysis

To begin the analysis of the data collected from the flow meter, all the data was organized by day. The meter took readings of the water being used once per minute, every minute of the day. A table was then made of the average demand of therms per hour for the 24 hours in that day. The flow meter data was recorded in gal/hr and had to be converted to therms. In order to do this, the values were multiplied by 0.00496. Once all the data was compiled, an analysis on the heating demand was generated.

To analyze the heating demand, a table was created. This table was used to find the average heating demand based on the time of the day. The total therms used in a specific hour were divided by the number of days of recordings to get the average demand. This data is in therms and in order to get to kWh, the following calculation was used:

$$1\ \text{therm} = 100{,}000\ \text{Btu}$$

$$1\ \text{Btu} = 0.000293071\ \text{kWh}$$

Data is shown in Figure 3.3 a. The chart has 3 horizontal lines on the graph; these represent the peak demand, the average demand, and the minimum demand (corresponding from top to bottom on the graph). Initially, it was intended to size the unit based on the minimum demand. However, the team noticed that the minimum demand did not require much heat addition compared to the other hours of the day; therefore, the CHP unit would not account for much of the domestic hot water heating. As a result, more analyses had to be performed to see what CHP size is needed for the Worcester County Jail.

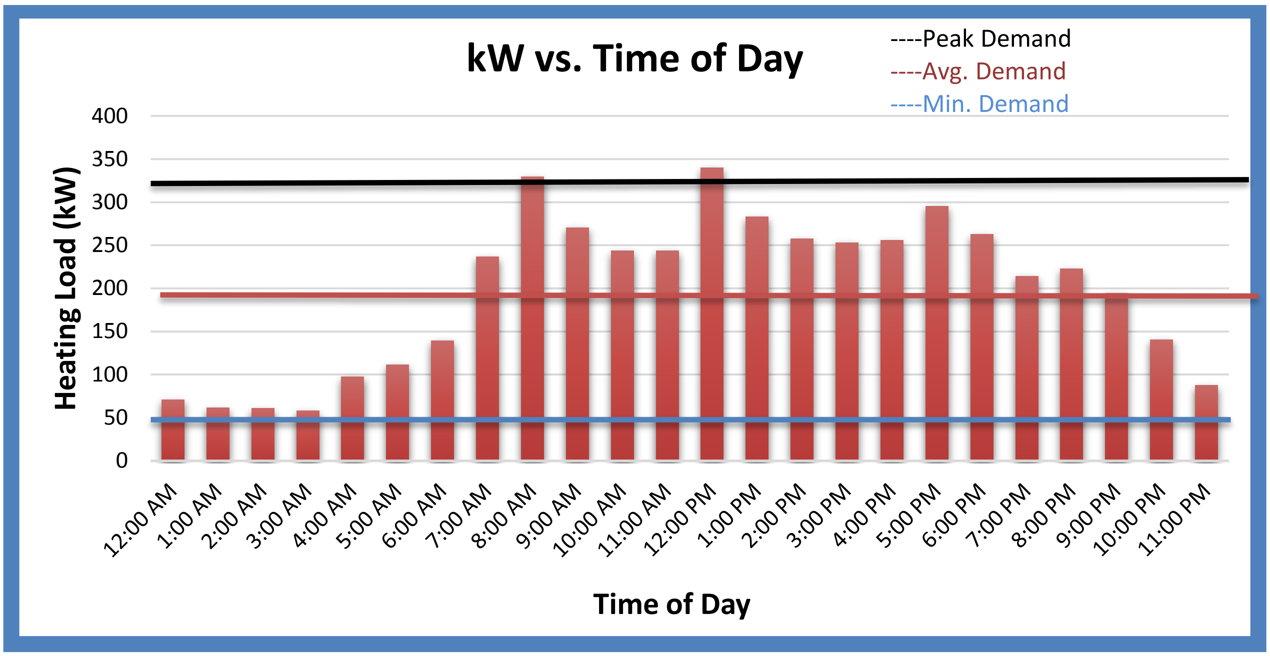

Figure 3.3 a: Graph of the Heating Load

To further the analysis, it was deemed necessary that the amount of heat required to heat up the 3 storage tanks to their recommended temperature should be calculated. Currently, the jail heats their tanks to 120 °F. According to Bart Bales, the engineer from the site visit, the tanks should be at a temperature of at least 128 °F to prevent Legionnaires disease conditions. To do this, the following calculations were used:

$$T_1 = \text{Initial Water in Pipe Temp.} = 73.4\ °\text{F (from Flow Meter Data)}$$

$$T_2 = \text{Storage Tank Initial Temp.} = 120\ °\text{F}$$

$$Q = \text{Heat generated}$$

$$m = \text{mass of water in the tanks}$$

$$c = \text{specific heat capacity of water}$$

$$Q = mc(T_2 - T_1)$$

The tanks have a volume of 700 gallons and the density equation was used to obtain the mass of the water in the tanks.

$$V = 700 \text{ gallons}$$

$$V = 2.6497 \text{ m}^3$$

$$\text{Density} = \frac{m}{V} = 1000 \ \frac{\text{kg}}{\text{m}^3}$$

$$m = 2649.7 \text{ kg}$$

After determining the mass, and knowing that the heat capacity is 4.19 kJ/kg*K, the total heat required could be calculated. For 3 tanks, the total heat required is:

$$Q_1 = 239.53 \text{ kWh}$$

In trying to determine a size, a table of all possible CHP unit sizes was created.

Table 3.3 a: Table for CHP Unit Sizing Selection

Total Heat Generated, Q (kWh)	Total Heat Generated, Q (kJ)	Storage Tank Temp, T2 (K)	Initial Temp, T1 (K)	Heat Required (All Tanks), Q1* (kJ)	Heat Required (All Tanks), Q1* (kWh)	Final Temperature, T3 (K)	Final Temperature, T3 (°F)
240	864,000	322.04	296.15	862,311	239.53	322.09	120.09
250	900,000	322.04	296.15	862,311	239.53	323.17	122.04
260	936,000	322.04	296.15	862,311	239.53	324.25	123.98
270	972,000	322.04	296.15	862,311	239.53	325.33	125.93
280	1,008,000	322.04	296.15	862,311	239.53	326.41	127.88
290	1,044,000	322.04	296.15	862,311	239.53	327.50	129.82
300	1,080,000	322.04	296.15	862,311	239.53	328.58	131.77
310	1,116,000	322.04	296.15	862,311	239.53	329.66	133.71
320	1,152,000	322.04	296.15	862,311	239.53	330.74	135.66
330	1,188,000	322.04	296.15	862,311	239.53	331.82	137.60
340	1,224,000	322.04	296.15	862,311	239.53	332.90	139.55

Depending on the estimated size, Q_1 would be subtracted from Q_{total} to obtain Q_2, which is the leftover heat generated after the tanks are heated to the required temperature.

$$Q_2 = Q_{total} - Q_1$$

After finding Q_2, the final temperature of the tanks was found.

$$Q_2 = mc(T_3 - T_2)$$

T_3 is the final temperature of the storage tanks.

After creating the table and using MS Excel to figure out the final temperature values, the best-fit size was determined. This was found to be a unit of roughly 280 kW of thermal generation, which would raise the temperature in the tanks to about 143 °F.

Using the selected value of 280 kW of thermal generation, a unit was found to meet that demand. A unit of roughly 150 kW of electric generation would be needed to meet the heating demand. The team decided that it would be best to follow a similar approach as WPI's Gateway Park. Gateway implemented two 75 kW CHP units instead of one 150 kW unit.

The calculations that were performed involved an assumption that the temperature for the initial water in the pipes was 73.4 °F. The value was gathered from the flow meter, which provided data for August and September. Therefore, the analysis catches a detailed look at one period of time. As a comparison, the temperature data was gathered for the water supply in Auburn, Massachusetts. The water average is 57 °F but fluctuates between 33 °F and 79 °F (EPA, 2015). The average value that was used in this proposal is for the summer data and if a bigger unit size was used (which would be the case if a temperature of 57 °F was assumed), the heat generated by the unit would be tossed away in the summer.

3.4 Create a detailed visualization of the proposed CHP unit

WBMLP needs a visual tool to use when talking to the Worcester County Jail about installation and when talking with the state to receive incentives for the project. One tool that can be utilized to accomplish this is SolidWorks. The SolidWorks rendering includes an accurate representation of the interior of the boiler room. This is possible due to the drawings of the existing boiler room being obtained from the Worcester County Jail.

Conclusions from Drawings

Although the drawings were from the 2007 remodeling, there were some key attributes that were of use to the team. The main discrepancy between the drawings and the actual Worcester County Jail boiler room was in the location/brand of storage tanks. They were listed as being 700 gallon Hubbell storage tanks and, in actuality, they were manufactured by Reco. It was assumed that the dimensions of the tanks have not changed from the drawings. Also, the locations of the tanks were different then the drawings. This may have been an on-the-fly change by the developers. Also, the drawings did not include the Raypak units, which are an important aspect for domestic hot water heating.

SolidWorks Model

All information gathered from the drawings was incorporated to produce the model shown below in Figure 3 j and k (in an isometric/top view). All necessary components needed for the functioning of the boiler room are shown in different colors, as well as some important plumbing aspects (specifically, the hot water supply/return lines). The colors are as follows: The storage tanks in blue, the Raypak units in green, the boilers in red, the hot water return lines in gold, the hot water supply lines in gray, and the CHP units that will be implemented in yellow. The roof is shown detached from the actual structure to allow for the interior to be seen.

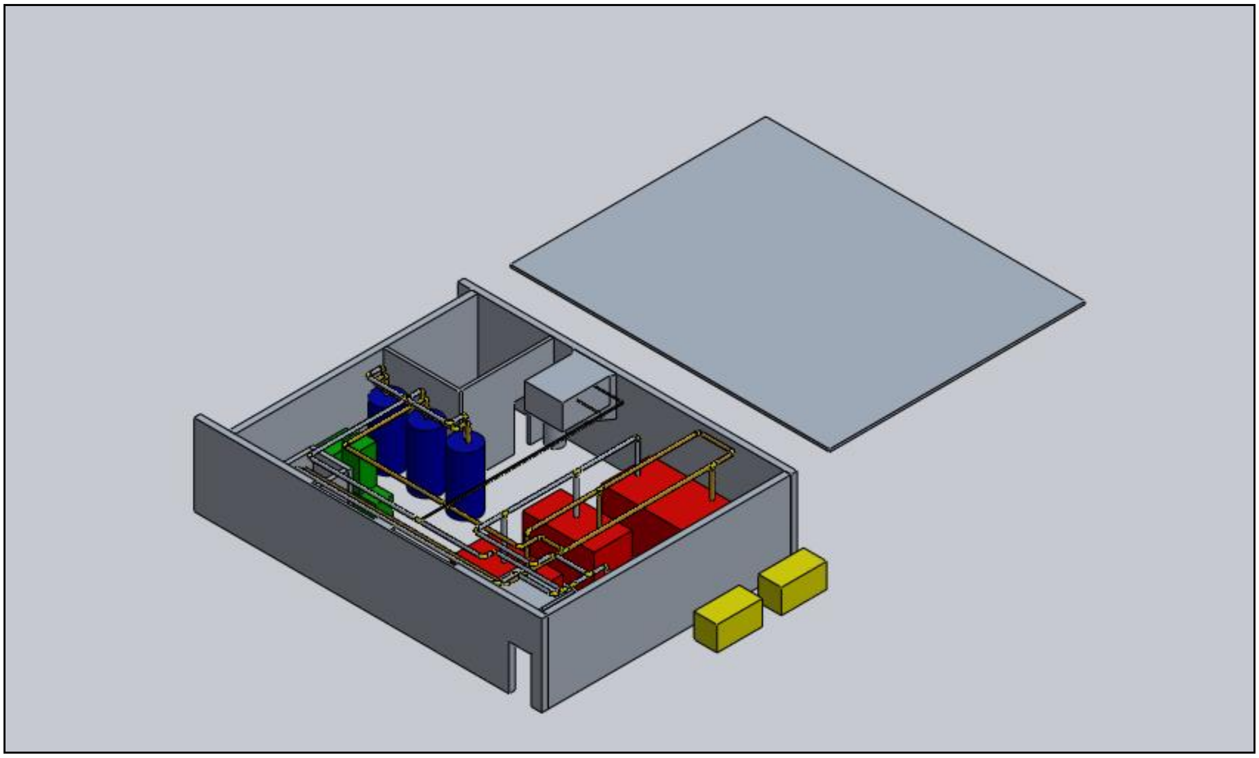

Figure 3.4 a: Isometric View of the SolidWorks Model of the Worcester County Jail

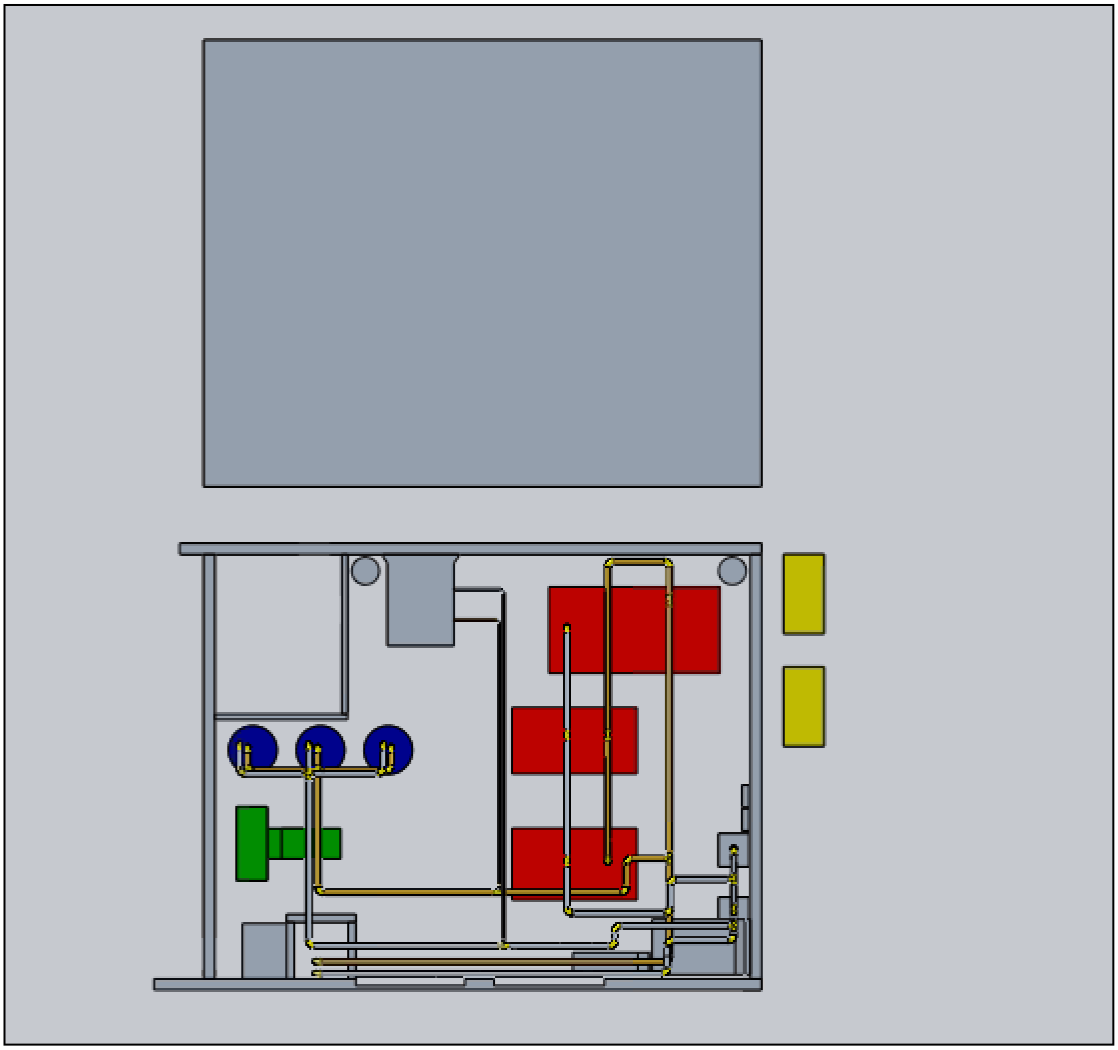

Figure 3.4 b: Top View of the SolidWorks Model of the Worcester County Jail

3.5 Review permitting requirements for installing CHP units

WBMLP requested that all permitting requirements be documented and reviewed in great detail. This will aid them in being able to properly prepare for meetings with the state and have everything in order for when installation of the CHP unit into the Worcester County Jail takes place.

In order to obtain permission to install a CHP unit, it is necessary to obtain approvals from (EPA, 2013):

- **Local Utility Companies** (Electric and Natural Gas Connection)
  - In the case of this project, the sponsor is WBMLP, who supplies the electricity and has a close relationship with Eversource, who supplies the natural gas. Therefore, it will not be an issue to obtain approval for this.
- **Planning Department**
  - It is required to have a land use and environmental assessment review before construction and an inspection once construction is completed
- **Building Department**
  - Approval of the design based on construction drawings and inspection after installation
- **Air Quality Agency**
  - Approval to construct the CHP system and confirmation that emission requirements are met after construction

The permitting process during the pre-construction phase of a CHP project involves three steps (EPA, 2013):

- The developer completing and submitting application forms and fees to the relevant parties
- The parties review the application, which may take multiple rounds of information exchange to ensure accuracy and completeness
- The parties complete the review and issues the permit

During post-construction, it is necessary for the agencies to confirm that the installation does not deviate from the approved application. This usually involves a site inspection and if the agency determines that the project falls short of compliance, then steps need to be taken to ensure the project is fixed (EPA, 2013).

There are a number of steps to facilitate the permitting process:

- Meet with city regulators early to determine the required permits
- Assess the concerns of the agencies early on, so delays will be minimized
- Submit everything on time

Permitting can require significant investments of time and money. Costs for permitting small CHP projects may approach 3 to 5 percent of the total project costs (EPA, 2013).

Local Zoning/Planning Requirements

Project siting and operation are governed by local jurisdictions such as (EPA, 2013):

- County and City Planning Bureaus
    - Govern land use and zoning issues
    - Conduct environmental impact assessments and are responsible for compliance with local ordinances
- State and Local Building and Fire Code Departments
    - Address CHP related safety issues, such as exhaust temperatures, natural gas pressure, fuel storage, and space limitation
- Environmental/Public Health Department
    - Focuses on hazardous materials and waste management requirements
- Water/Sewer and Public Works Authorities
    - Rule on water supply and discharge matters
    - Ensure that a project is compliant with the federal Clean Water Act and decide whether local water standards are being met

It may be beneficial to schedule an Interdepartmental Review Team (IRT) Meeting with the City of West Boylston. In attendance are representatives from key departments, including Planning, Law, Public Works, and the Fire Department. These meetings take place to review all new and proposed applications to the Planning Board and Zoning Board of Appeals, prior to application submittals. This review service expedites permitting, reduces redundancy, and increases the overall efficiency of Board reviews (City of West Boylston, 2015). All of the local zoning/planning requirements can be addressed at one IRT Meeting.

Local Air Quality Requirements

Air quality agencies/districts at the state and local levels are responsible for administering air quality regulations, with a focus on air pollution control (the primary pollutants that they look for are NO_X, CO, and SO_2 particulates). They ensure that a project complies with federal and state Clean Air Act mandates. Construction permits are obtained from these authorizes based on review of the project design. Operating permits are received post-construction based on emissions performance (EPA, 2013).

Specifically, in Massachusetts, it is necessary to complete an ambient air quality analysis, complete a noise analysis, and meet pollutant-specific emission limits referenced by the Nonattainment New Source Review (NSR) Program to gain construction and operating air quality permits (Harvard, 2013).

- Air quality dispersion modeling can show that emissions from the CHP project do not result in air quality exceeding Massachusetts or National Air Quality Standards.
- Noise modeling can be used to show that the system complies with state noise guidelines.
- The New Source Review is a preconstruction permitting program that establishes and documents air pollution emission limitations from large sources of air pollution. Nonattainment NSR applies to areas where the air quality is classified as not meeting the National Ambient Air Quality Standards (NAAQS) for one or more criteria pollutants regulated under the Clean Air Act (EPA, 2013).

3.6 Review potential incentives that can be received

In 2008, Massachusetts enacted critical legislation that boosts energy efficiency and encourages investment in renewable energy. This is known as the Green Communities Act, and it includes a number of provisions that are making Massachusetts a leader in clean energy technology (CLF, 2016). As a result of this initiative, the law requires utilities to increase investments and financing relating to projects in energy efficiency measures and renewable energy.

An online database, dCHPP (CHP Policies and Incentives Database) was used to find incentives/polices in the State of Massachusetts as shown in the table below. Based on the criteria of the project, only the following four policies in the table are applicable. In addition, the table describes the policy and incentive types.

Table 3.6 a: dCHPP Incentive Database

#	Policy/Incentive Name	Policy/Incentive Type
1	Community Clean Energy Resiliency Initiative	Grant
2	Industry Performance Standards for Combined Heat and Power	Environmental Regulation
12	MassSave - Utility Energy Efficiency Program	Rebate
13	Massachusetts Alternative Energy Portfolio Standard	Portfolio Standard

The following are descriptions taken from the CHP Policies and Incentives Database to help describes the policy and the incentive types.

- Environmental Regulation and Policy: Federal and state regulations supportive of CHP such as output-based regulations, special permitting procedures for CHP, and regional initiatives (EPA, 2015).

- Grant: State or federal grants that support CHP projects or activities (either specifically, or where eligibility includes CHP) (EPA, 2015).
- Portfolio Standard: State regulations that require utilities to obtain a certain amount of the electricity they sell from specified sources and/or achieve specified reductions in electricity consumption (EPA, 2015).
- Rebate: State, federal, or utility rebates that support CHP projects or activities (EPA, 2015).

There ended up being 4 incentives/policies that would be beneficial to this project. They are: the Community Clean Energy Resilience Initiative, the Industry Performance Standards for Combined Heat and Power, the Massachusetts Alternative Energy Portfolio Standard, and the MassSave - Utility Energy Efficiency Program. Each incentive is described in the following sections.

Community Clean Energy Resilience Initiative

The Community Clean Energy Resilience Initiative is a grant program geared towards municipal resilience. This will focus on solutions to protect communities from interruptions in energy service in the wake of severe climate events. Grants are available for communities to harden critical energy services using clean energy technology for buildings or structures where the loss of electrical services would result in disruption of public safety (DOER, 2014). Some important aspects of the initiative are as follows:

- Eligible Fuel: Natural Gas, Other
- Eligible Project Size (MW): Does not Specify
- Minimum Efficiency Required (%): At least 65%
- Website: http://www.mass.gov/eea/docs/doer/energy-resiliency-fact-sheet.pdf
- Applications: www.commBuys.com

Industry Performance Standards for Combined Heat and Power

The Massachusetts Department of Environmental Protection (DEP) is the state agency responsible for ensuring clean air and water, the safe management of toxics and hazards, the recycling of solid and hazardous wastes, and the timely cleanup of hazardous waste sites (DEP, 2016).

The purpose of this policy is to encourage the installation of CHP systems. A CHP system that meets the eligibility requirements may receive a compliance credit against its actual emissions based on the emissions that would had been created by a conventional separate system used to generate the same thermal output (DEP, 2016). The credit is then subtracted from the actual CHP system emissions for the purpose of calculating compliance with the emissions limitations. Then the credit is limited such that total emissions form CHP systems can be no greater than the sum of emissions from two separate systems producing the same amount of electrical and thermal output (DEP, 2016). Some important aspects of the initiative are:

- Eligible Fuel: Natural Gas, Other
- Eligible Project Size (MW): CHP Engines > 0.05MW and Turbines <10MW
- Minimum Efficiency Required (%): Greater than 55%
- Website: http://www.mass.gov/dep/air/laws/729final.doc

MassSave Incentives

The MassSave initiative is sponsored by Massachusetts' gas and electric utilities and energy efficiency service providers. This assists residents and businesses in their efforts to manage energy use costs related to energy efficiency measures. The program provides incentives and technical assistance to customers who are making renovations, upgrading, or implementing more efficient equipment. MassSave published a guide for their incentives program named 'The Combined Heat and Power (CHP) Guide' to help customers increase the likelihood that the project is eligible for receiving incentives. This section is a summary of the guide.

Thermal load is key; in order to receive maximum benefits from a CHP installation, the thermal energy generated should be fully utilized by the facility. This should be coupled with high annual hours of operation and continuous thermal load. Thermal load and high annual hours are both of utmost importance in receiving a return on the capital investment within an acceptable amount of time (MassSave, 2014).

Qualifying Criteria of the Benefit Cost Ratio (BCR)

The issues that should be considered during initial planning stages of the CHP project are discussed below. The proposed equipment must undergo a utility Benefit/Cost Analysis utilizing methodology prescribed by the Department of Public Utilities (DPU) (MassSave, 2014).

1. The power (kW) output of the CHP system
2. Annual net kWh generated
3. Installed cost of the equipment
4. Annual maintenance costs
5. Fuel Type
6. Timing of the power production (winter/summer hours, peak versus off-peak hours)

Incentive Levels

As a result of this specific project falling under the new construction program, it will be qualified to receive the Tier 1 CHP incentive. However, this is at the discretion of the PA and depends on the available funding. The incentive given shall not exceed 75% of the incremental costs of the CHP project. If successful, 80% of the Tier 1 incentive shall be paid upon the installation of the system and once all the interconnection requirements have been completed, the remaining 20% of the Tier 1 incentive will be paid after the commissioning of the CHP system (MassSave, 2014).

CHP Application Form - New Construction

1. Custom New Construction Application Form

   http://www.masssave.com/~/media/Files/Business/Applications-and-Rebate-Forms/New-Construction/2015_Custom-New-Construction-Form-Mass-Save.pdf

2. Technical Assistance Form

   http://www.masssave.com/~/media/Files/Business/Applications-and-Rebate-Forms/2015_Engineering-Services.pdf

Massachusetts Alternative Energy Portfolio Standard

The Alternative Energy Portfolio Standard (APS) offers an opportunity to receive an incentive for installing eligible alternative energy systems, which are not renewable. Potential CHP applicants are encouraged to review the Statement of Qualification (SQA) package well in advance of detailed design and procurement, to ensure that approved metering technology is well understood and included in both the project design and budget (MassDOER, 2011). The APS application is web-based.

The necessary attributes of the CHP unit that are necessary to receive APS incentives are:

a) An overall efficiency of 33% for electrical energy delivered to the end-use from a central plant via the grid (both generation and transmission losses considered) (MassDOER, 2011).
b) An overall efficiency of 80% for thermal energy delivered to a stand-alone heating unit on site (MassDOER, 2011).

For a new unit, the basic formula for determining the number of Alternative Energy Credits (AECs) per year for a new CHP system is expressed in prose as follows (all quantities are expressed in MWh):

$$(\text{Electricity Generated} / 0.33) + (\text{Useful Thermal Energy Output} / 0.8) - (\text{Total Fuel Consumed by CHP}) = \text{Number of AECs}$$

It is required that all meters must conform to all applicable laws and standards. In addition to this, they must be reliable and it is preferred to have the ability to transmit a signal for remote reading. An independent verifier must be selected for generation units whose output is not monitored and reported to the NEPOOL GIS by ISO-NE (DOER, 2016). The duty of the independent verifier is to access/read the electricity output meter of the unit, assure itself that the reading is reasonable, and accurately report the generation of the unit to the NEPOOL GIS on a quarterly basis (DOER, 2011).

The process of review will begin as soon as the Massachusetts Department of Energy Resources (DOER) receives a Statement of Qualification Application. It will be reviewed it for completeness, accuracy, appropriate signatures, and certification. The DOER strives to notify applicants of their qualification within 30 days of receipt of their application (DOER, 2011). Once the project is approved, WBMLP will receive a Statement of Qualification from the DOER.

- Online Application: http://www.mass.gov/eea/docs/doer/rps-aps/aps-sqa.pdf

3.7 Create a budget for the CHP unit installation which includes financial returns

Economic Spreadsheet

An economic spreadsheet was created to calculate the annual cost benefit for WBMLP from the CHP project and the yearly cost reduction for the Worcester County Jail from using the heat provided by the CHP system. The spreadsheet also investigates how changes in interest rates for bank loans could affect the feasibility of the CHP project. Most of the values used in this spreadsheet were received from a buyer who recently purchased similar CHP units. Two screenshots of the spreadsheet can be seen below.

Table 3.7 a: Economic Spreadsheet - Profit and Cost Reduction

	A	B
1	Initial Loan ($)	540091
2	Intrest rate	0.033
3	# of times compounded per year	12
4	number of monthly payments	180
5	Initial Monthly Payments ($)	3808
6	Construction Time (months)	6
7	Money from incentives ($)	234000
8	**Post Construction Monthly Payments**	
9	Present value of [a sub 1] ($)	20425.11
10	Present value of [F] ($)	192581.22
11	Amount still owed at the End of Construction	327084.67
12	number of monthly payments left	174
13	Monthly Payments after reciept of Incentives ($)	1880
14	**Profit for WBMLP**	
15	CHP Electricity Output (kW)	150
16	Yearly Electrical Output of CHP (kWh)	1310400
17	Yearly Transmission losses (kWh)	120164
18	Actual Yearly Electrical Output of CHP (kWh)	1190236
19	Price of Electricity per kWh ($)	0.148
20	Yearly Income from selling Electricity ($)	176154.98
21	Yearly Transmission Costs ($)	28042.56
22	Yearly Fuel Costs ($)	90414.588
23	Yearly Cost of CHP Maintenance ($)	26908
24	Yearly Cost of running CHP ($)	145365.15
25	Yearly Profit from selling Electricity ($)	30789.83
26	Yearly Income from selling Energy Credits ($)	12000
27	Yearly Profit ($)	42789.83
28	**Cost Reduction for Worcester County Jail**	
29	Yearly Thermal Output of CHP (Therms)	85459
30	Cost per therm of heating from Spark Energy Gas ($)	0.605
31	Yearly Cost Reduction for WCJ ($)	51702.70

Table 3.7 b: Economic Spreadsheet - Varying Interest Rates

	J	K	L	M	N
3	Intrest Rate (%)	Intial Montly Payment ($)	Post rebate monthly payments ($)	Total Cost of paying back loan ($)	Total Profit over 15 years ($)
4	3	3730	1862	346368	295479
5	3.3	3808	1880	349968	291879
6	3.5	3861	1892	352374	289473
7	4	3995	1921	358224	283623
8	4.5	4132	1949	363918	277929
9	5	4271	1976	369450	272397
10	5.5	4413	2002	374826	267021
11	6	4558	2027	380046	261801

The values for initial loan (cost of CHP unit and installation), money for incentives (total utility incentive (rebate)), and yearly income from selling energy credits were obtained from a recent buyer that also purchased a 150 kW CHP system. In creating the spreadsheet, it was assumed that the installation of the CHP unit would occur within 6 months of purchase. It was also assumed that a bank bond would be taken out to purchase the CHP unit. This bank loan would need to be paid back monthly for a period of 15 years, at an interest rate of 3.3% (compounded monthly). It was assumed that the total utility incentive (rebate) would be received as soon as the CHP unit was operational and would immediately be used to offset as much of the loan as possible.

If interest rates on bank loans were to change before the project's implementation, it could affect the feasibility of the CHP project. Part of the spreadsheet looks at whether or not the project would still be feasible (make a profit) if the interest rate increased. It was found that even if the interest rate almost doubles to 6%, the project would still be very profitable.

It was determined that installing a 150 kW CHP system at the Worcester County Jail would result in a yearly profit (from selling electricity) to WBMLP of $42,789.83 and a yearly cost reduction to the Worcester County Jail of $51,702.70. The formulas and values used for these calculations are outlined below:

<u>Post Construction Monthly Payments</u>

- Assumption made that incentives do not kick in until construction/commissioning is completed.

$$P_1 = a_1 \frac{(1+i)^n - 1}{i(1+i)^n} = \$20,425.11$$

P_1 = present value of initial monthly payments ($)

a_1 = initial monthly payment ($) = 3,808

i = interest rate = 0.033

n = Construction time (months) = 6

$$P_2 = F\,(1+i)^{-n} = \$192,581.22$$

P_2 = present value of future money from investments ($)

F = Money from incentives ($) 234,000 = Total utility incentive (rebate)

Debt at end of construction = Initial Loan - P_1 – P_2 = $540,091 - P_1 – P_2 = $327,084.67

$n_2 = n_t - n = 180 - 6 = 174$

n_2 = number of monthly payments after construction

n_t = total number of monthly payments (including during and after construction) = 180

a_2 = Debt at end of construction / n_2 = $1,879.80

a_2 = monthly payments after receipt of incentives ($)

Profit for WBMLP

Yearly Electrical Output of CHP (kWh) = CHP Electricity Output (kWh) * 24 hours * 364 days

Number of operational days per year = 364 due to 24 hour shut down for maintenance once a year (Spratt, 2015)

Where CHP Electricity Output (kWh) = 150

Yearly Transmission losses (kWh) = 0.0917 * Yearly Electrical Output of CHP (kWh)

Where 0.0917 = Literature value for the region (EPA, 2015)

Actual Yearly Electrical Output of CHP (kWh) = Yearly Electrical Output of CHP (kWh) - Yearly Transmission losses (kWh)

Yearly Income from selling Electricity ($) = Actual Yearly Electrical Output of CHP (kWh) * $0.148/kWh

Where $0.148/kWh = estimated selling price of Electricity in Massachusetts

Yearly Transmission Costs ($) = $0.0214/kWh * Yearly Electrical Output of CHP (kWh)

Where $0.0214/kWh = Transmission cost provided by Mr. Fitch

Yearly Cost of running CHP ($) = Yearly Transmission Costs ($) + Yearly Fuel Costs ($) + Yearly Maintenance Costs ($)

Yearly Profit from selling Electricity ($) = Yearly Income from selling Electricity ($) - Yearly Cost of running CHP ($)

Yearly Profit ($) = Yearly Profit from selling Electricity ($) + Yearly Income from selling Energy Credits ($)

= $42,789.83

<u>Cost Reduction for the Worcester County Jail</u>

Yearly Cost Reduction for WCJ ($) = Yearly Thermal Output of CHP (Therms) * $0.605/therm

Where $0.605/therm = calculated as an average of values provided from Aug-13 to Dec-14

Yearly Thermal Output of CHP (Therms) = 978,000 Btu * (1.00024*10^{-5}therm/Btu) * 24 hours/day * 364 days/year

= 85459 therms

Yearly Cost Reduction for WCJ ($) = 85693 therms * $0.605/therm

= $51,702.70

Effect of Varying Interest Rates

The initial monthly payments and post rebate monthly payments were calculated at different interest rates using an online mortgage calculator (Mortgage Calculator, 2016).

Total Cost of Paying Back Loan = (6 * initial monthly payments) + (174 * post rebate monthly payments)

The above formula is based on the assumptions that the loan is paid back over 15 years (180 months), the total utility incentive (rebate) would be received as soon as the CHP unit was operational and would immediately be used to offset as much of the loan as possible and a construction time of 6 months. The calculations show that even if the interest rate nearly doubled to 6%, WBMLP would still be able to pay back the loan and make a profit of $261,801 over 15 years.

<u>3.8 Create a schedule for integration of the CHP unit</u>

The project construction schedule is essential to ensuring the success of the CHP installation. This allows the project team to integrate different engineering processes and plans to see how each element can influence one another. With proper sequencing and appropriate relationships, this management tool will help to get the installation done on time. The team worked closely with Bill Spratt, Director of Facilities and Operations at WPI, who designed a similar construction schedule for the CHP project at WPI's Gateway Park.

With the information gathered from Bill Spratt, a construction schedule was designed to model the project for the implementation of the CHP unit at the WCJ. Microsoft Project was utilized to model the entirety of the project with a Gantt chart. Figures 3.8 a and b are pictures of said implementation. The main take-away from the construction schedule is that it is estimated to take 153 days for the whole process of approval and implementation to take place. This is roughly 5 months. This is very important for the WCJ because they want to minimize the time that workers are on their premises.

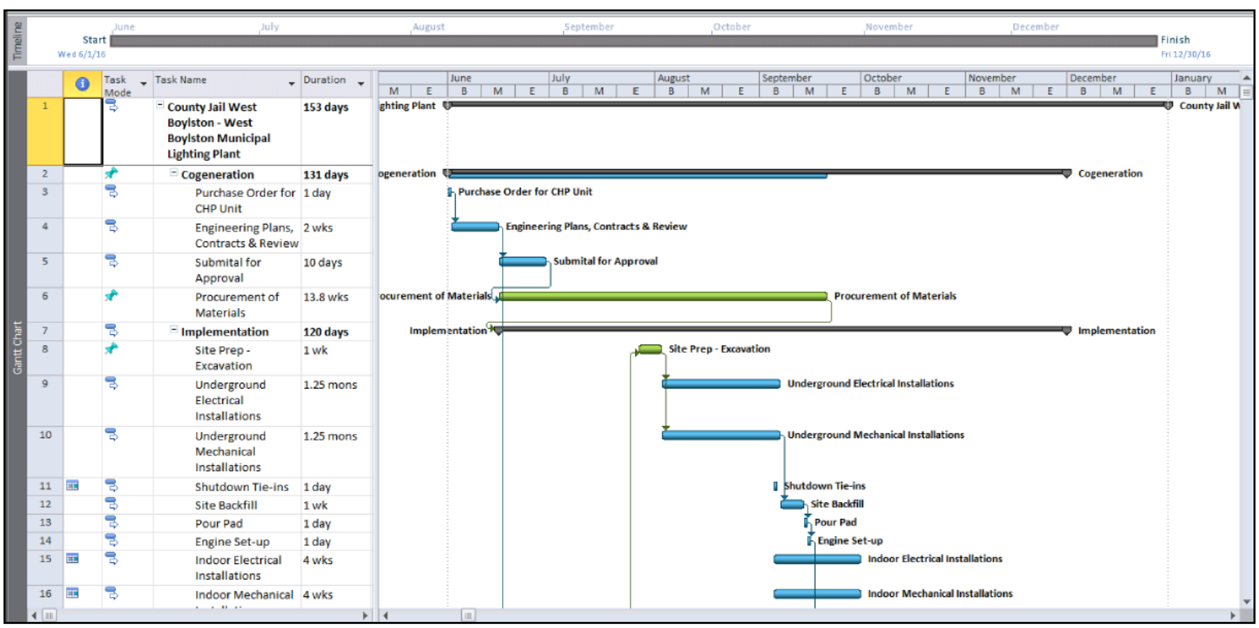

Figure 3.8 a: Construction Schedule for Implementing the CHP Unit into the WCJ

Task Mode	Task Name	Duration
	County Jail West Boylston - West Boylston Municipal Lighting Plant	**153 days**
	Cogeneration	**131 days**
	Purchase Order for CHP Unit	1 day
	Engineering Plans, Contracts & Review	2 wks
	Submital for Approval	10 days
	Procurement of Materials	13.8 wks
	Implementation	**120 days**
	Site Prep - Excavation	1 wk
	Underground Electrical Installations	1.25 mons
	Underground Mechanical Installations	1.25 mons
	Shutdown Tie-ins	1 day
	Site Backfill	1 wk
	Pour Pad	1 day
	Engine Set-up	1 day
	Indoor Electrical Installations	4 wks
	Indoor Mechanical	4 wks

Figure 3.8 b: Detailed Look into the Timeframe of the Construction Schedule

4.0 Conclusions

This project studied the feasibility of using the heat generated by a West Boylston Municipal Lighting Plant (WBMLP) owned and operated combined heat and power (CHP) unit to provide domestic water heating for the Worcester County Jail (WCJ). After a site visit and analysis of data gathered by a flow meter installed in the boiler room of the WCJ, the team determined the jail's domestic water heating load and decided on an appropriate CHP unit size to meet this demand. After numerous calculations, the team found the project to be financially and environmentally feasible. During the duration of the project, the team concluded the following:

1. The CHP units will need to be installed outside the boiler room due to space restrictions. The exact location where it can be installed is shown in the SolidWorks model (Figure 3.4 b) in the "Create a detailed visualization of the proposed CHP unit" section.

2. In order to accommodate the domestic water heating load of the Worcester County Jail, a CHP system with an electrical output of 150 kW is required (Two 75 kW units proposed).

3. By installing two 75 kW CHP units, carbon dioxide emissions can be reduced by 36 pounds per hour.

4. The CHP project could qualify for the following incentives:

    a) Community Clean Energy Resiliency Initiative
    b) Industry Performance Standards for Combined Heat and Power
    c) MassSave – Utility Energy Efficiency Program
    d) Massachusetts Alternative Energy Portfolio Standard

5. The CHP project is financially feasible. Based on the team's estimates, WBMLP will be able to make an annual profit of $42,789.83 from the sale of electricity and the WCJ will be able to save $51,702.70 per year on their heating bill.

5.0 Recommendations

In the opinion of the team, the next steps that need to be completed are:

1. WBMLP installs two 75kW Tecogen CHP units beside the existing boiler room of the WCJ, as shown in Section 3.4.

2. WBMLP follows the steps outlined in Section 3.7 to apply for the following incentives:

   a) Community Clean Energy Resiliency Initiative
   b) Industry Performance Standards for Combined Heat and Power
   c) MassSave – Utility Energy Efficiency Program
   d) Massachusetts Alternative Energy Portfolio Standard

3. WBMLP follows the construction schedule outlined in Section 3.8 to plan construction and installation logistics when installing the CHP units.

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Appendices

Appendix A: Boiler Optimization

The Worcester County Jail's current heating system (space heating and domestic hot water heating) was evaluated to determine its operational performance. Performing these calculations would enable WBMLP to have another tool to use to convince the WCJ to allow for the proposed CHP project to take place.

WCJ's current system in place includes 5 different units: 2 Raypak units for domestic hot water heating and 3 Cleaver Brooks Boilers for space heating in the winter. The Raypak units are identical and each have a power output of 1.29 million BTUH. This value was obtained from a manual produced by Raypak in April of 2015. Of the 3 boilers, there are two identical smaller boilers and one bigger boiler. The smaller boilers each have a power output of 2.9 million BTUH and the bigger boiler has a power output of 5.3 million BTUH. These values were obtained on the site visit to the WCJ from the nameplate data of the boilers.

On the site visit, the team was told that the system operates in the winter by continuously running the bigger boiler, one of the smaller boilers, and one Raypak unit for 24 hours each day. The other smaller boiler and the other Raypak unit are then turned on during peak heating demands.

The first step in analyzing the heating system in the winter season was to choose what power output value needed to be met by the units in place. It was decided that the February 2015 gas bill data would be chosen, due to the fact that it was the maximum BTU used in a month. This value was then converted to BTU/day, which resulted in a value of 173 million BTU. This number is the maximum number of BTUs needed to heat the WCJ in a day during the wintertime.

A table was then created with the power outputs (given above in BTUH) in instances where the units would be running from 0 to 24 hours a day. The table can be seen below:

Number of Hours Running	BTUH				
	Raypak 1	Raypak 2	Boiler1 (Bigge	Boiler 2	Boiler 3
1	1.29E+06	1.29E+06	5.33E+06	2.91E+06	2.91E+06
2	2.57E+06	2.57E+06	1.07E+07	5.82E+06	5.82E+06
3	3.86E+06	3.86E+06	1.60E+07	8.74E+06	8.74E+06
4	5.14E+06	5.14E+06	2.13E+07	1.16E+07	1.16E+07
5	6.43E+06	6.43E+06	2.66E+07	1.46E+07	1.46E+07
6	7.71E+06	7.71E+06	3.20E+07	1.75E+07	1.75E+07
7	9.00E+06	9.00E+06	3.73E+07	2.04E+07	2.04E+07
8	1.03E+07	1.03E+07	4.26E+07	2.33E+07	2.33E+07
9	1.16E+07	1.16E+07	4.79E+07	2.62E+07	2.62E+07
10	1.29E+07	1.29E+07	5.33E+07	2.91E+07	2.91E+07
11	1.41E+07	1.41E+07	5.86E+07	3.20E+07	3.20E+07
12	1.54E+07	1.54E+07	6.39E+07	3.49E+07	3.49E+07
13	1.67E+07	1.67E+07	6.93E+07	3.79E+07	3.79E+07
14	1.80E+07	1.80E+07	7.46E+07	4.08E+07	4.08E+07
15	1.93E+07	1.93E+07	7.99E+07	4.37E+07	4.37E+07
16	2.06E+07	2.06E+07	8.52E+07	4.66E+07	4.66E+07
17	2.18E+07	2.18E+07	9.06E+07	4.95E+07	4.95E+07
18	2.31E+07	2.31E+07	9.59E+07	5.24E+07	5.24E+07
19	2.44E+07	2.44E+07	1.01E+08	5.53E+07	5.53E+07
20	2.57E+07	2.57E+07	1.07E+08	5.82E+07	5.82E+07
21	2.70E+07	2.70E+07	1.12E+08	6.11E+07	6.11E+07
22	2.83E+07	2.83E+07	1.17E+08	6.41E+07	6.41E+07
23	2.96E+07	2.96E+07	1.23E+08	6.70E+07	6.70E+07
24	3.08E+07	3.08E+07	1.28E+08	6.99E+07	6.99E+07

After tabulating this table, the different scenarios of how the units worked together took place. The jail's current system operation was analyzed first. As mentioned above, it consists of the bigger boiler, one smaller boiler, and one Raypak unit operating continuously throughout the day. The power output produced by this combination of units was 228 million BTU in one day. This far exceeds the necessary maximum value needed to sufficiently heat the jail in the winter. Therefore, the combination of units that the jail uses could be improved.

Two new combinations of units were then offered as potential options on how the WCJ can better use their heating system (shown in the figures below). Option 1 was to run the bigger boiler and one Raypak unit continuously throughout the 24 hours and keep the other Raypak unit on for a specified number of hours. It was determined that if the second Raypak was on for 12 hours a day then the power output necessary to satisfy the maximum heating demand of the jail would be met. Option 2 was to run the bigger boiler continuously and have one of the smaller units for a certain amount of hours. The smaller boiler would need to run 16 hours each day in addition to the bigger boiler running for 24 hours to meet the maximum heating demand.

Option 1: Jail Uses Big Boiler and Raypak1 for all 24 hrs, different hours for Raypak 2		
1.600E+08	1	
1.613E+08	2	
1.626E+08	3	
1.638E+08	4	
1.651E+08	5	
1.664E+08	6	
1.677E+08	7	
1.690E+08	8	
1.703E+08	9	
1.715E+08	10	
1.728E+08	11	
1.741E+08	12	24 hrs for Big Boiler and Raypak1, Raypak2 for 12 hours
1.754E+08	13	
1.767E+08	14	
1.780E+08	15	
1.793E+08	16	
1.805E+08	17	
1.818E+08	18	
1.831E+08	19	
1.844E+08	20	
1.857E+08	21	
1.870E+08	22	
1.883E+08	23	
1.895E+08	24	

Option 2: Big Boiler on for 24 hrs and Different Hours for Small Boiler		
1.308E+08	1	
1.337E+08	2	
1.366E+08	3	
1.395E+08	4	
1.424E+08	5	
1.453E+08	6	
1.482E+08	7	
1.512E+08	8	
1.541E+08	9	
1.570E+08	10	
1.599E+08	11	
1.628E+08	12	
1.657E+08	13	
1.686E+08	14	
1.715E+08	15	
1.744E+08	16	24 hrs for Big Boiler, Small Boiler for 16 hours
1.774E+08	17	
1.803E+08	18	
1.832E+08	19	
1.861E+08	20	
1.890E+08	21	
1.919E+08	22	
1.948E+08	23	
1.977E+08	24	

There are many combinations that could be used to more adequately run the heating system and two are given in this summary. Although the current combination of units could be improved, they are still not considered oversized. According to literature on boilers, if the heat output is within 140% of the necessary load, then it is not considered to be operating inadequately (EPA, 2015). The heat output produced by the current combination of units that the jail uses is 131 % of the necessary load. Consequently, it is not necessary to alter the current combination of units, but there are possible ways that could improve performance.

Appendix B: Different Scenarios

The project goal was focused on implementing a cogeneration unit to solely meet the demand of hot water supply. However, the team looked into other options such as:

1. Sizing a bigger unit that could account for both domestic water and space heating
2. Using an alternative source of power generation such as photovoltaic panels (PV panels).

These options were researched in order to obtain comparable data and to supply WBMLP with data on future projects.

Bigger Unit:

A bigger CHP unit would account for the space heating demand and the domestic hot water demand. This would eliminate the need for all three boilers and both Raypak units (some would remain as back-up options). However, with the size of the jail being roughly 567,000 square feet, the size of the unit that would be needed to meet the heating load would be rather large.

To calculate the heat load of the entire jail, including both domestic hot water and space heating, the team used the gas bills that the jail provided. The average heat demand is much higher in the winter months rather than the summer months; therefore, only the winter month gas usages were considered.

From the gas bills, a daily average of 36,725 kWh was calculated. This number was then divided by 24 hours to get roughly 1530 kW, which is the average amount of kW that is required per hour in the winter months. Due to the large heat demand, a unit that would be needed to meet the demand would have to be custom ordered. As a result, exact efficiencies of a certain model could not be determined, so assumptions had to be made about the efficiencies to properly size the unit. It was assumed that the CHP unit as a whole would be roughly 80% efficient: 50% heat and 30% electric (CHP units are specified based on the electrical output it delivers).

Given that the heat efficiency is 50%, the average amount of kW used (1530 kW) must be half the amount of total energy that is gained from burning the fuel. That value ends up being roughly 3060 kW. Lastly, since the electrical efficiency is 30%, the total energy value was multiplied by 30% (or 0.30) in order to get the electrical output of the unit. This value turned out to be about 920 kW electric. Due to convenience, this value should be rounded up to 1000 kW, or 1 MW, as the ordering process would be simpler.

PV Panels – To Supply Both Domestic and Space Heating:

Another viable option the team took into consideration was PV panels. An individual PV panel is small and has a tiny wattage (100 – 300 W). However, the price of a single PV panel unit compared to a single CHP unit is much cheaper. In fact, for the analysis, the Astronergy CHSM6610P-260 Silver Poly Solar Panel was used as a reference. These units cost $260 each, hence why they can be bought in bulk for areas that have large heat demands. Determining how many panels that would be needed was the next step.

Multiple scenarios of how many panels were needed were carried out. The first scenario was to use the Worcester County Jail's summer heating bill to determine how many panels were needed to supply heat for both domestic hot water and space heating. From the heating bill, it was determined that the average number of kilowatt-hours used daily by the jail was about 6,027 kWh. One downside of PV panels is that they rely solely on the sun to generate power. Therefore, a 25% load factor was taken into affect that would account for factors such as poor weather conditions, maintenance issues, etc. This brought the kilowatt-hour total to 7,534 kWh.

There are only a certain amount of peak sunlight hours in the day, so the average value for peak sunlight hours in the summer for Massachusetts was looked up. This value ended up being 4.62 hours (EPA, 2013). The next step was to determine the total energy load the PV panels would need to hold. This was done by dividing the daily kilowatt-hours by the peak sunlight hours. Once this value was obtained, the total number of PV panels needed could be calculated by dividing it by the wattage of an individual panel, which is 260 Watts.

From these calculations, the team estimates that based on the summer heating bill, the jail would need roughly 6,272 PV panels to accommodate for both their space heating and domestic hot water heating. This would roughly cost $1.6 million on the product alone. Further analysis was done in the same fashion using the winter heating bill, and the BTU meter data that the team received from Jonathan Fitch. A chart of the results can be seen below.

	PV Panel Wattage (Watts)	Peak Sunlight Hours	Daily Average (kW*hr)	Daily Average w/Tol (kW*hr)	PV Panel Energy Load (kW)	# of Panels	Cost
Summer	260	4.62	6,027	7,534	1,631	6,272	$1,630,631
Winter	260	3.09	36,725	45,906	14,856	57,140	$14,856,430
BTU Meter	260	4.62	4,723	5,903	1,278	4,915	$1,277,805

PV Panels – To Supply Just Domestic Water Heating (Feasibility Study):

A spreadsheet was created to study the feasibility of using PV panels in place of a CHP unit to provide domestic water heating to the Worcester County Jail. A screenshot of the spreadsheet can be seen on the next page. The cost (initial loan) of the PV panels is $1,277,805 (Wholesale Solar, 2016). This cost includes installation and maintenance costs during the 25 years that the product is under warranty. The lifetime of the product is also 25 years (Maehlum, 2014). Potential incentives and energy credits were not taken into account for this spreadsheet. In creating the spreadsheet, it was assumed that a bank loan would be taken out to purchase the PV panels. This bank loan would need to be paid back monthly over the panels' lifespan of 25 years, at an interest rate of 3.3% (compounded monthly). The monthly payments and total cost of repaying the loan were calculated using an online mortgage calculator (Mortgage Calculator, 2016).

During the first year of their implementation, the PV panels would save the jail $51,702 (same as the CHP). After that, the PV panels' power output would decrease by 1% every year for the first 10 years and by 0.66% every year after that. Based on this, the WCJ would be able to save a total of $1,166,027.90 on their gas bill over 25 years. However, the cost of repaying the loan taken out to purchase the PV panels is $1,878,226 which would result in an overall loss of over $700,000. Therefore, the project is not feasible.

	K	L
14		**PV Panel**
15	Initial Loan ($)	1277805
16	Intrest rate	0.033
17	# of times compounded per year	12
18	number of monthly payments	300
19	Monthly Payments ($)	6261
20	Total Cost ($)	1878226

21	**Yearly savings for WCJ ($)**	
22	year 1	51702.70
23	year 2	51185.67
24	year 3	50673.81
25	year 4	50167.07
26	year 5	49665.40
27	year 6	49168.75
28	year 7	48677.06
29	year 8	48190.29
30	year 9	47708.39
31	year 10	47231.30
32	year 11	46914.85
33	year 12	46600.52
34	year 13	46288.30
35	year 14	45978.17
36	year 15	45670.12
37	year 16	45364.13
38	year 17	45060.19
39	year 18	44758.28
40	year 19	44458.40
41	year 20	44160.53
42	year 21	43864.66
43	year 22	43570.76
44	year 23	43278.84
45	year 24	42988.87
46	year 25	42700.84
47	**Total ($)**	1166027.90