

## **ABSTRACT**

KESLING, HARRISON FIELD. Economic Analysis of Wood Waste Gasification for Use in Combined Heat and Power Applications (Under the direction of Dr. Stephen Terry).

A significant issue facing the world is that of waste, primarily wasted material and wasted energy. A response to this has been “green” type programs to help reduce the amount of waste generated through recycling and improving energy efficiency in devices as well as installing renewable energy. One specific area of note is that of converting waste to usable energy. This is the primary focus of the findings presented in this thesis. The specific focus is using waste wood material to generate a natural gas type substitute through gasification and then using that gas to power a reciprocating gas engine with the exhaust being used to provide process hot water or run an Organic Rankine Cycle. While the process of replacing fossil fuels with biomass materials is certainly greener, there are still some disadvantages, particularly when it comes to the economics of installing these types of systems. The results of this study have found that the economics are highly dependent on offsetting the costs of disposing of the waste as well as the current costs electricity and natural gas. The lower the cost of waste disposal, electricity, and natural gas, the less likely the economics will work in favor for a facility to install a system such as the one described. The economics are also highly dependent on how the waste heat from the engine exhaust is used. The two scenarios studied were piping hot water to a distribution network and installing an organic Rankine cycle. For the specific application studied the hot water piping network was found to be too costly to install with an IRR around 0.54%. The Organic Rankine Cycle was less cost effective with an IRR around -3.19%. The hurdle rate for the facility was 35% which means that these two options do not come close to being economically viable options to implement.

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Economic Analysis of Wood Waste Gasification for Use in Combined Heat and Power  
Applications

by  
Harrison Field Kesling

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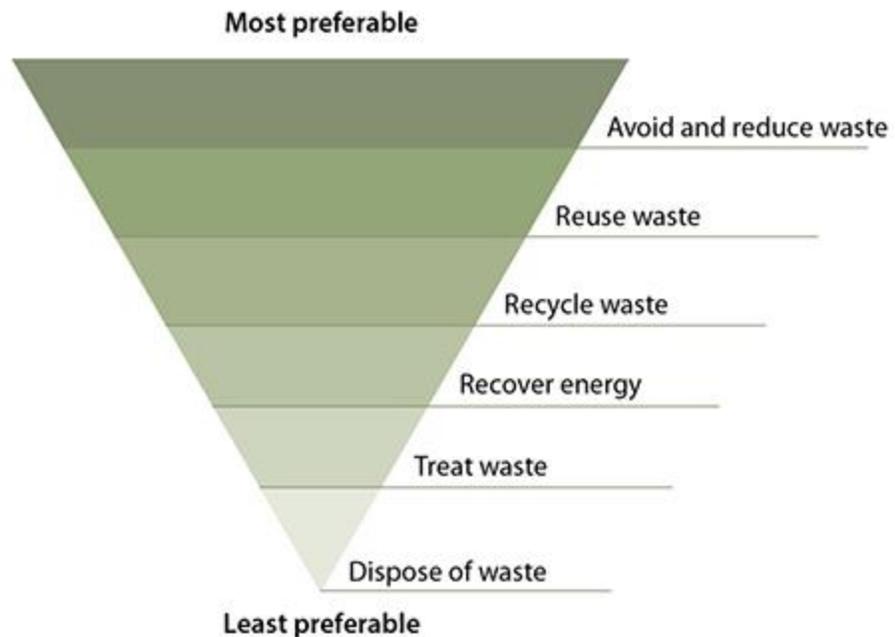
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## CHAPTER 1 - Introduction

The topic of waste is an important topic to discuss in the 21<sup>st</sup> Century. Waste (or wastes) are unwanted or unusable materials which are discarded after primary use, and are worthless or defective. Examples of waste include municipal solid waste, hazardous waste, agricultural waste, industrial waste, wastewater (such as sewage), radioactive waste, and electronic waste (e-waste). Every year the world dumps around 2 to 2.1 billion tons of this waste, which if put on trucks, would encircle the world 24 times [1]. There are serious environmental, social, and economic costs to producing all of this waste. Improperly handled waste can attract rodents and insects which can harbor diseases, exposure to hazardous waste can cause various other diseases including cancer. Toxic waste can contaminate surface water, groundwater, soil, and air which can cause more problems for humans, other species, and ecosystems [2]. Waste treatment and disposal can produce significant greenhouse gas emissions, notably methane, which contribute significantly to climate change [3]. Another issue is that there is a significant need to expand waste treatment and disposal facilities worldwide, but residents in particular areas adopt a “not in my backyard” (NIMBY) attitude to the development of these facilities close to them [4]. This has ultimately resulted in the transboundary movement of waste across international borders. Although most waste flows between developed nations, a significant amount is transferred from developed to developing nations, effectively concentrating the environmental issues in these areas and hindering the growth of those nations [5]. Couple all of these issues with that fact that global waste generated per year will increase by 70 percent by the year 2050 [6] and you have a recipe for disaster. Fortunately, there are tools that can be used to evaluate processes that impact the environment from most to least favorable actions [7]. One of these tools is the waste management hierarchy shown in Figure 1.

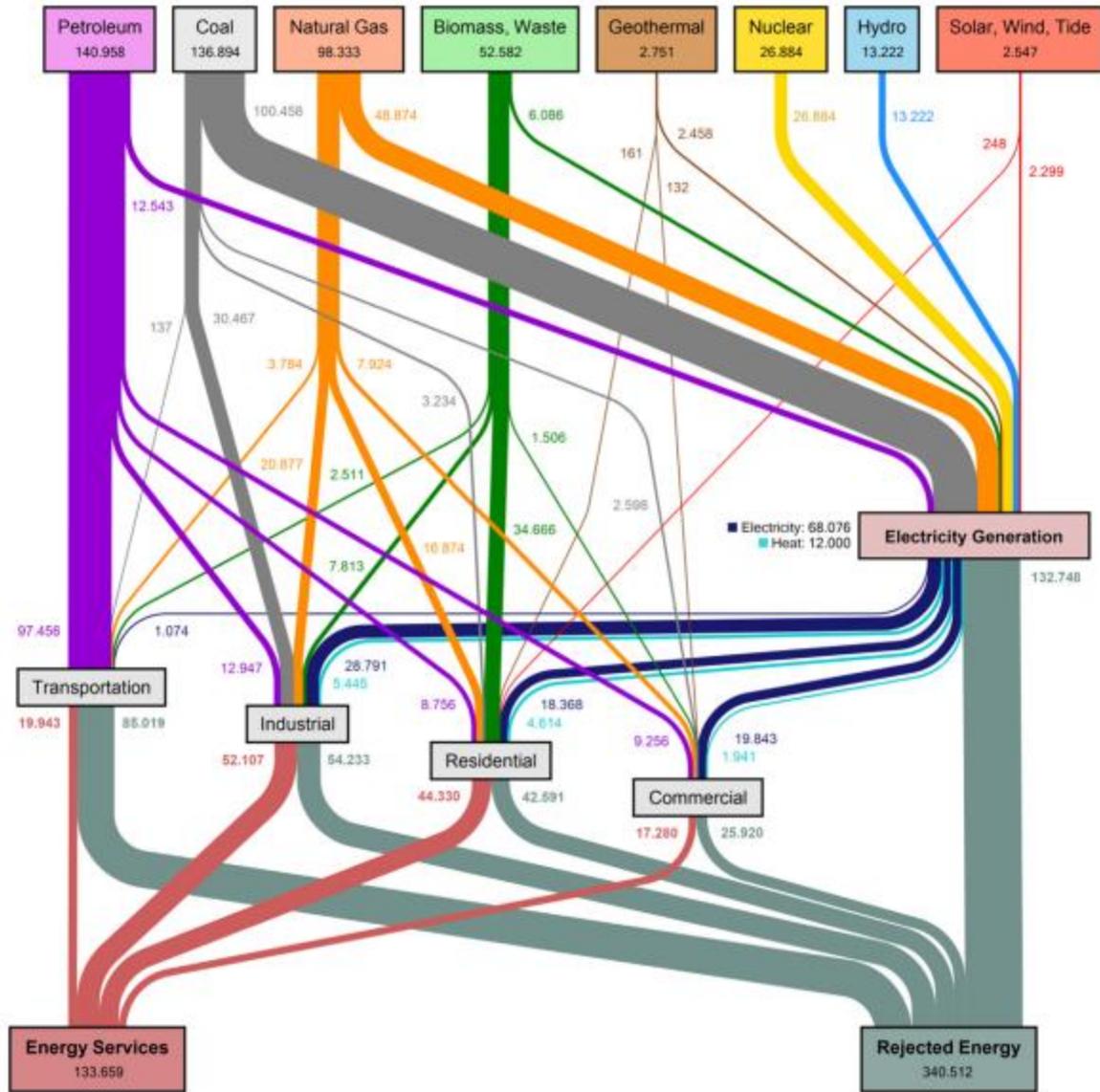


**Figure 1: Waste Management Hierarchy [8]**

The waste management hierarchy indicates the order of preference for action to reduce and manage waste and captures the progression of a material through successive stages of waste management [9]. This is the expanded version of the “Reduce, Reuse, Recycle” message that accompanied the passing of the Resource Conservation and Recovery Act of 1976 [10]. Along with these three important aspects of the hierarchy is the opportunity to recover energy from waste streams. This involves using non-recyclable waste materials and extracting the stored chemical energy to produce heat and/or electricity through a variety of processes including anaerobic digestion, incineration, and gasification [11].

Another form of waste not covered in the traditional waste literature is that of wasted or rejected energy. The primary form of wasted energy is that of waste heat. Waste heat is produced by machines as a byproduct of doing work. This is because it is not possible to convert one form of energy to another with 100% efficiency as per the laws of thermodynamics. Some of the energy is lost or wasted. Forman et al. estimated that global

energy usage is 474.2 PJ or 474.2 quadrillion joules. This is equivalent to 2.26 times the amount of energy released by the Tsar Bomba, the largest man-made nuclear explosion. From Figure 2 it is shown that the amount of energy that is wasted is around 72% of the global total [12]. This means that 3.57 units of energy needs to be sourced to provide 1 unit of useful energy with 2.57 units of energy being wasted. This has prompted the growth of the energy efficiency industry in the United States and elsewhere. The primary goal of this industry is to meet the needs of the present with the lowest amount of energy as possible, thereby reducing the amount of energy that needs to be sourced. Dr. Stephen Terry at North Carolina State University has coined a phrase to describe the collective efforts of this industry which is similar to the mantra used for waste management: “Reduce, Recover, Renewables” [13].



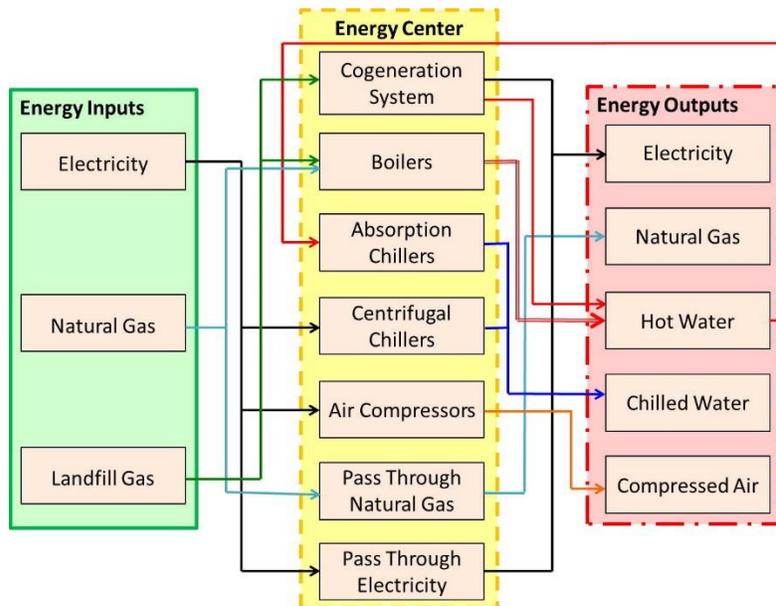
**Figure 2: Estimated World Energy Use of 2012 in PJ [12]**

The first step is to reduce the amount of energy that is being consumed through conservation measures. The second step is to recover as much of the wasted energy as possible in a given situation. The third step, which should come after the first two steps have been addressed, is to implement renewable energy to provide the remaining energy needs. The United States Department of Energy sponsors a program to help address the need to reduce the amount of energy that is consumed in the United States by facilities known as the Better Buildings Initiative. A subset of this initiative is the Better Plants Program which offers valuable

technical assistance in the form of tools and trainings. One benefit in particular is access to DOE Industrial Assessment Centers (one of which is located at NC State University). These centers provide energy auditing services to qualifying manufacturing facilities. The primary purpose of these assessments is to find opportunities for these facilities to reduce and recover the energy they use. The largest opportunity for energy efficiency is to utilize the energy that is rejected, the majority of which is in the form of waste heat. Waste heat utilization along with opportunities to source waste material for energy, will be the primary topic of discussion. While the discussion will center on applying these technologies to a specific manufacturing industry and facility, the findings presented can be considered universal in their application.

## CHAPTER 2 – Background on the Automotive Industry in the United States

It is estimated that the automotive vehicle industry in the U.S. spends around \$3.6 billion per year on energy to drive manufacturing operations [14]. Automotive assembly plants have three main manufacturing departments: body shop, paint shop, and final assembly shop. The body shop is where the vehicle panels are formed and welded together to form a body-in-white structure. The paint shop is where the paint and sealant are added for corrosion protection and attractive appearance. The final assembly shop is where all the components of the vehicle including powertrain marriage to body are assembled together [15]. These manufacturing processes are driven through five main energy carriers: electricity, natural gas, hot water, chilled water, and compressed air [16]. Figure 3 shows the specific pathways for onsite energy conversion and transmission in automotive assembly plants.



**Figure 3: Automotive Assembly Manufacturing Energy Carriers [16]**

The facility studied is an automotive vehicle manufacturer with facilities located around the world. The company is continually pursuing renewable energy sources to provide power for

these facilities. Green energy made up 63% of this manufacturer’s energy demands in 2016, but the company wants that number to be 100% [17]. The company is continually searching for ways to reach this goal. For example, at their facility in Spartanburg, SC, they have implemented a cogeneration system that relies on gas from a local landfill. They have also converted all of their material handling vehicles to use hydrogen fuel cells that run on hydrogen generated from a hydroelectric power station. The motivation of the research conducted was to find other opportunities to implement renewable energy at the Spartanburg, SC facility. The goal is to use renewably generated energy to provide for the facility. Table 1 shows the average energy consumption for the facility that was studied.

**Table 1: Automotive Assembly Facility Average Energy Consumption [18]**

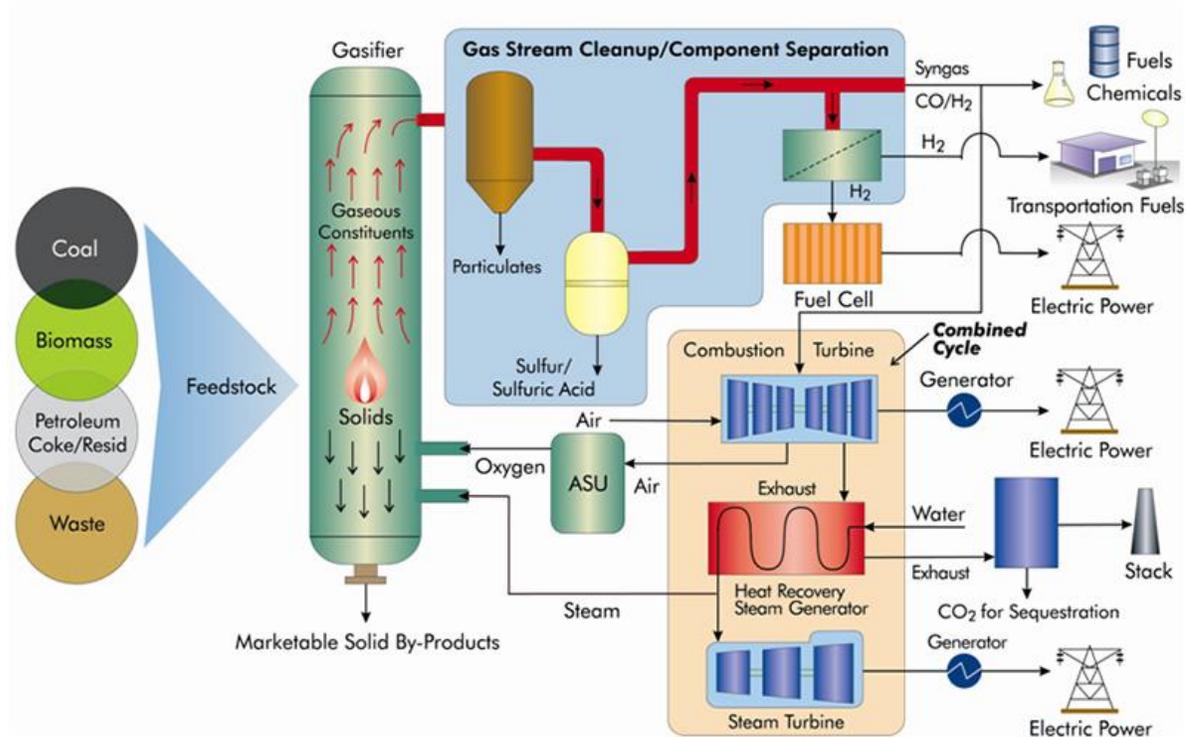
Electricity Consumption	Hourly	Daily	Monthly	Yearly
Summer (6 Months)	65 MW	1,560 MWh	46,800 MWh	280,800 MWh
Winter (6 Months)	40 MW	960 MWh	28,800 MWh	172,800 MWh
Yearly Average	52.5 MW	1,260 MWh	37,800 MWh	453,600 MWh

The specific opportunity that was investigated involves utilizing the wood waste generated by the facility. This wood waste comes from wooden pallets used for shipping parts to the facility. After the pallets are unloaded, they are sent to a wood chipper to be turned into wood chips. The wood chips are then picked up by one of two manufacturing facilities in the area for use in their manufacturing processes. Interest has been expressed in utilizing this wood waste to provide energy for the facilities manufacturing process. A utilization that is being discussed is using this wood waste for heat and/or power applications. An option already explored was the direct combustion of the wood chips using a wood chip boiler to make hot water for process purposes. This exploration found that the direct combustion of the wood chips was not feasible due to the high logistical cost of transporting wood/ash to/from the wood chip boiler,

respectively. Another option for conversion is gasification. While gasification is not new, utilizing a gasification system for the conversion of biomass materials is still an emerging technology. The main question to answer is whether a gasification system for use in combined heat and power is feasible for implementation at the facility. This will be explored by first understanding the gasification technology, understanding the feedstock material, understanding combined heat and power technology, and by conducting an economic analysis of the current technology to determine the capital and operating costs.

### **CHAPTER 3 - Gasification**

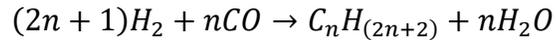
Gasification is a thermochemical conversion process whereby a limited amount of oxygen is reacted with a carbonaceous feedstock material (coal, petroleum coke, biomass, etc.) to convert it into a gas called synthesis gas or producer gas. The technology is highly versatile and offers a vast amount of flexibility. For example, gasification technology can be used for waste disposal. One of the challenges for today's municipalities is finding effective ways to mitigate the problems associated with solid waste disposal [19]. In 1960, the United States only produced 88.1 million tons of municipal solid waste, but by 2014 that number increased to 258.5 million tons [20]. Effective management of this waste is a top priority for municipalities and local governments. Traditional methods of waste disposal involve landfilling and incineration, however there are some limitations to these methods. Landfilling, while inexpensive, takes up land area [21] and can leach organic and nitrogenous pollutants into the surrounding land area contaminating surface and groundwater. Incineration on the other hand has high capital and operational costs and produces ash and CO<sub>2</sub> [20]. Gasification offers a reliable solution to these issues in that it does not take up a large land area and can reduce the mass and volume of waste streams, destroy hazardous compounds, and provide energy or chemicals that can be used for other purposes [19] [20] [21]. The produced syngas is a highly useful fuel product that can be used in a variety of applications ranging from generating heat and power to making transportation fuels or production chemicals [22]. Figure 4 depicts this flexibility.



**Figure 4: Gasification System Flexibility [23]**

The benefit to converting the solid feedstock material to a gas is that the gas can be standardized in its quality and is easier and more versatile to use than the original feedstock material [24]. This gas is made up of Hydrogen (H<sub>2</sub>), Carbon Monoxide (CO), Carbon Dioxide (CO<sub>2</sub>), and Methane (CH<sub>4</sub>) [20] [25]. The properties and quality of the produced syngas depend on a variety of things, such as the type of feedstock, the type of gasifier, the type of gasifying agent, as well as operational parameters such as temperature and pressure. Ultimately, the optimal operational characteristics of a gasification system will depend on the end use of the produced gas. For example, synthesis gas produced by gasification may be converted into liquid biofuel using the Fischer-Tropsch (FT) Process [26]. This allows easier transportation of the fuel. In this process, catalytic reactions of hydrogen and carbon monoxide form hydrocarbon chains of various length (CH<sub>4</sub>, C<sub>2</sub>H<sub>6</sub>, C<sub>3</sub>H<sub>8</sub>, etc.) [22].

The following equation shows this process called the Fischer-Tropsch synthesis reaction.



Before the syngas can be used for the Fischer-Tropsch process, not only does it need to be cleaned of contaminants, it also needs the proper H<sub>2</sub> to CO ratio. Traditionally, syngas produced through gasification has a higher amount of CO than is desired, which requires conditioning after the gasification reactions [22]. Recent research into gasification has looked into producing a syngas with a higher amount of H<sub>2</sub> through the use of steam injection into the gasification reactor vessel [20]. Alternatively, the produced gas can be used to generate electricity [27] and heat in stationary power applications located at or near the site of gasification. This is known as combined heat and power (CHP) and is an efficient and clean approach to generating electric power and useful thermal energy from a single fuel source [28]. In this application, the chemical makeup of the fuel gas is irrelevant to the extent that the gas mixture has a high heating value. The following sections will discuss a brief history of the gasification technology, the fundamentals of gasification, types of gasifiers, and gas cleaning procedures.

### 3.1 - History of Gasification

Gasification was initially developed in the early 1800s to gasify coal. The coal gas was primarily used for town street lighting and became known as manufactured gas or town gas [22]. Gasification was also utilized during World War's 1 & 2 for use in vehicles and natural gas type applications when petroleum products became scarce [29]. Interest in gasification diminished as the petroleum industry stabilized and natural gas became more available. It wasn't until the 1970s Energy Crisis that coal gasification once again came into prominence as a source of clean energy and to decrease dependence on foreign oil [22]. While the use of biomass gasification is still small compared to coal gasification, it is expected to grow in the future. Figure 5, Figure 6, and Figure 7 show data obtained from the Gasification & Syngas Technologies Council on the gasification industry.

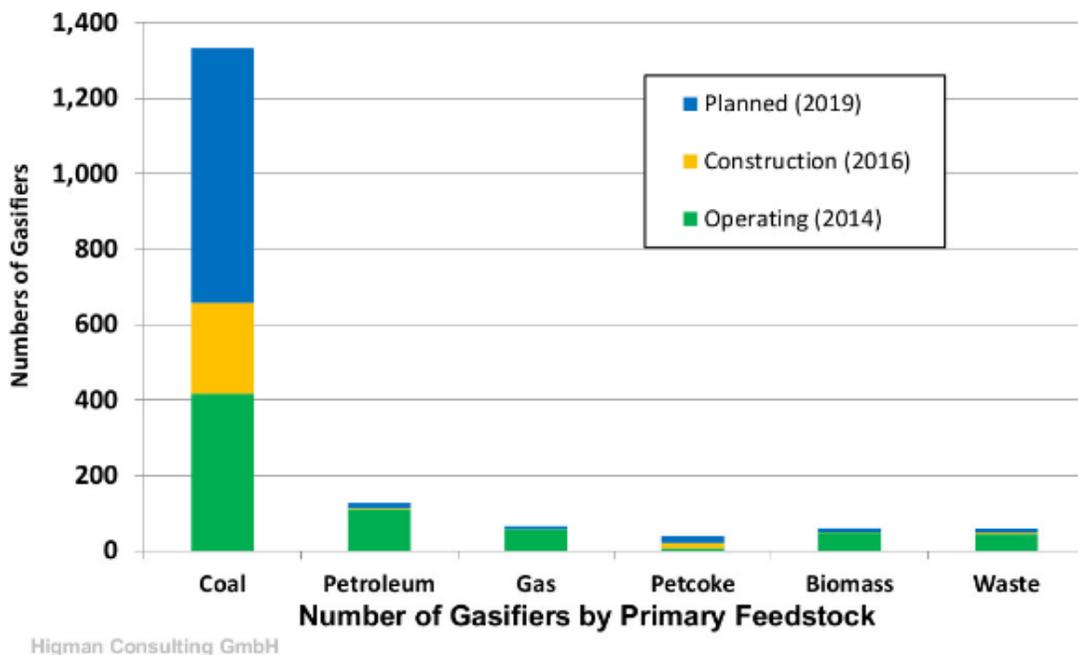
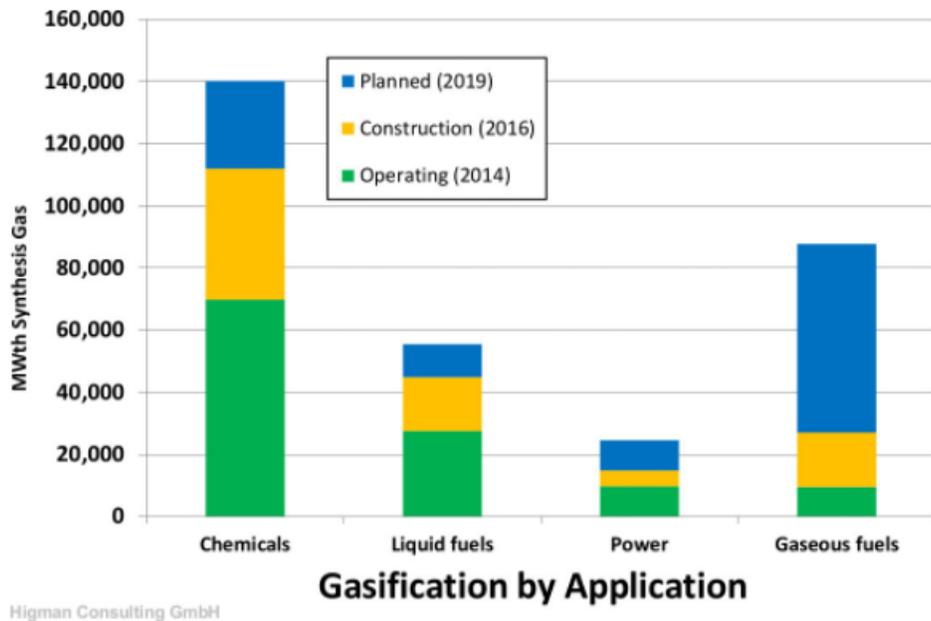
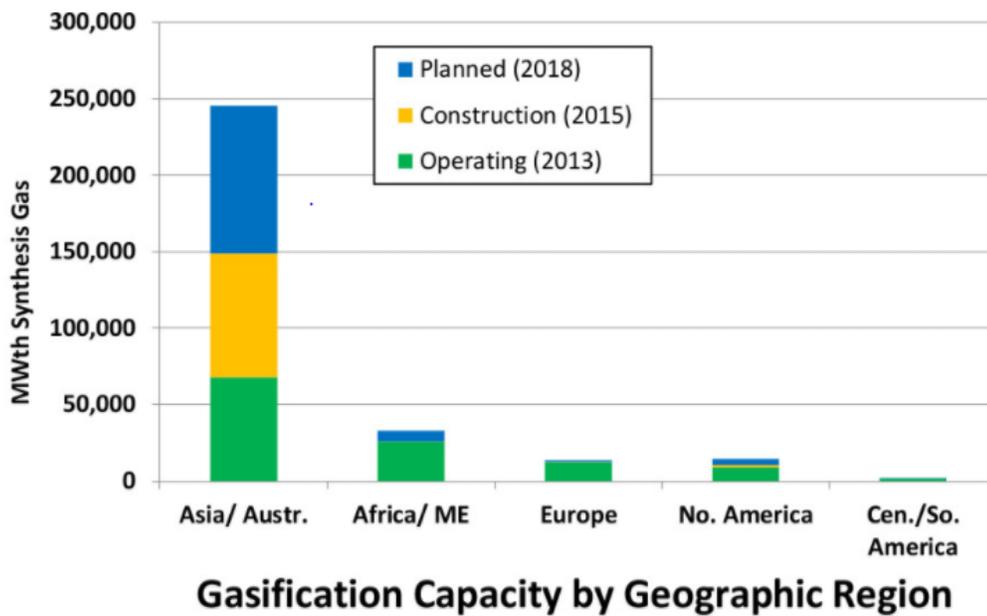


Figure 5: Number of Gasifiers by Primary Feedstock [30]



Higman Consulting GmbH

Figure 6: Gasification by Application [30]



Higman Consulting GmbH

Figure 7: Gasification Capacity by Geographic Region [30]

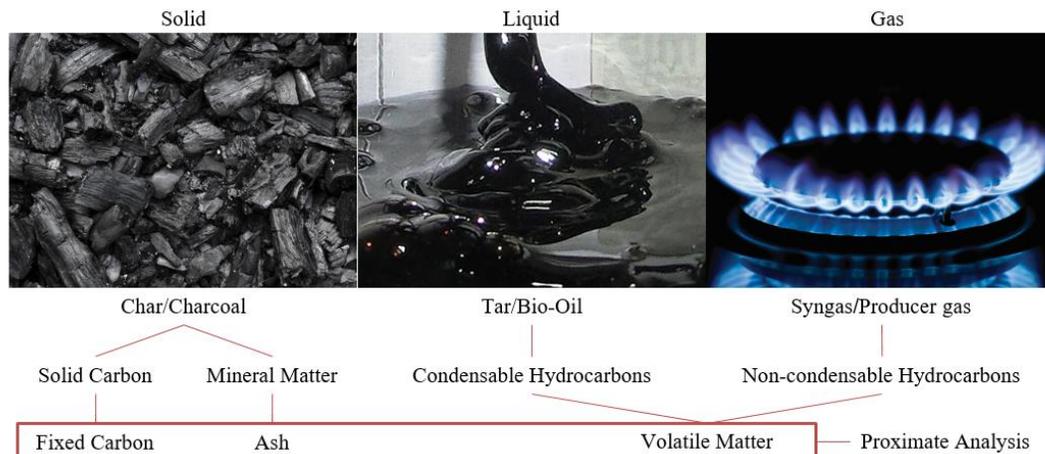
An example of note is that of the Chemicals from Coal Facility developed by Eastman Chemical Company. Eastman began operation of a coal gasification facility in 1983 that converted coal into acetic anhydride and acetic acid. The facility initially produced 500 million

pounds but expanded to 1.14 billion after an expansion in 1991. This has proven to be a commercially viable operation for Eastman and the profitability of the company can be attributed to this system [31].

### **3.2 - Fundamentals of Gasification**

The first step in any thermochemical conversion process such as gasification is drying. This is because the moisture in the feedstock material will have a tremendous impact on the conversion process [22]. The heating value of the fuel is reduced when the moisture content is above 30% [24]. For combined heat and power applications, the heating value of the fuel is the most important characteristic. However it should be noted that some amount of moisture is beneficial to the process due to the complex nature of the gasification reactions [32]. While increasing the moisture content of the feedstock material increases the hydrogen content of the produced gas, it also increases the amount of carbon dioxide and decreases the amount of carbon monoxide [32]. The next step in a gasification process is pyrolysis. Pyrolysis is an irreversible thermal decomposition process whereby the feedstock material is heated in the absence of oxygen. The main products of the pyrolysis process are char/charcoal (solid portion), tar/bio-oil (liquid portion), and syngas/producer gas (gas portion). Pyrolysis is also known as destructive distillation since the process is used to breakdown feedstock material into distillate parts. To understand how the feedstock material is broken down it is important to understand some basic organic chemistry. Coal, petroleum, natural gas, and biomass materials are made up of organic compounds. Hydrocarbons, compounds containing hydrogen and carbon, are the simplest organic compounds. These are molecules such as methane, propane, and butane. Natural gas is mostly methane, but petroleum is made up of several types of hydrocarbons and requires distillation to make useful products. Coal is mostly made up of large matrices of inorganic carbon with some trace organic compounds mixed in. Conducting a proximate analysis of the feedstock material reveals several important characteristics. These characteristics determine to a certain extent what products can be expected in the

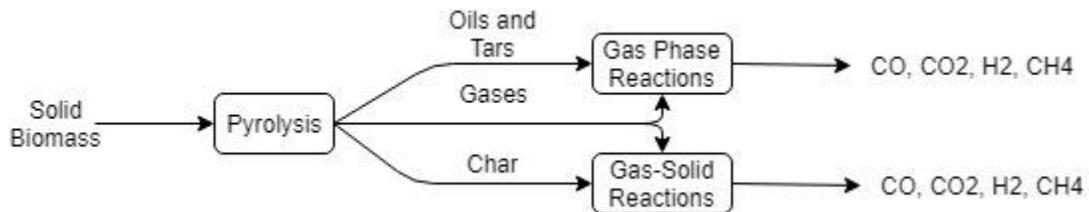
pyrolysis/distillation phase of the thermochemical conversion processes. The characteristics are the ash content, volatile matter, and fixed carbon. The ash content refers to mineral matter that will be left over after the conversion is complete. It can be said that the higher the ash content, the higher the ash removal cost. Therefore, material with low ash content is preferred to material with high ash content. Volatile matter refers to the organic compounds in the material. The liquid portion can be considered condensable hydrocarbons while the gaseous portion can be considered non-condensable hydrocarbons and inorganic gases [22]. Total pyrolysis yield and the amount of char residue can be roughly estimated from the proximate analysis of the fuel. Volatile matter corresponds to the pyrolysis yield, while the combination of fixed carbon and ash content can be used to estimate the char yield [26]. Figure 8 shows the relationship between the products of pyrolysis and the proximate analysis.



**Figure 8: Pyrolysis Products**

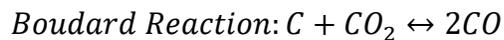
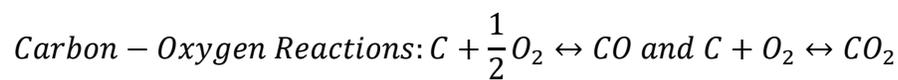
The fixed carbon refers to the inorganic compounds containing carbon in the material. Coal typically has higher amounts of fixed carbon to volatile matter, whereas biomass typically has higher volatile matter relative to fixed carbon. Knowing the amount of volatile matter and fixed carbon is important in determining the various products of the pyrolysis step in the various thermochemical conversion processes [22]. The liquid fraction consists of heavy hydrocarbons

in a vapor state while they are still hot. These heavy hydrocarbons can be referred to as condensable hydrocarbon vapors. Depending on the type of gasifier used, the final syngas can have a high amount of these heavier hydrocarbon vapors which can condense and form what is known as “tar”. This tar is undesirable because it can block valves and filters and interferes with downstream conversion processes. Steam injection and addition of catalysts to the reactor is sometimes used to shift products toward lighter hydrocarbons that will remain as a gas when cooled. The next steps in gasification involve reacting the solid, liquid, and gaseous distillates with each other and with a gasifying agent to form the final syngas product. These steps can be broken down into gas-phase and gas-solid reactions [22]. Figure 9 shows the pyrolysis and reaction steps.



**Figure 9: Pyrolysis and Reduction [22]**

The primary gas-solid reactions are as follows [22]:



The primary gas phase reactions are as follows [22]:



While these are the primary reactions associated with gasification there can be up to 17 additional reactions all happening simultaneously including steam-reforming, oxidation, and tar cracking reactions. As was stated earlier in the pyrolysis section, the proportion of the solid, liquid, and gaseous portion of the pyrolysis products will depend on the material used and the operating conditions. The final gas composition will be determined by the amount of air added to the system, as well as the residence time and temperature within the gasifier. Gasification processes should be designed so that the heat released balances with the heat required for the drying and pyrolysis steps. In addition, the reaction characteristics determine conditions under which desired products may be maximized. Calculations can only be completed using sophisticated computer models that take these factors into account. Most gasification models predict the fraction of CO<sub>2</sub>, CO, H<sub>2</sub>, CH<sub>4</sub>, and H<sub>2</sub>O in the syngas and the variables used can include the following:

- Fuel composition and amount
- Amount and type of oxidant
- Water input as steam or with the fuel
- Heat loss or heat required in the gasifier
- Gasifier temperature and residence time

Generally speaking, low temperature and high pressures favor the formation of CH<sub>4</sub>, while high temperatures and low pressures favor the formation of H<sub>2</sub> and CO. The discussion will now turn to the various types of gasifiers currently available.

### 3.3 - Gasifier Types

Gasifiers are mainly classified by the design of the reactor vessel and the gasifying agent [33]. Gasifiers can be broken down into four types: fixed bed, fluidized bed, entrained flow, and plasma. Fixed bed gasifiers were among the first developed for use in gasifying coal. They have lower conversion efficiencies when compared to fluidized bed with the advantage that they are lower in cost. There are two types of fixed bed gasifiers currently in use: updraft and downdraft. In both types of gasifiers, the material is fed at the top. The distinguishing characteristic between the two gasifiers is which way the air flows. In an updraft gasifier the air comes in at the bottom and gas goes out at the top (the draft goes up). This can also be called a counter-current gasifier because the air flows counter to the flow of the feedstock material [22]. Figure 10 shows a typical updraft gasifier.

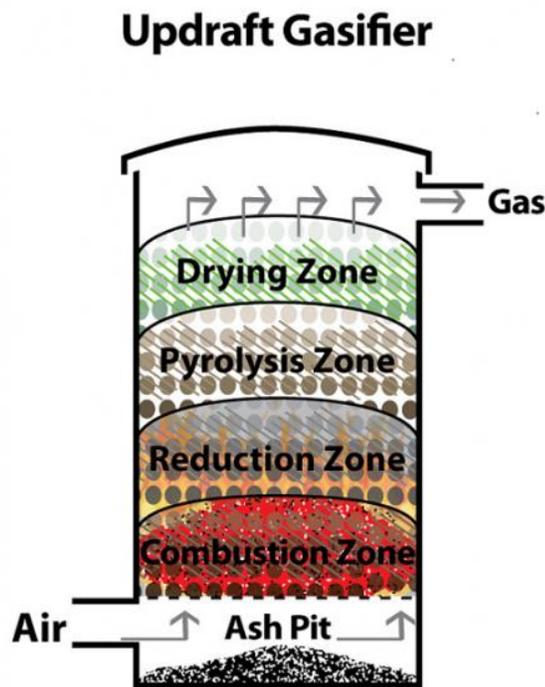
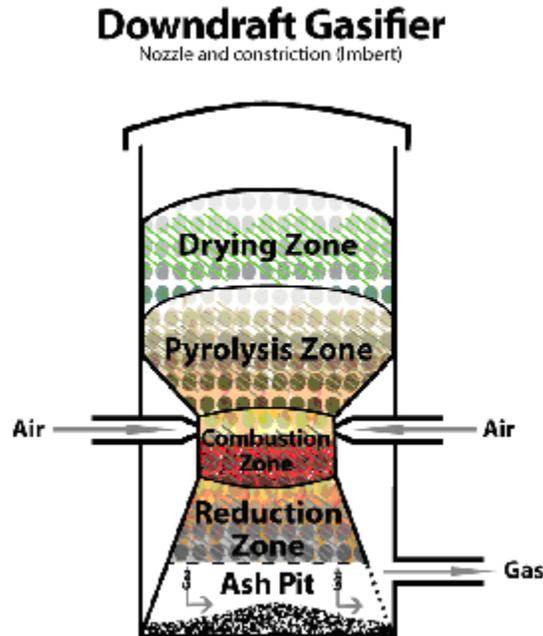


Figure 10: Updraft Gasifier [34]

In a downdraft gasifier the air comes in from the top for an open top design or around the middle of the gasifier for a close top design. The producer gas is then exported from the bottom

of the reactor (the draft goes down). This is also called a co-current gasifier because the air flows with the flow of the feedstock material [22]. Figure 11 shows a typical close top downdraft gasifier.

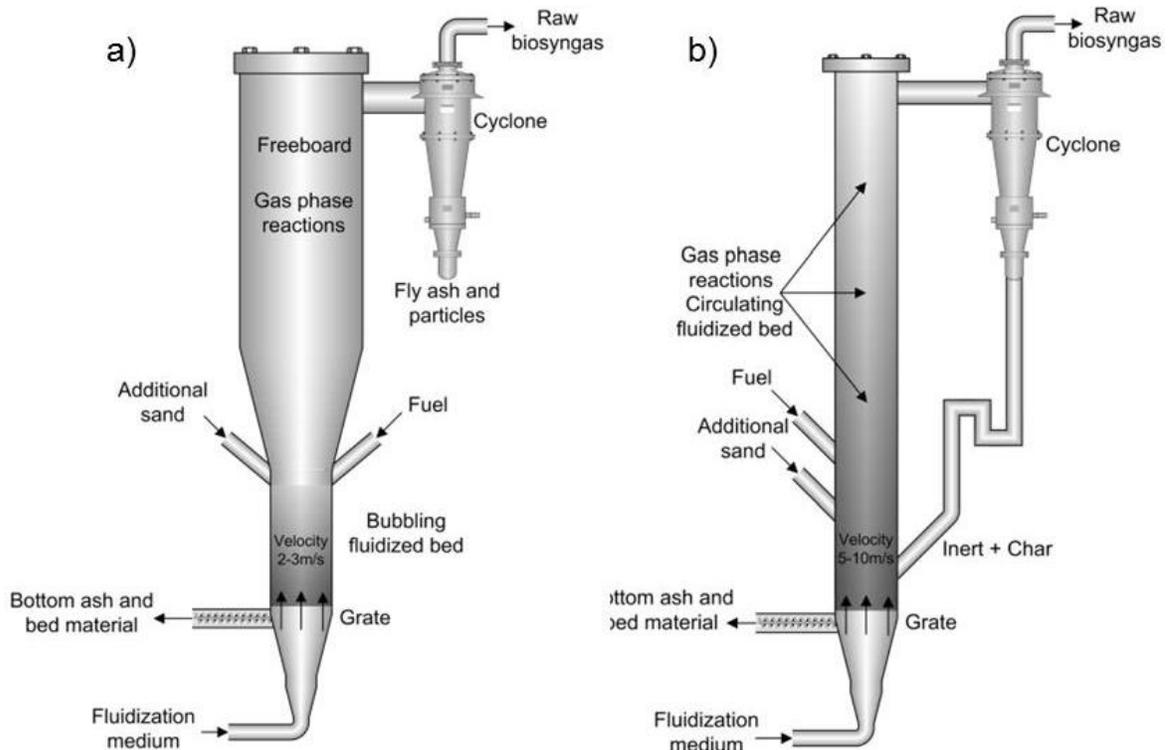


**Figure 11: Downdraft Gasifier [34]**

The combustion zones can be thought of as oxidation zones where the oxygen reacts with the various constituents to form various products of combustion. However, since the amount of air/oxygen is reduced, the result is lower amounts of carbon dioxide and water vapor. The products of combustion are not the desired result, they serve as a catalyst for the reduction reactions where the final composition of the syngas is determined. The reduction reactions are the gas-solid and gas-phase reactions discussed earlier [22].

For fixed bed gasifiers, the length of the reactor is important to ensure the feedstock material has a long enough residence time to ensure adequate conversion and a high operational efficiency. While a longer reactor length will improve the operational efficiency of the gasifier, it will also result in higher manufacturing costs. It is recommended that the ratio of the volume of the reduction zone and the area of the reactor's throat should be greater than  $0.5 \text{ m}^3/\text{m}^2$  [35].

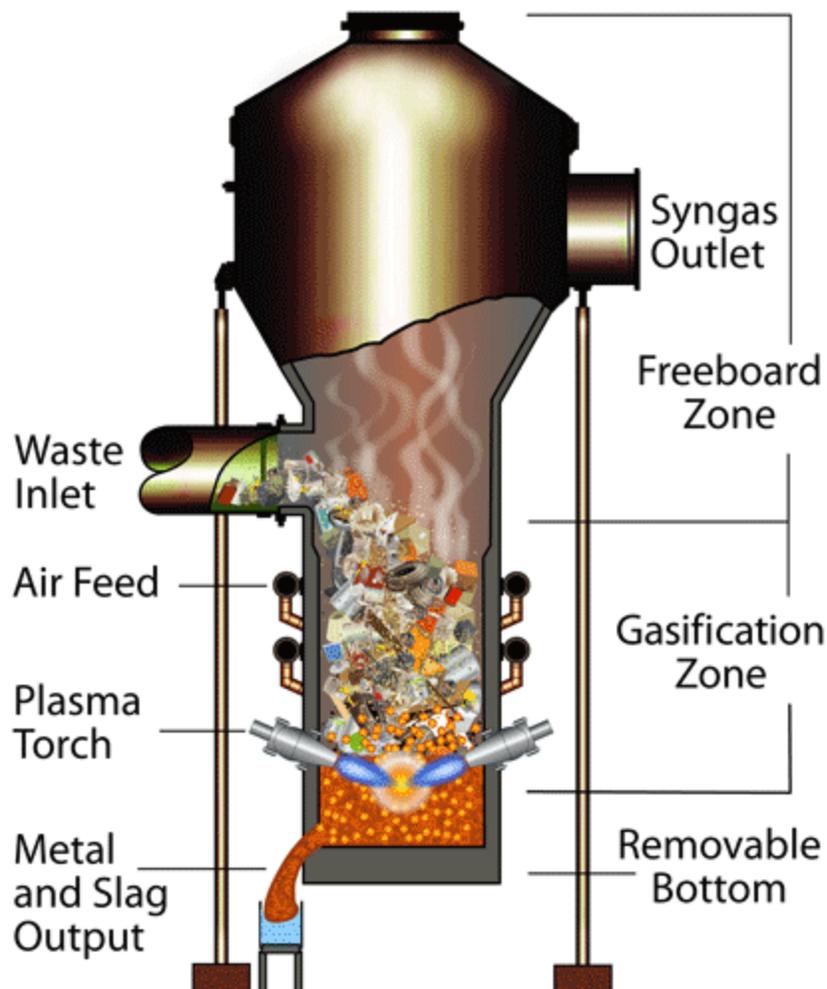
Fluidized bed reactors are of relatively recent development with the effort of achieving higher conversion efficiencies. These reactors operate through what is known as fluidization, whereby a solid bed of material is transformed into a fluid-like state through contact with a gas. This enhances the gasification reactions. The way a fluidized bed reactor works is that it takes a bed of feedstock material and forces air up through it from underneath. This results in a phenomenon that makes the feedstock behave like a fluid, hence the name fluidized bed [26]. There are two types of fluidized bed gasifiers as shown in Figure 12: bubbling fluidized bed and circulating fluidized bed. The difference between the two reactors is that the bubbling fluidized bed reactor does not recirculate particulate material back into the reactor, while the circulating fluidized bed reactor does circulate particulate material.



**Figure 12: Fluidized Bed Gasifiers [36]**

Entrained flow gasifiers have a high degree of feedstock flexibility and a low amount of tar formation. Entrained flow gasifiers operate at higher pressures and temperatures than fixed and fluidized bed gasifiers [20]. Entrained flow gasifiers operate by co-feeding fine feedstock material and the gasifying agent. This results in the gasifying agent surrounding or entraining the feedstock particles. This phenomena as well as the high temperatures and pressures results in a high conversion efficiency compared to fixed and fluidized bed gasifiers with the typical residence time lasting only a few seconds. A downside to entrained flow gasifiers is that the higher temperatures tend to shorten the life of system components [37]. Entrained flow should be looked at if it is decided to bring in other feedstock types such as municipal solid waste.

Plasma gasifiers can treat all hazardous and non-hazardous wastes and have a low ash content but require a large initial investment as well as high operating and maintenance costs. Figure 13 shows what a typical plasma gasification system looks like.



**Figure 13: Plasma Gasification [38]**

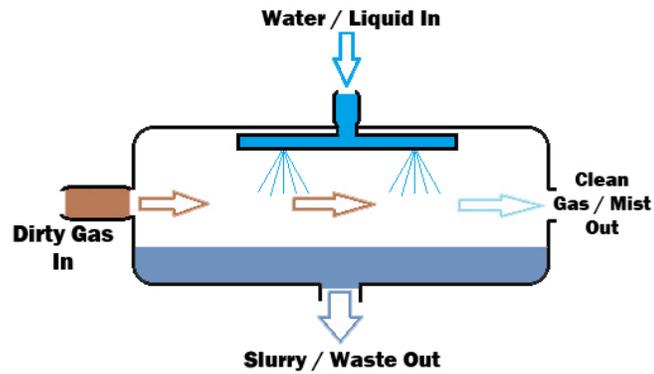
The main constituents of gasification reactions are C, CO, CO<sub>2</sub>, H<sub>2</sub>, H<sub>2</sub>O, and CH<sub>4</sub> as well as heavier hydrocarbon species. The operating conditions of the gasification reactor should be optimized to result in the highest energy content gas with the least number of detrimental byproducts. Due to the highly endothermic reactions involved in gasification the most important parameter to control is the temperature. Increasing the temperature of the reaction results in a decrease in the amount of tar and an increase in the amount of H<sub>2</sub> and CH<sub>4</sub> in the product gas [22]. Gasification can also be classified by its gasifying agent: air, steam, and oxygen. Each agent has its advantages and disadvantages. Steam yields a gas with a high energy content, but it requires an external heat source for steam-reforming reactions. Air is

simpler to utilize and operate and is cost effective to implement, but the resultant gas has a low energy content because of dilution due to nitrogen. Oxygen yields a gas that has a heat content between that of air and steam, but it requires a high capital cost to implement a pure oxygen source [20].

### **3.4 - Gas Cleaning**

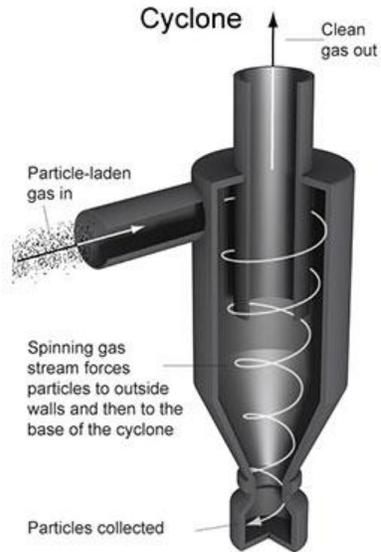
The contaminants in the producer gas from gasification include particulates, tar, alkali metals, sulfur compounds, chlorine compounds and nitrogenous compounds [22]. These compounds can have detrimental effects on equipment components and would thus need to be removed to effectively utilize the gas. The composition of the producer gas generally depends upon the type of biomass feedstock, gasifier type, gasifying agent and operating parameters of the gasification process. Specific to contaminants, the amount of particulate matter and tar in the producer gas mainly depends upon the type of gasifier used, while alkalis, sulfur and chlorine compounds mainly depend on the type of material used as a feedstock. In an updraft gasifier, the vapors will flow up after the pyrolysis zone. This includes the lighter non-condensable hydrocarbon gases that make up syngas, as well as the heavier condensable hydrocarbon vapors. While the solid char makes it down to the reduction zone where it will be further reduced and turned into gas, the condensable vapors never get reduced into lighter hydrocarbon species. The result of this is that the final gas from an updraft gasifier will have a high amount of tars that will need to be removed before use. A downdraft gasifier on the other hand will have a low amount of tars because the condensable vapors will go through the reduction zone and get reduced into the lighter hydrocarbons. However, since the gas outlet is close to where the solid char gets reduced, the result is that some of the ash and particulates can be carried away in the gas stream. This will require different cleaning equipment from the updraft gasifier to remove the particulate matter. The methods for removing tar include using wet scrubbers and thermal cracking. The methods for removing particulate matter include using cyclones, filters, and electrostatic precipitators.

Wet scrubbing works by ducting the dirty gas goes through scrubber where water is sprayed. The heavy condensable hydrocarbons will condense onto the water droplets and fall out of the gas stream leaving the lighter hydrocarbons. Figure 14 shows an example of this.



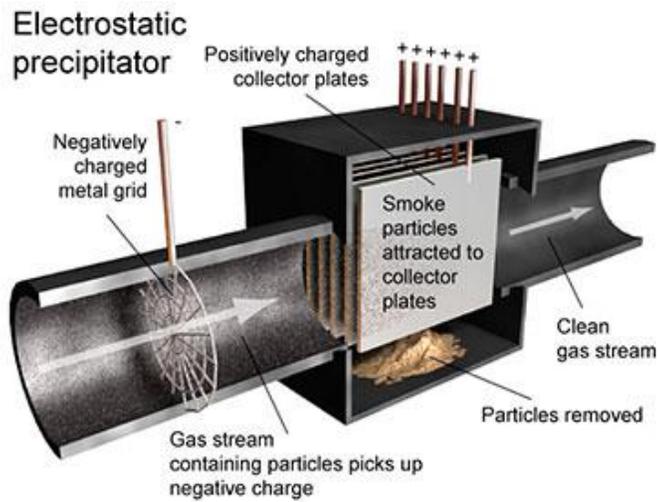
**Figure 14: Wet Scrubbing [39]**

Thermal cracking works by heating the gas stream to reduce or “crack” the heavier hydrocarbons into lighter hydrocarbons. A cyclone works by spinning the gas, “like a cyclone”, down to the bottom where the particulate matter is able to drop out of the gas stream. Figure 15 shows the basic principles.



**Figure 15: Gas Cyclone [40]**

An electrostatic precipitator works by charging the particulates in the gas stream negatively. A collection of positively charged plates attract the negatively charged particles thus removing them from the gas stream.



**Figure 16: Electrostatic Precipitator [40]**

The degree of gas cleaning depends not only on the type of gasifier and type of material used, but also on the end use of the gas.

### **3.5 - Syngas Usage**

Syngas can be used for a wide variety of potential applications from stationary combined heat and power to produce liquid fuels for vehicles that can be easily transported as well as manufacturing various types of chemicals. For example, manufacturing synthetic fuels and methanol are dependent on having a clean gas with low hydrocarbons and a specific ratio of the mass of hydrogen to the mass of carbon monoxide. For these applications, the heating value is not as important, but rather the chemical composition. When producing only hydrogen, it is expected that the gas is still clean, but the hydrogen to carbon monoxide ratio should be higher. When the syngas is used as a fuel gas for combined heat and power applications the chemical composition is not the primary concern, but rather the heating value of the gas. The gas needs to be free of particulates, but the CHP applications can handle higher amounts of hydrocarbons. Table 2 shows the desired characteristics the syngas should have for different applications.

**Table 2: Desirable Syngas Characteristics for Different Applications [41]**

Product	Synthetic Fuels	Methanol	Hydrogen	Fuel Gas	
	FT Gasoline & Diesel			Boiler	Turbine
H <sub>2</sub> /CO	0.6 <sup>a</sup>	~2.0	High	Unimportant	Unimportant
CO <sub>2</sub>	Low	Low <sup>c</sup>	Not Important <sup>b</sup>	Not Critical	Not Critical
Hydrocarbons	Low <sup>d</sup>	Low <sup>d</sup>	Low <sup>d</sup>	High	High
N <sub>2</sub>	Low	Low	Low	Note <sup>e</sup>	Note <sup>e</sup>
H <sub>2</sub> O	Low	Low	High <sup>f</sup>	Low	Note <sup>g</sup>
Contaminants	<1 ppm Sulfur Low Particulates	<1 ppm Sulfur Low Particulates	<1 ppm Sulfur Low Particulates	Note <sup>k</sup>	Low Part. Low Metals
Heating Value	Unimportant <sup>h</sup>	Unimportant <sup>h</sup>	Unimportant <sup>h</sup>	High <sup>i</sup>	High <sup>i</sup>
Pressure, bar	~20-30	~50 (liquid phase) ~140 (vapor phase)	~28	Low	~400
Temperature, °C	200-300 <sup>j</sup> 300-400	100-200	100-200	250	500-600

- (a) Depends on catalyst type. For iron catalyst, value shown is satisfactory; for cobalt catalyst, Near 2.0 should be used.
- (b) Water gas shift will have to be used to convert CO to H<sub>2</sub>; CO<sub>2</sub> in syngas can be removed at same time as CO<sub>2</sub> generated by the water gas shift reaction.
- (c) Some CO<sub>2</sub> can be tolerated if the H<sub>2</sub>/CO ratio is above 2.0 (as can occur with steam reforming of natural gas); if excess H<sub>2</sub> is available, the CO<sub>2</sub> will be converted to methanol.
- (d) Methane and heavier hydrocarbons need to be recycled for conversion to syngas and represent system inefficiency.
- (e) N<sub>2</sub> lowers the heating value, but level is unimportant as long as syngas can be burned with a stable flame.
- (f) Water is required for the water gas shift reaction.
- (g) Can tolerate relatively high water levels; steam sometimes added to moderate combustion temperature to control NO<sub>x</sub>.
- (h) As long as H<sub>2</sub>/CO and impurities levels are met, heating value is not critical.
- (i) Efficiency improves as heating value increases.
- (j) Depends on catalyst type; iron catalysts typically operate at higher temperatures than cobalt catalysts
- (k) Small amounts of contaminants can be tolerated

## CHAPTER 4 – Feedstock Materials

The quality and chemical composition of the syngas will depend on the type of feedstock gasified. Table 3 shows the typical feedstock's that can be used in gasification processes with their respective values for the ultimate analysis and proximate analysis.

**Table 3: Potential Biomass Gasifier Feedstock's [41]**

	Ultimate Analysis (wt% dry basis)						Proximate Analysis (wt% dry basis)			
	C	H	N	O	S	Ash	Moisture	Volatiles	Fixed Carbon	Heating Value HHV (MJ/kg)
<b>Agricultural Residues</b>										
Sawdust	50	6.3	0.8	43	0.03	0.03	7.8	74	25.5	19.3
Bagasse	48	6.0	-	42	-	4	1	80	15	17
Corn Cob	49	5.4	0.4	44.6	-	1	5.8	76.5	15	17
<b>Short Rotation Woody Crops</b>										
Beech Wood	50.4	7.2	0.3	41	0	1.0	19	85	14	18.4
<b>Herbaceous Energy Crops</b>										
Switchgrass	43	5.6	0.5	46	0.1	4.5	8.4	73	13.5	15.4
Straw	43.5	4.2	0.6	40.3	0.2	10.1	7.6	68.8	13.5	17
Miscanthus	49	4.6	0.4	46	0.1	1.9	7.9	79	11.5	12
<b>Municipal Solid Waste</b>										
Dry Sewage	20.5	3.2	2.3	17.5	0.6	56	4.7	41.6	2.3	8
<b>Coals</b>										
Subbituminous	67.8	4.7	0.9	17.2	0.6	8.7	31.0	43.6	47.7	24.6
Bituminous	61.5	4.2	1.2	6.0	5.1	21.9	8.7	36.1	42.0	27.0

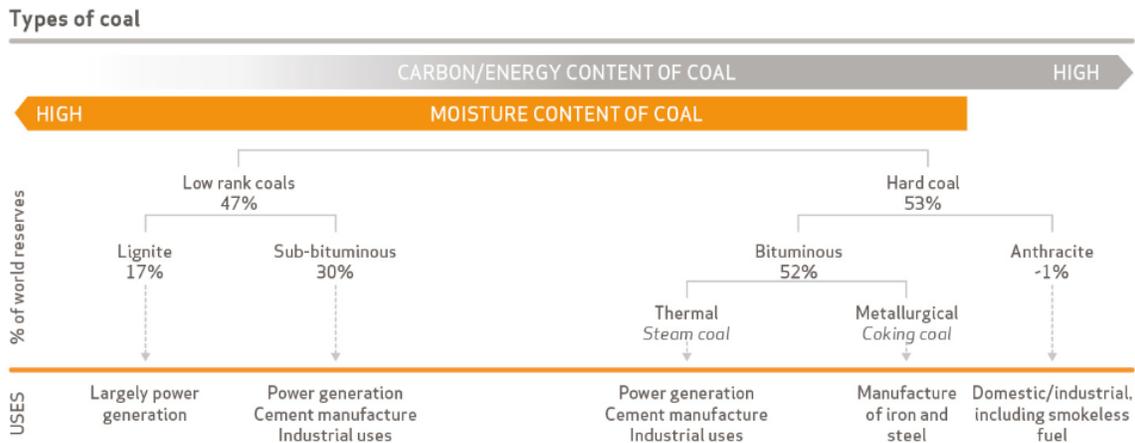
Compositions are approximate and may not sum exactly to 100.0%.

Biomass moisture contents reported are for dried feedstocks.

### 4.1 - Coal

As was stated earlier, gasification was originally used to gasify coal for town street lighting [22]. Coal originates from the partially decayed remains of vegetation, known as peat. Peat is composed of plant material that has accumulated in water-saturated environments and in the absence of oxygen [42] and includes trees, bushes, ferns, mosses, vines, and other forms of plant life which flourished in large swamps and bogs between 360 to 290 million years ago [43] [44]. These swamps and bogs were subsequently buried due to the buildup of other sediments and the movement of the earth's crust. With burial, the plant material was subjected to high temperatures and pressures which transformed it from peat to coal [44]. This transformation from peat to coal is known as coalification and the degree to which the coal is

transformed will determine the physical and chemical characteristics of the coal [44]. Coal is classified based on these physical and chemical characteristics into one of four distinct categories: lignite, subbituminous, bituminous, and anthracite [43]. Figure 17 compares the different rankings of coal and shows the availability and usage of each one.



**Figure 17: Types of Coal [44]**

## 4.2 - Petroleum Coke

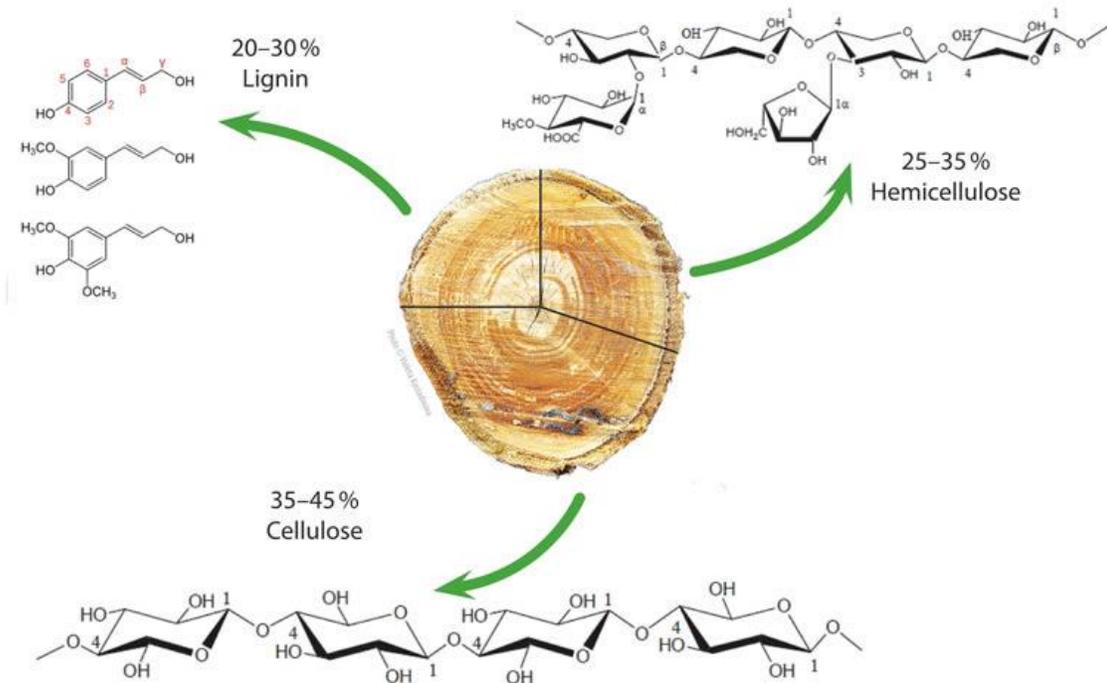
Petroleum coke, also known as petcoke is another feedstock material that can be used in gasification processes. It is a byproduct of the oil refining process [45]. Petroleum coke typically has a higher amount of fixed carbon and heating value with a lower moisture and ash content when compared to coal. However, some issues with petroleum coke include high sulphur and vanadium content, and low reactivity [46].

## 4.3 - Woody Biomass

For woody materials, this refers to cellulose, hemicellulose, and lignin. Cellulose is made up of long chains of glucose molecules bonded together in a straight line. Hemicellulose is like cellulose except that glucose is not the only sugar molecule in the structure. The structure of hemicellulose is also not in a straight line like cellulose. Lignin comes from the Latin word for

wood, *lignum*, and acts as a glue for the wood. It is not made up of sugar molecules however.

Figure 18 shows what the different chemical compounds look like.



**Figure 18: Chemical Structures in Wood [47]**

#### 4.4 - Municipal Solid Waste

Municipal and industrial wastes would be an example of a usable gasification feedstock. These feedstocks are ideal from an economic perspective as they could be deemed worthless or even costly to treat, but can be transformed into high-value products through gasification. A main issue with municipal solid waste is its high moisture content. This high moisture content might reduce the operating temperature and degrade performance of the thermochemical conversion process. The gasification will need to have this feedstock flexibility capability to utilize municipal solid waste. A fluidized bed reactor is an attractive option for dealing with municipal solid waste due in part to its uniform temperature distribution and ability to handle highly heterogeneous or wet fuels [48]. The price of the input fuels is a major issue when assessing the economic profitability of gasification technology [49].

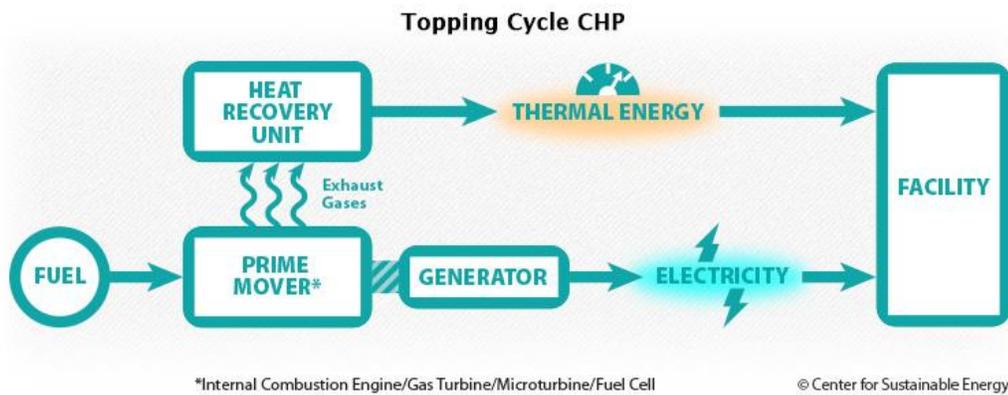


## **CHAPTER 5 – Cogeneration**

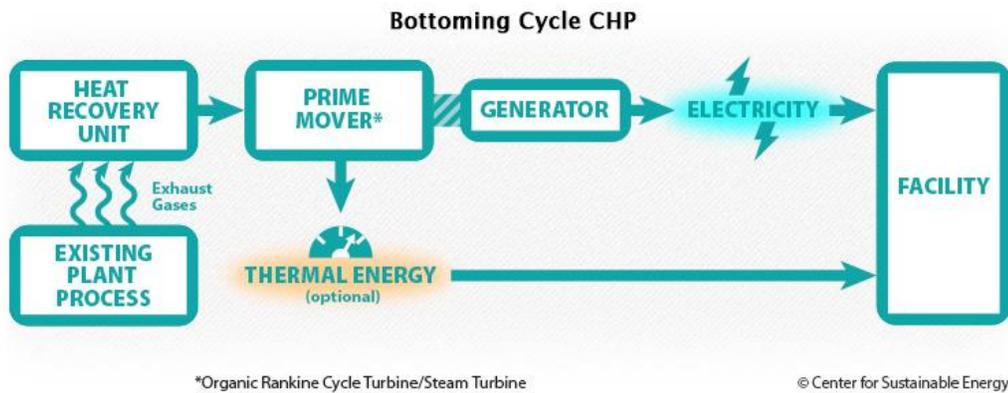
Cogeneration, also known as combined heat and power (CHP), is the generation of both electric or mechanical power and useful heat from the same source of fuel. The thermodynamic efficiency of a cogeneration/CHP system is higher than if the power and heat were generated from separate sources of fuel, making it appealing for improving the efficiency of energy usage.

### **5.1 - Classifications**

Cogeneration/CHP systems can be classified two ways, depending on whether electricity or heat is the priority. These are called topping and bottoming cycles. What distinguishes the two is whether the generation of electricity comes before or after the utilization of the heat. If the electricity is generated first with the waste heat being utilized elsewhere it is a topping cycle. If the heat is generated and used first and the waste heat is used to make electricity it is a bottoming cycle. The way to remember this is that in a topping cycle, the electricity is generated at the higher (or top) temperatures, whereas in a bottoming cycle, the electricity is generated at the lower (or bottom) temperatures. Figure 19 and Figure 20 show a topping cycle and bottoming cycle, respectively.



**Figure 19: Topping Cycle [50]**



**Figure 20: Bottoming Cycle [50]**

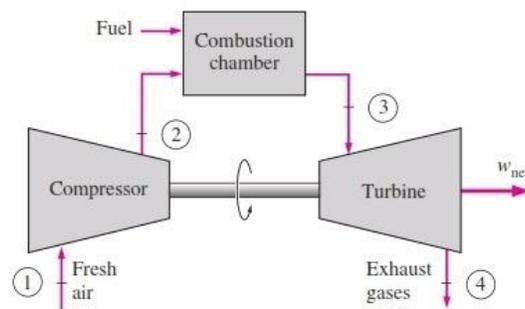
These two cycles can be put together in what is known as combined cycle. The basic idea is the waste heat from the topping cycle is used to generate electricity in the bottoming cycle. An example of this is using a gas turbine to make electricity with the waste heat being used to make steam to drive a steam turbine to make more electricity.

## 5.2 - Technologies

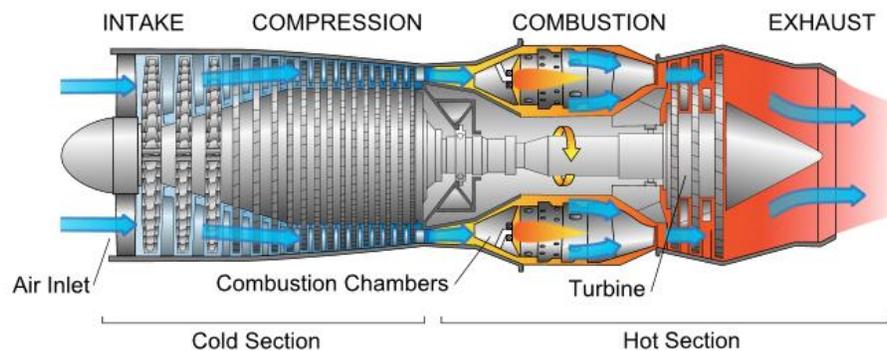
There are several different technologies used for cogeneration including gas turbines, reciprocating engines, and fuel cells which will be briefly discussed.

### 5.2.1 Gas Turbine

A gas turbine operates on the principles of what is called a Brayton cycle and includes a compressor, combustion chamber, and a turbine section. Figure 21 shows the basic idea of an open Brayton cycle while Figure 22 shows the basic anatomy of a gas turbine.

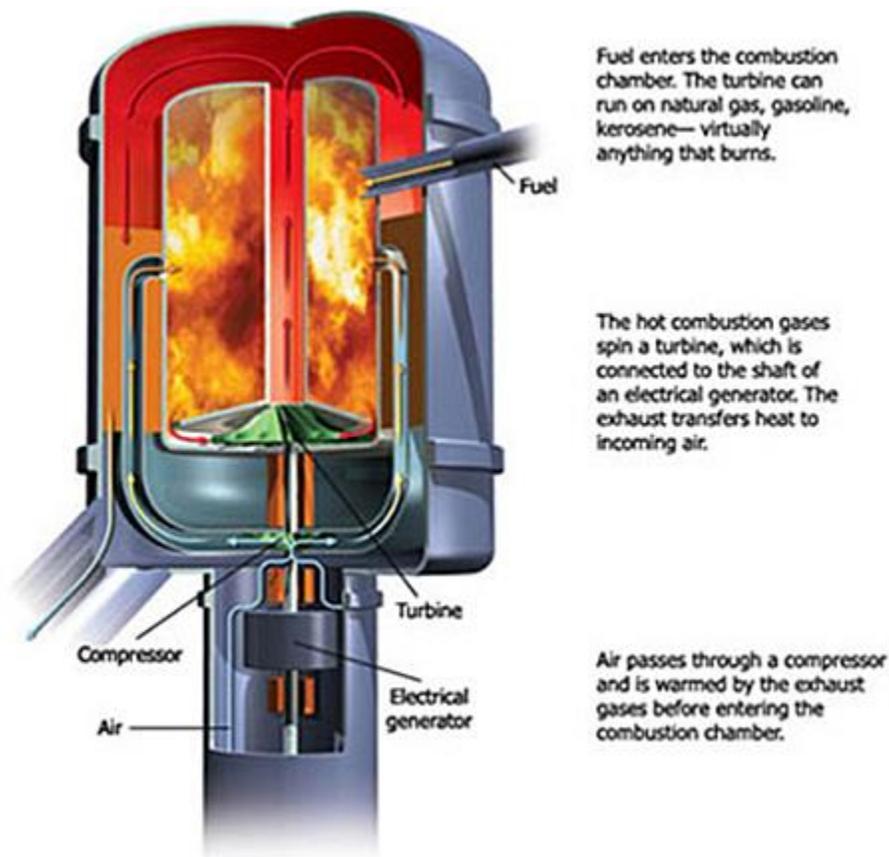


**Figure 21: Brayton Cycle [51]**



**Figure 22: Gas Turbine [52]**

Another technology that falls under the title of gas turbine is what is called a microturbine. These are operated under the same Brayton cycle principles as their heavy industrial counterparts, except that they are much smaller. Figure 23 shows the basic anatomy of a microturbine.

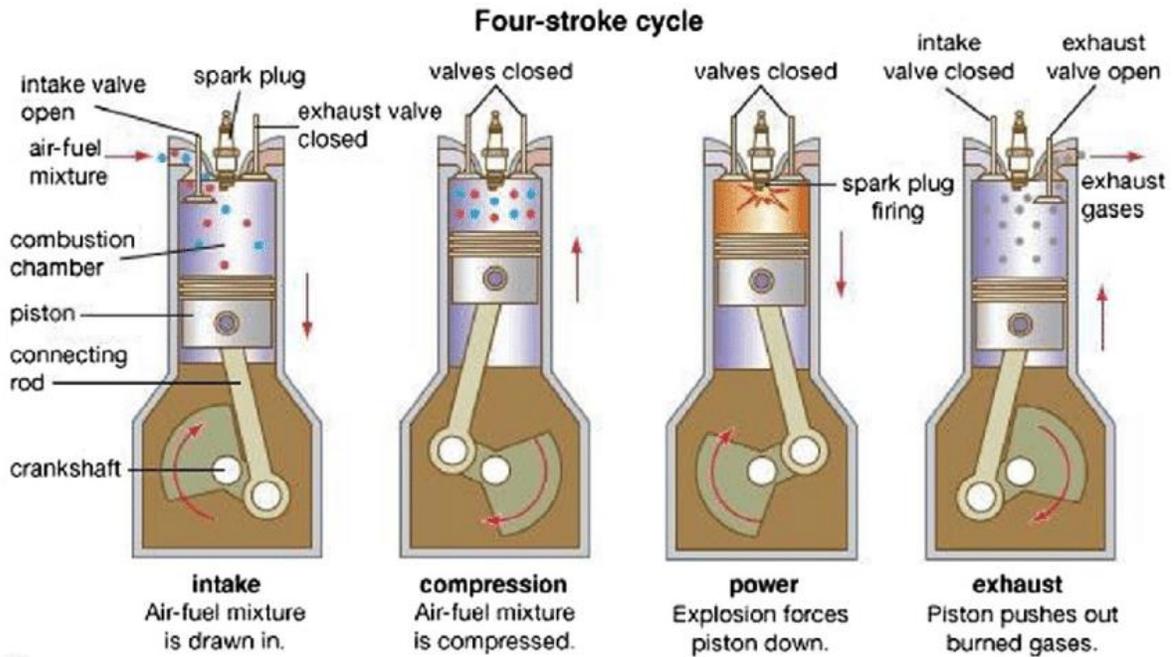


**Figure 23: Microturbine [53]**

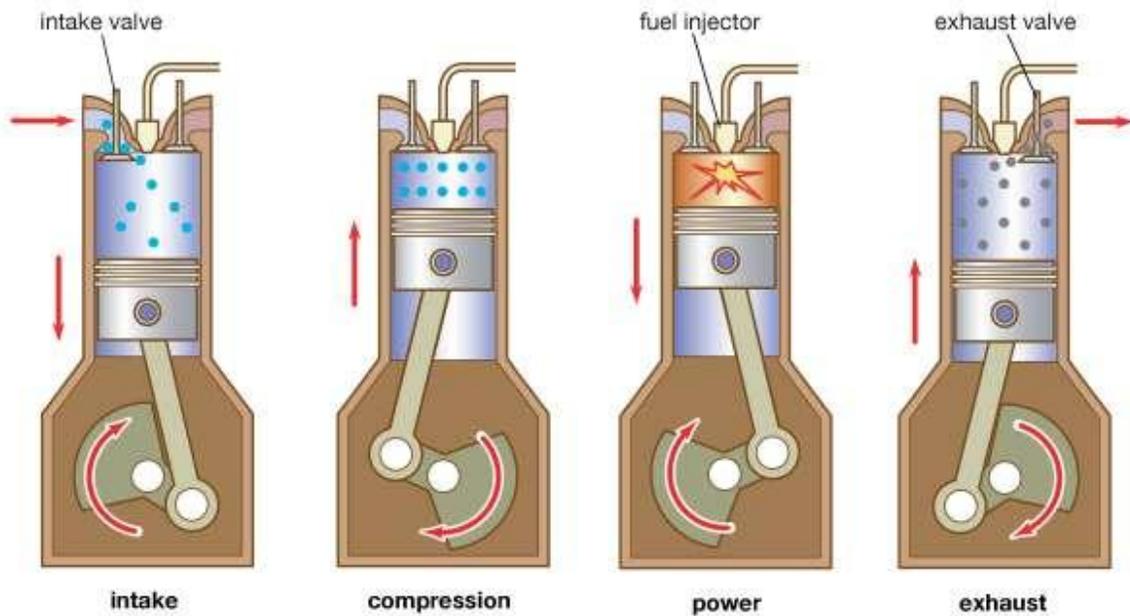
### 5.2.2 Reciprocating Internal Combustion Engine

Reciprocating internal combustion engines are a type of heat engine that uses reciprocating pistons to convert pressure into rotating motion. The technology is well-established and widely used for both transportation and stationary use. Their durability and reliability makes them an economic choice for CHP applications. The thermal energy from reciprocating engines can be used to generate hot water, low pressure steam, and chilled water through an absorption chiller. They are available in sizes from 10 kW to over 18 MW and be combined to provide increased plant capacity and availability. The technology has improved dramatically over the years leading to power density improvements, increased fuel efficiency, and reduced emissions. Compared to gas turbines, reciprocating engines have higher efficiencies and thus lower fuel-

related operating costs. The upfront cost is also lower than that of gas turbines, however, the maintenance costs are generally higher. The two main types of reciprocating engines are the spark ignition Otto-cycle engine and the compression ignition Diesel-cycle engine. Both use a cylindrical combustion chamber with a close-fitting piston that travels the length of the cylinder. The piston(s) connect to a crankshaft that transforms the linear motion of the piston to rotate the crankshaft. The main difference between the two engines is the way the fuel is ignited. Spark ignition Otto-cycle engines use a spark plug to ignite a premixed air fuel mixture in the cylinder. Compression ignition Diesel-cycle engines compress air that is introduced in the cylinder, thereby raising the temperature to the auto-ignition temperature of the fuel [28]. Figure 24 and Figure 25 show the operating principles of spark ignition and compression ignition engines, respectively.



**Figure 24: Spark Ignition Otto-Cycle Engine [54]**



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**Figure 25: Compression Ignition Diesel-Cycle Engine [55]**

Both the spark ignition and diesel engine can be used for combined heat and power applications; however, diesel engines are restricted to emergency standby or limited duty cycle service due to air emission concerns. This makes natural gas fueled spark ignition engines the predominant technology used in electric generation and CHP applications for operating hours greater than 500 hrs./yr. [28]. The economics of reciprocating engines depends on the effective use of the thermal energy contained in the exhaust gas and cooling systems. An analytical tool is needed to predict engine performance using syngas relative to pipeline quality natural gas [56].

### 5.2.3 Fuel Cells

Another interesting option is to use fuel cells. Fuel cells are like batteries, except they use *supplied* chemical energy as opposed to *stored* chemical energy. There are several types of fuel cells and most require pure hydrogen to operate, however there are two that can operate using hydrocarbons and carbon monoxide. These are solid oxide fuel cells and molten carbonate fuel cells. Figure 26 shows the basic principles of a solid oxide fuel cell and Figure 27 shows the basic principles of a molten carbonate fuel cell.

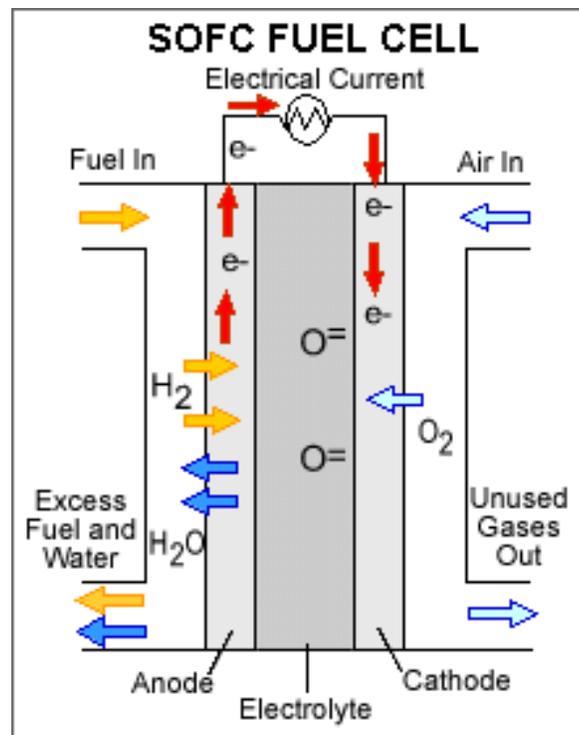


Figure 26: Solid Oxide Fuel Cell [57]

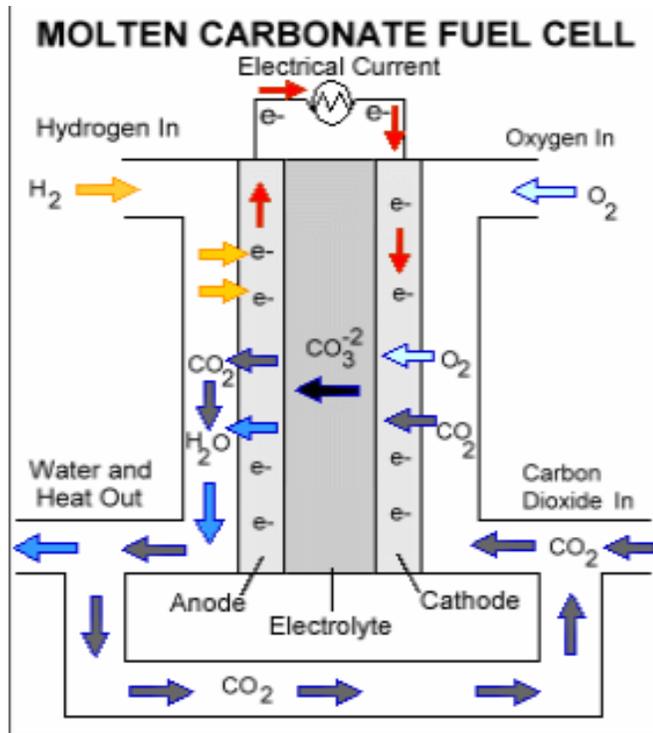


Figure 27: Molten Carbonate Fuel Cell [58]

### 5.3 - Integrating Biomass Combined Heat and Power

The industrial facilities that have developed biomass CHP applications are the paper, chemical, wood products, and food-processing industries. The biggest industrial user of bioenergy is the forest products industry. Manufacturing facilities that utilize these products can typically generate more than half of their energy from wood waste. It should be noted that the success of any biomass-fueled CHP project is heavily dependent on the availability of a suitable biomass feedstock [59].

## **5.4 - IGATE-E Tool**

The Industrial Geospatial Analysis Tool for Energy Evaluation (IGATE-E) is a tool developed by the Department of Energy for industrial energy evaluation [60]. The tool estimates electrical energy consumption of manufacturing industries using the Department of Energy's Industrial Assessment Center database and Energy Information Administration Manufacturing Energy Consumption Survey database, in addition to others. This tool is intended to be a decision support tool to a wide spectrum of energy analysts, researchers, government organizations, private consultants, industry partners, and the like. The motivation behind the development of this tool is that energy professionals and researchers often must rely on limited or unreliable information for initiating projects or performing analyses. Professionals in the manufacturing sector are further challenged with performing these analyses because industrial energy consumption is dependent on the type of manufacturing process, production volume, plant size, location, operational parameters, and other variables that are usually proprietary for each facility. The residential and commercial sectors are easier to analyze since their energy consumption is dependent on population densities, floor area, and building type all of which is made publicly available.

## CHAPTER 6 – Economic Analysis of Gasification

### 6.1 - Design of Biomass Gasifiers

The design of a gasifier is done following three major phases: process design and preliminary sizing, optimization of design, and detailed mechanical design. For cost estimation and/or submission of initial bids most manufacturers use the first step of sizing the gasifier. A typical process design starts with a mass balance and energy balance [33].

#### 6.1.1 Mass Balance

Mass balancing equations are used to determine the product gas flow rate and fuel feed rate. Typically, the required power output,  $Q$  ( $MW_{th}$ ), is specified by the client. The designer will then make an estimation on the amount of fuel to be fed and the amount of the gasifying agent. The volume flow rate of the product gas,  $V_g$  ( $m^3/s$ ), for a desired lower heating value,  $LHV_g$  ( $MJ/m^3$ ), is found via the following equation [61]:

$$V_g = \frac{Q}{LHV_g}$$

The lower heating value of the product gas,  $LHV_g$ , can be calculated from its composition [33]. In the absence of this information, a reasonable guess can be made from published data [33]. It should be noted that natural gas and fuel oil are specified with their higher heating values [13]. The higher heating value is determined by bringing all the products of combustion back to pre-combustion temperatures and condensing all of the water vapor formed during combustion. The lower heating value is obtained by subtracting the latent heat of vaporization from the higher heating value [62]. The gas would be roughly the same temperature and pressure of the gasifier operating temperature and pressure.

The fuel feed rate,  $M_f$  ( $kg/s$ ), is found by dividing the required power output by the lower heating value of the fuel,  $LHV_{bm}$  ( $MJ/kg$ ), and the gasifier efficiency,  $\eta_{gef}$  [33]. This is described by the following equation:

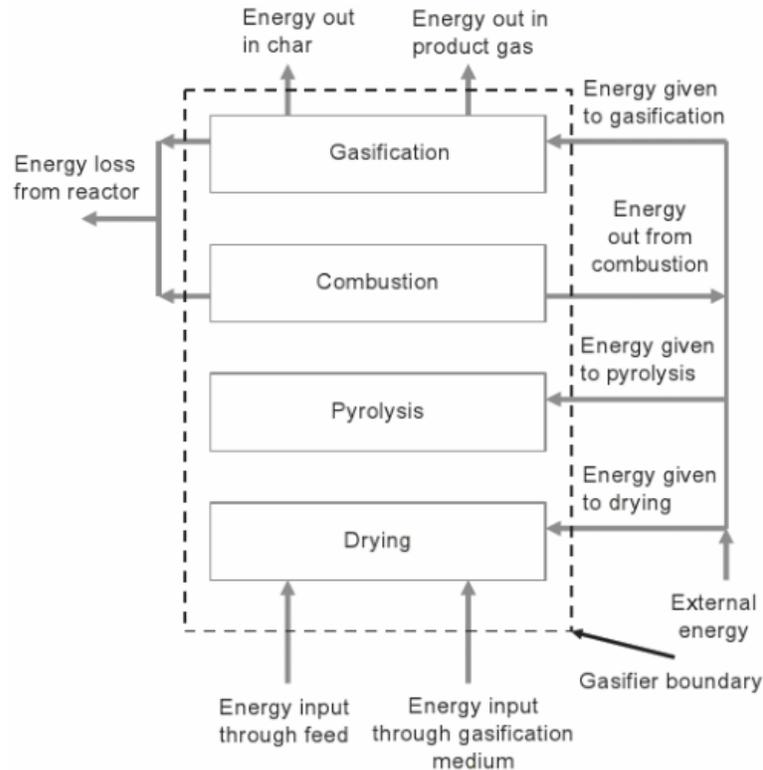
$$M_f = \frac{Q}{LHV_{bm}\eta_{gef}}$$

For the system studied, these equations were done in opposite order. This is because the subject facility is less concerned with the output power of the gasifier and more concerned with utilizing their waste wood. Currently there is 5,000 metric tons of wood waste generated per year which equates to 5,000,000 kg per year. Assuming that all of the wood waste generated will be gasified in the year that it is generated, the fuel feed rate can be estimated. It is estimated that the gasification system will operate 24 hours per day, 7 days per week, for 46 weeks per year with the remaining weeks being used for routine inspection and maintenance. This results in the gasification system operating for 7,728 hours per year. This results in a fuel feed rate of 0.18 kg/s, equivalent to processing 15 tons of wood waste per day. The gasification reactor will have to handle this amount of wood fuel to be viable. Taking data from the Biomass Combined Heat and Power Catalog of Technologies Report Published by the U.S. Environmental Protection Agencies Combined Heat and Power Partnership reveals that fixed bed gasifiers are limited to processing less than 30 tons per day whereas fluidized bed gasifiers are limited to processing greater than 30 tons per day [59]. This means that a fixed bed gasification system is the most feasible for this application. The average efficiency of fixed bed gasifiers is reported to be roughly 50 - 80% [33] [35] [63] [64]. An average value of 65% is estimated for the efficiency of the gasification process. The lower heating value of the wood waste was found to be 18.4 MJ/kg based on analytical testing by the facility. The results of this test can be found in the appendix. Combined with the fuel feed rate and the gasification

efficiency, the power output is found to be 2.15 MW<sub>th</sub>. The lower heating value of the final product gas generated using a fixed bed gasifier was reported to be between 4 and 7 MJ/m<sup>3</sup> [33] [63] [65] [61]. Using a conservative value of 5 MJ/m<sup>3</sup> for the lower heating value of the product gas, the volume flow rate was found to be 0.43 m<sup>3</sup>/s.

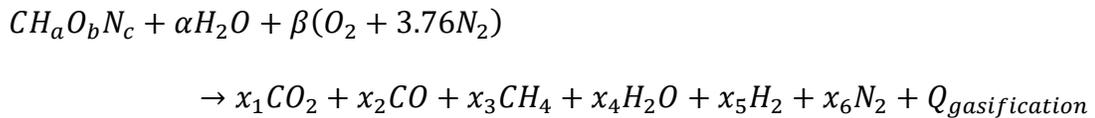
### *6.1.2 Energy Balance*

Performing an energy balance of the gasification system is an important step to follow. This is because unlike combustion, most gasification reactions are endothermic, meaning that they require heat to be supplied to the reactor vessel for the gasification processes to be maintained. The amount of heat that will need to be supplied depends on the endothermic reactions in the gasification vessel as well as the operating temperature of the system [33]. The amount of heat supplied can be determined through what is known as the heat of reaction. The heat of reaction is the amount of heat that must be added or removed to keep all of the substances present at the same temperature [66]. Figure 28 shows the general balance of a gasification system.



**Figure 28: Energy Flow In and Out of a Gasifier [33]**

To calculate the heat of reaction value for gasification, it is necessary to consider an overall gasification reaction where 1 mole of biomass ( $CH_aO_bN_c$ ) is gasified in  $\alpha$  moles of steam and  $\beta$  moles of air, shown below [33]:



The chemical composition of the biomass is found by conducting an ultimate analysis of the fuel material. This determines the percentages of carbon, hydrogen, and oxygen in the biomass material as well any nitrogen or sulfur present [22]. Once the percentages are determined the approximate chemical representation can be determined by dividing the percentage of each element by the percentage of carbon.

This is shown with the following equations:

$$a = \frac{\% H}{\% C}$$

$$b = \frac{\% O}{\% C}$$

$$c = \frac{\% N}{\% C}$$

The value for  $\alpha$  is found using the moisture content (MC), ash, and molecular weight of the biomass material ( $M_b$ ) [67]. This is derived from the following equation:

$$\alpha = \frac{N_w}{N_b}$$

Where  $N_w$  is the moles of water and  $N_b$  is the moles of biomass. This equation can be expanded out as follows:

$$\alpha = \frac{mass_w/M_w}{mass_b/M_b}$$

$$\alpha = \frac{mass_w}{mass_b} \cdot \frac{M_b}{M_w}$$

Where  $M_w$  is the molecular weight of water and  $M_b$  is the molecular weight of the biomass material. The molecular weight of water is found by summing the molecular weights of the hydrogen and oxygen atoms in one water molecule which is 18 grams/mole. The molecular weight of the biomass is found by summing the weights of the atoms in the biomass material.

This equation is shown below:

$$M_b = MW_C + MW_H \cdot a + MW_O \cdot b + MW_N \cdot c$$

$$M_b = 6 + 1a + 16b + 14c$$

The mass ratio of water to biomass can be expressed using weight percentages

$$\frac{mass_w}{mass_b} = \frac{\%wt\ Moisture\ Content}{\%wt\ Dry\ Ash\ Free\ Biomass}$$

The weight percent of the water in the biomass is simply the moisture content in the biomass material, however the weight percent of the dry ash free biomass needs to be determined. To find the weight-percent of dry ash-free biomass, the weight-percent of the dry biomass should be determined. This is done via the following equation:

$$\%wt\ Dry\ Biomass = \%wt\ Biomass - \%wt\ Moisture\ Content$$

$$\%wt\ Dry\ Biomass = 1 - MC$$

The weight-percent of ash also needs to be removed from the biomass material, however since moisture content and ash are not calculated the same way, the ash-free weight percent needs to be determined.

$$\%wt\ Ash\ Free\ Biomass = \%wt\ Biomass - \%wt\ Ash$$

$$\%wt\ Ash\ Free\ Biomass = 1 - Ash$$

The weight-percent of the ash-free biomass and the dry biomass are multiplied together to get the weight-percent of the dry, ash-free biomass. This is shown below:

$$\%wt\ Dry\ Ash\ Free\ Biomass = \%wt\ Dry\ Biomass \cdot \%wt\ Ash\ Free\ Biomass$$

$$\%wt\ Dry\ Ash\ Free\ Biomass = (1 - MC)(1 - Ash)$$

The water to biomass weight-percent ratio can be determined via the following equation:

$$\frac{mass_w}{mass_b} = \frac{MC}{(1 - MC)(1 - Ash)}$$

The water to biomass weight-percent ratio multiplied by the biomass to water molecular weight ratio yields the value for  $\alpha$ .

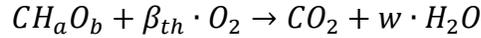
This is shown in the following equation:

$$\alpha = \left( \frac{MC}{(1 - MC)(1 - Ash)} \right) \frac{M_b}{18}$$

The value for  $\beta$  is determined using the equivalence ratio,  $\phi$ , and the chemical makeup of the biomass material [67]. This is derived from the following equation:

$$\phi = \frac{\beta_{th}}{\beta}$$

Where  $\beta_{th}$  is the fuel air ratio at stoichiometric conditions. This can be determined by considering the following stoichiometric combustion reaction:



The value for  $\beta_{th}$  can be found by conducting an atom balance for the Hydrogen and Oxygen elements:

$$H: a = 2w$$

$$O: b + 2\beta_{th} = 2 + w$$

$$w = \frac{a}{2}$$

$$2\beta_{th} = 2 + w - b$$

$$\beta_{th} = 1 + \frac{a}{4} - \frac{b}{2}$$

Rearranging the equivalence ratio equation discussed earlier and substituting the theoretical value for  $\beta$  yields the following:

$$\beta = \frac{\left( 1 + \frac{a}{4} - \frac{b}{2} \right)}{\phi}$$

The mole fractions of the product species  $x_1$ ,  $x_2$ ,  $x_3$ ,  $x_4$ ,  $x_5$ , and  $x_6$  are found using a stoichiometric equilibrium model. The values for the mole fractions are found by conducting

an atom balance of the stoichiometric equation as well as determining equilibrium constants of specific gasification reactions. The following equations show the atom balance equations:

$$C: 1(1) = x_1(1) + x_2(1) + x_3(1)$$

$$H: 1(a) + \alpha(2) = x_3(4) + x_4(2) + x_5(2)$$

$$O: 1(b) + \alpha(1) + \beta(2) = x_1(2) + x_2(1) + x_4(1)$$

$$N: 1(c) + \beta(3.76)(2) = x_6(2)$$

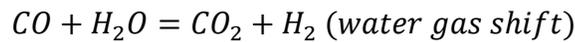
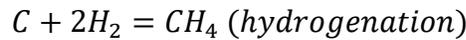
The equation to determine the mole fraction of nitrogen in the product gas can be solved once the values for c and  $\beta$  are determined. Simplifying the other equations yields the following:

$$0 = x_1 + x_2 + x_3 - 1$$

$$0 = x_3 + 2x_4 + 2x_5 - a - 2\alpha$$

$$0 = 2x_1 + x_2 + x_4 - b - \alpha - 2\beta$$

The coefficients  $x_1$  to  $x_6$  are found using the atom balance equations listed above as well as considering the equilibrium of the hydrogenation and water-gas shift reactions [67]. These reactions are shown below:



The equilibrium constants for these reactions are calculated with the following equations:

$$K_h = \frac{(n_{CH_4})(n_{total})}{(n_{H_2})} = \frac{x_3 x_{total}}{x_5^2} = \exp\left(-\frac{\Delta g_h^o}{RT}\right)$$

$$K_w = \frac{(n_{CO_2})(n_{H_2})}{(n_{CO})(n_{H_2O})} = \frac{x_1 x_5}{x_2 x_4} = \exp\left(-\frac{\Delta g_w^o}{RT}\right)$$

Where  $\Delta g_m^o$  and  $\Delta g_w^o$  are the standard Gibbs function of reaction for the methanation and water-gas shift reactions, respectively.

These values are determined using the Gibbs free energy constants for the species in the reactions with the following equations.

$$\Delta g_h^o = g_{CH_4}^o - 2g_{H_2}^o$$

$$\Delta g_w^o = g_{CO_2}^o + g_{H_2}^o - g_{CO}^o - g_{H_2O}^o$$

The equilibrium equations along with the atom balance equations need to be solved simultaneously to get the correct values. This was done using the Solver add-in in Excel. Once the mole fractions are found, the heat of reaction can be found using the heats of formation of the product and reactant species [33]. This is done via the following equation:

$$\text{Heat of Reaction} = \sum_{i=prod} \Delta H_{fi}^o \cdot x_i - \sum_{j=react} \Delta H_{fj}^o \cdot x_j$$

Expanding this equation out gives the following:

*Heat of Reaction*

$$\begin{aligned} &= \Delta H_f^o(CO_2) \cdot x_1 + \Delta H_f^o(CO) \cdot x_2 + \Delta H_f^o(CH_4) \cdot x_3 + \Delta H_f^o(H_2O) \cdot x_4 \\ &+ \Delta H_f^o(H_2) \cdot x_5 + \Delta H_f^o(N_2) \cdot x_6 - \Delta H_f^o(H_2O) \cdot \alpha - \Delta H_f^o(O_2) \cdot \beta \\ &- \Delta H_f^o(Biomass) \end{aligned}$$

This equation will find the heat of reaction at 25°C, or 298 K. Once the heat of reaction at this temperature is found, the heat of reaction at the actual operating temperature should be found. Gasification reactor vessels operate at temperatures around 1,000 K to 1,200 K [33]. The heat of reaction for elevated temperatures is found via the following equation:

$$\Delta H_T^o = \Delta H_{298}^o + \sum \left( \int_{298}^T x_i \cdot c_{p,i} \cdot dT \right)_{product} - \sum \left( \int_{298}^T x_j \cdot c_{p,j} \cdot dT \right)_{reactant}$$

This determines the net heat supplied to the gasification reactor vessel at a given operating temperature. If this value is negative, then the overall gasification reactions are exothermic,

therefore heat does not need to be supplied to sustain the reactions [33]. Although the enthalpy of formation for biomass material cannot be readily known, since the feedstock material is wood (which has a high energy content) it can be assumed that the reactions are exothermic. An ultimate analysis of the wood fuel was not performed for the subject facility, so a representative analysis is taken from the literature. The data was taken from an article discussing gasification of wood chips in a fixed bed gasifier and is represented in Table 4.

**Table 4: Elemental Composition of Wood Chips [64]**

Element	Value (%)
C	49.18
H	7.25
O	40.49
N	1.5
S	0.17
Ash	1.41

Based on the elemental composition, the chemical representation of the biomass is found to be  $CH_{0.15}O_{0.82}N_{0.031}$ . The molecular weight of this representation is found to be 25.747 g/mol. The moisture content of the subject facilities wood waste was found to be 9.25% based on the analytical test results found in the appendix. The resultant value for  $\alpha$  is found to be 0.14. The equivalence ratio for gasification must be relatively low, typically between 0.2 and 0.3. This is to ensure that the gasification reactions do not turn into combustion reactions [33]. A value of 0.25 was used for the equivalence ratio. With this equivalence ratio, the value for  $\beta$  is found to be 2.50. With the values for  $c$  and  $\beta$  found, the mole fraction of  $N_2$  in the product gas is found to be 9.42. The mole fractions for the rest of the product gas species will be more difficult to determine and will require iterative calculations to determine. These are done using the atom balance equations and the equilibrium equations. For the equilibrium equations the Gibbs free energy for the methanation and water-gas shift reactions are found to be -50.7 and -28.6 kJ/mol, respectively. Specifying a gasification temperature of 800°C (1073 K), the equilibrium

constants for the methanation and water gas shift reactions are found to be 294.71 and 24.72, respectively. Plugging values into the atom balance and equilibrium equations yields the following:

$$0 = x_1 + x_2 + x_3 - 1$$

$$0 = x_3 + 2x_4 + 2x_5 - 0.43$$

$$0 = 2x_1 + x_2 + x_4 - 5.97$$

$$0 = 294.71x_5^2 - x_3x_{total}$$

$$0 = 24.72x_2x_4 - x_1x_5$$

$$x_{total} = x_1 + x_2 + x_3 + x_4 + x_5 + 9.42$$

Solving these equations requires advanced analytical techniques using sophisticated software [67], therefore a chemical composition based on experimental results found in literature is used. The results are shown below in Table 5.

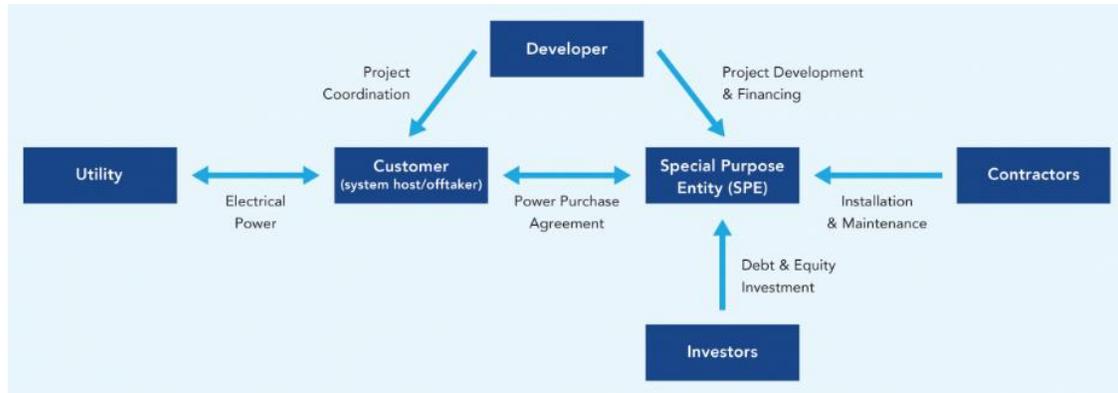
**Table 5: Wood Gas Chemical Composition [68]**

Chemical	Value (%)
CH <sub>4</sub>	6
CO	29
H <sub>2</sub>	19
N <sub>2</sub>	38
CO <sub>2</sub>	8

## **6.2 - Cost Estimating**

The subject facility is primarily interested in the costs associated with installing and operating a gasification system to process their waste wood and to provide heat and power for plant purposes. It is often difficult to find good information regarding the economics of biomass gasification systems. This is often the case for those with limited commercial implementation such as biomass gasification [69]. Specifically they are interested in the costs associated with installing a system themselves versus having a third party developer install, own, and operate the system with the facility purchasing the power generated through a power purchase agreement (PPA) [18] [70]. Using a PPA is very attractive for the subject facility for a few specific reasons. The specific advantages of using a power purchase agreement are that PPAs can usually cover 100% of the project cost with the electricity purchased typically being less than the retail rate for electricity. The customer can avoid the risk and complexity of equipment ownership through third party installation, ownership, and operation. Another advantage is that PPAs are designed to be an off-balance sheet financing solution, with payments treated as an operating expense similar to a standard utility bill. PPAs also lock-in energy prices at an agreed upon rate that protects the customer from utility rate fluctuations. The disadvantages are that PPAs have an annual price escalator which may result in the customer paying higher than the market rate if the electricity prices decline or increase slower than the escalator. Some states have laws that prevent the usage of PPAs which limits the availability of the agreements. PPAs

can also have complex contracts and higher transaction costs than buying a system outright [70]. Figure 29 shows the general structure of a power purchase agreement.



**Figure 29: Power Purchase Agreement Structure [70]**

The subject facility has already entered into power purchase agreements for the landfill gas CHP and solar panels installed at the facility [18]. The retail rate for the subject facility is \$0.06/kWh which is among the lowest in the country [71]. This makes renewable energy projects difficult to justify economically when compared to buying electricity at as low a rate as it currently is. The cost for natural gas is approximately \$4.50/dekatherm (\$4.50/MMBtu) [72]. Based on review of the CHP Technologies, it is determined that a reciprocating engine is the best option to use. The electrical output of using a reciprocating engine can be determined using the electrical efficiency of the engine which ranges between 30% for smaller engines to 42% for larger engines. The thermal efficiency of an engine is also important for CHP applications with typical values ranging between 35% and 50% [73]. The remaining energy that does not get converted to electricity or useful heat will be expelled from the system in the form of waste heat. The amount of electricity and thermal energy that can be harnessed with a CHP system can be represented as follows:

$$P_e = \eta_e \cdot Q_{gasification}$$

$$P_{th} = \eta_{th} \cdot Q_{gasification}$$

$$Waste\ Heat = Q_{gasification} - P_e - P_{th}$$

With a gasification capacity calculated earlier to be 2.15 MW<sub>th</sub> and using conservative values of 30% and 35% for the electrical efficiency and thermal efficiency, respectively, the electric and thermal output of a gasification CHP system can be estimated as follows:

$$P_e = 30\% \cdot 2.15\ MW$$

$$P_e = 645\ kW_e$$

$$P_{th} = 35\% \cdot 2.15\ MW$$

$$P_{th} = 753\ kW_{th}$$

$$Waste\ Heat = 2.15\ MW - 0.645\ MW - 0.753\ MW$$

$$Waste\ Heat = 752\ kW_{th}$$

The total electricity that could be generated in a given year can be found by multiplying the electric power by the operating hours per year. The operating hours can be determined by considering the operating schedule of a gasification system. It is assumed that the gasifier will be able to process the wood waste 24/7 for most of the year. It is estimated that the gasifier will operate for 46 weeks out the year with the remaining time being used for routine downtime and maintenance. The calculation to determine operating hours is shown below:

$$Operating\ Hours = 24\ \frac{hrs.}{day} \cdot 7\ \frac{days}{wk.} \cdot 46\ \frac{wks.}{yr.}$$

$$Operating\ Hours = 7,728\ \frac{hrs.}{yr.}$$

With the operating hours determined, the electricity generated can be determined. This is shown in the following calculation:

$$Electricity\ Generated = P_e \cdot Operating\ Hours$$

$$Electricity\ Generated = 645\ kW \cdot 7,728\ \frac{hrs.}{yr.}$$

$$\text{Electricity Generated} = 4,983,333 \text{ kWh/yr.}$$

The electricity that is generated from gasification CHP system would help offset the cost of purchasing electricity from the facilities utilities service provider. The annual electrical cost savings from installing this system can be determined by multiplying the energy generated by the electricity cost of \$0.06/kWh.

$$\text{Electrical Cost Savings} = \text{Electricity Generated} \cdot \$0.06/\text{kWh}$$

$$\text{Electrical Cost Savings} = 4,983,333 \text{ kWh/yr.} \cdot \$0.06/\text{kWh}$$

$$\text{Electrical Cost Savings} = \$299,000/\text{yr.}$$

The total heat that could be utilized in a given year can be found by multiplying the hourly heat rate by the annual operating hours, however, since the cost for natural gas is given per MMBtu, the useful thermal heat will need to be converted from kW to MMBtu/hr. These calculations are shown below:

$$\text{Conversion: } 1 \text{ kW} = 0.003142 \text{ MMBtu/hr.}$$

$$P_{th} (\text{MMBtu/hr.}) = 753 \text{ kW}_{th} \cdot \frac{0.003142 \text{ MMBtu/hr.}}{1 \text{ kW}}$$

$$P_{th} (\text{MMBtu/hr.}) = 2.36 \text{ MMBtu/hr.}$$

$$\text{Heat Generated} = P_{th} \cdot \text{Operating Hours}$$

$$\text{Heat Generated} = 2.36 \text{ MMBtu/hr.} \cdot 7,728 \text{ hrs./yr.}$$

$$\text{Heat Generated} = 18,267 \text{ MMBtu/yr.}$$

The heat that is utilized from a gasification CHP system would help offset the cost of purchasing natural gas from the facilities utilities service provider and burning it in combustion boilers. The annual natural gas cost savings from installing this system can be determined by multiplying the heat utilized by the natural gas cost of \$4.50/MMBtu and dividing by the efficiency of the natural gas boilers assumed to be 80%.

$$\text{Natural Gas Cost Savings} = \frac{\text{Heat Utilized} \cdot \$4.50/\text{MMBtu}}{\eta_{\text{boiler}}}$$

$$\text{Natural Gas Cost Savings} = \frac{18,267 \text{ MMBtu/yr.} \cdot \$4.50/\text{MMBtu}}{80\%}$$

$$\text{Natural Gas Cost Savings} = \$102,753/\text{yr.}$$

The cost savings from generating electricity and utilizing the heat from the CHP system can be determined by combining the cost savings of the electricity and heat produced. This is shown in the following calculation:

$$\text{Total Energy Cost Savings} = \text{Electricity Cost Savings} + \text{Natural Gas Cost Savings}$$

$$\text{Total Energy Cost Savings} = \$299,000/\text{yr.} + \$102,753/\text{yr.}$$

$$\text{Total Energy Cost Savings} = \$401,753/\text{yr.}$$

Reviewing the International Energy Agencies Energy Technology Essentials Biomass for Power Generation and CHP, the capital cost of installing a gasification CHP system is \$3,000 - \$4,000/kW which is the cost per kW of electric generation for gasification CHP systems [74]. A value of \$4,000/kW was chosen to represent the maximum capital cost for the gasification system. With an electric generation rate of 645 kW<sub>e</sub>, the calculation to determine the capital cost of is shown below:

$$\text{Capital Cost} = \$4,000/\text{kW} \cdot 645 \text{ kW}$$

$$\text{Capital Cost} = \$2,580,000$$

This is only the capital costs for the gasification system itself and does not include the ongoing operating and maintenance costs for the system. The International Renewable Energy Association has detailed fixed and variable operating and maintenance costs in their Cost Analysis of Biomass for Power Generation report. The fixed operating and maintenance are expressed as a percentage of capital costs and consist of labor, scheduled maintenance, routine

component/equipment replacement, insurance, etc. For gasification systems this is estimated to be 3% to 6% of the total installed cost. The variable operation and maintenance costs depend on the output of the system and are expressed as a value per unit of output (\$/kWh). They include non-biomass fuel costs, ash disposal, unplanned maintenance, equipment replacement and incremental servicing costs. The variable O&M is estimated to be \$3.70/MWh for gasification systems [75]. Assuming that the gasification system will have a capital cost \$2,580,000 and assuming that the fixed operation and maintenance costs will be 6% of the capital costs, the fixed annual operating and maintenance cost is calculated as follows:

$$\text{Fixed O\&M Cost} = \$2,580,000 \cdot 6\%/yr.$$

$$\text{Fixed O\&M Cost} = \$154,800/yr.$$

The energy used to calculate the variable operating and maintenance costs can be found by taking the gasification capacity of 2.15 MW<sub>th</sub> and multiplying by the operating hours per year of 7,728 hrs./yr. This calculation is shown below:

$$\text{Gasification Capacity (MWh)} = \text{Operating Hours} \cdot \text{Gasification Capacity (MW)}$$

$$\text{Gasification Capacity (MWh)} = 7,728 \text{ hrs./yr.} \cdot 2.15 \text{ MW}$$

$$\text{Gasification Capacity (MWh)} = 16,615 \text{ MWh/yr.}$$

The variable operation and maintenance can be found as follows:

$$\text{Variable O\&M Cost} = \text{Gasification Capacity (MWh)} \cdot \$3.70/\text{MWh}$$

$$\text{Variable O\&M Cost} = 16,616 \text{ MWh/yr.} \cdot \$3.70/\text{MWh}$$

$$\text{Variable O\&M Cost} = \$61,476/yr.$$

The total operating costs can be found by adding the variable and fixed operating costs together. This is shown as follows:

$$\textit{Total O\&M Cost} = \textit{Variable O\&M Cost} + \textit{Fixed O\&M Cost}$$

$$\textit{Total O\&M Cost} = \$61,476 + \$154,800$$

$$\textit{Total O\&M Cost} = \$216,276/\textit{yr}.$$

The total cost savings can be found by subtracting the total operation and maintenance cost from the energy cost savings. This is shown in the following calculation:

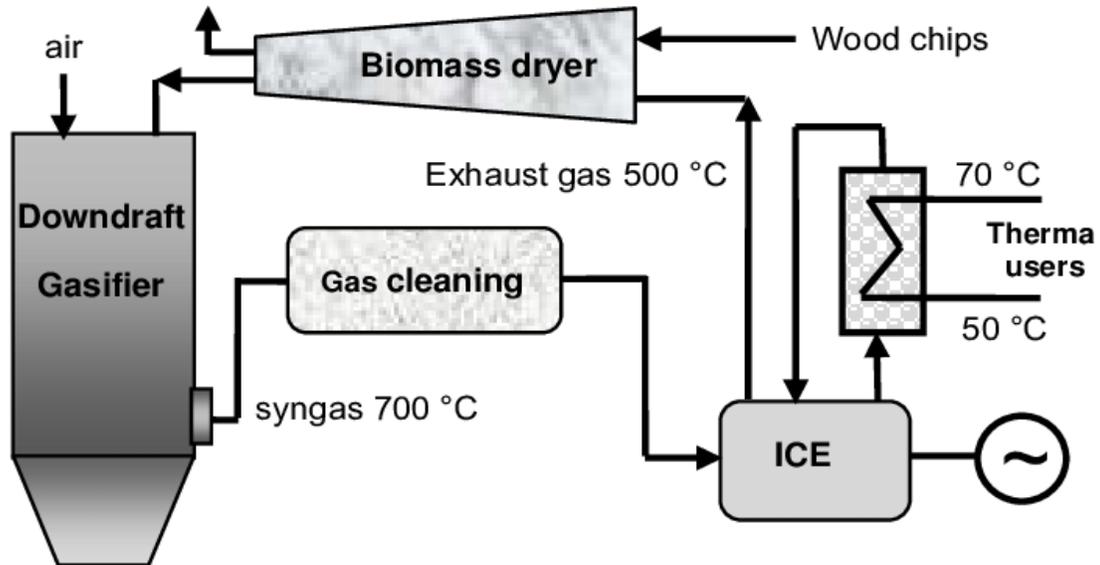
$$\textit{Total Cost Savings} = \textit{Total Energy Cost Savings} - \textit{Total O\&M Cost}$$

$$\textit{Total Cost Savings} = \$401,753/\textit{yr}. - \$216,276/\textit{yr}.$$

$$\textit{Total Cost Savings} = \$185,530/\textit{yr}.$$

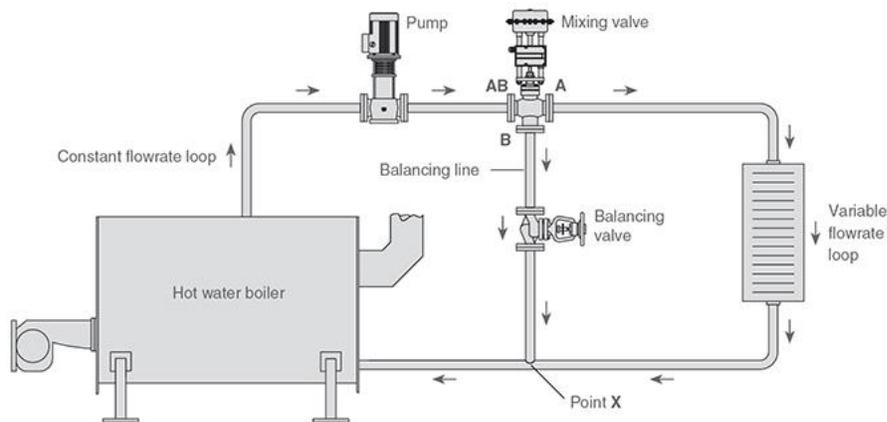
Since there is no waste disposal cost, there is no waste disposal cost savings from installing this system. The electricity cost of a gasification system is also described in the IEA's Biomass for Power Generation and CHP is \$0.11/kWh [74]. This is above the retail rate for electricity at the facility of \$0.06/kWh making the power purchase agreement a less attractive option. Based on review of the companies that specialize in gasification there are two main ways to convert the wood waste into electricity. The first is with small modular packaged gasification units that can be combined and scaled to meet processing needs. These systems would have individual gasification, cleaning, and engine modules packaged in a shipping container style containment. These systems are highly developed and commercially viable as each individual system is practically identical. The second is to use one large gasification system that can process the full amount of waste generated by the facility. These systems will have larger gasification and engine units that typically need to be designed and engineered to meet the specific needs of the facility. The benefit of using packaged gasification CHP units is that a

small pilot scale system can be installed to determine the feasibility of a larger scaled system [76]. Figure 30 shows what a typical biomass gasification system would look like.



**Figure 30: Gasification CHP System [77]**

The heat exchanger on the exhaust of the reciprocating engine would connect to hot water piping that travel to facilities existing hot water loop. It is estimated that about one mile (5,280 ft) of piping is needed to connect the gasification system to the existing hot water loop. Figure 31 shows a simplified diagram of the existing hot water loop.



**Figure 31: Hot Water System [78]**

The subject facility looked into a gasification system with a company called Arensis and worked towards installing a pilot scale system before the company went bankrupt. The proposed final system would have consisted of 11 packaged gasification units providing 50 kW of electricity for a total installed capacity of 550 kW. Figure 32 and Figure 33 show the location and proposed system overview for this system.

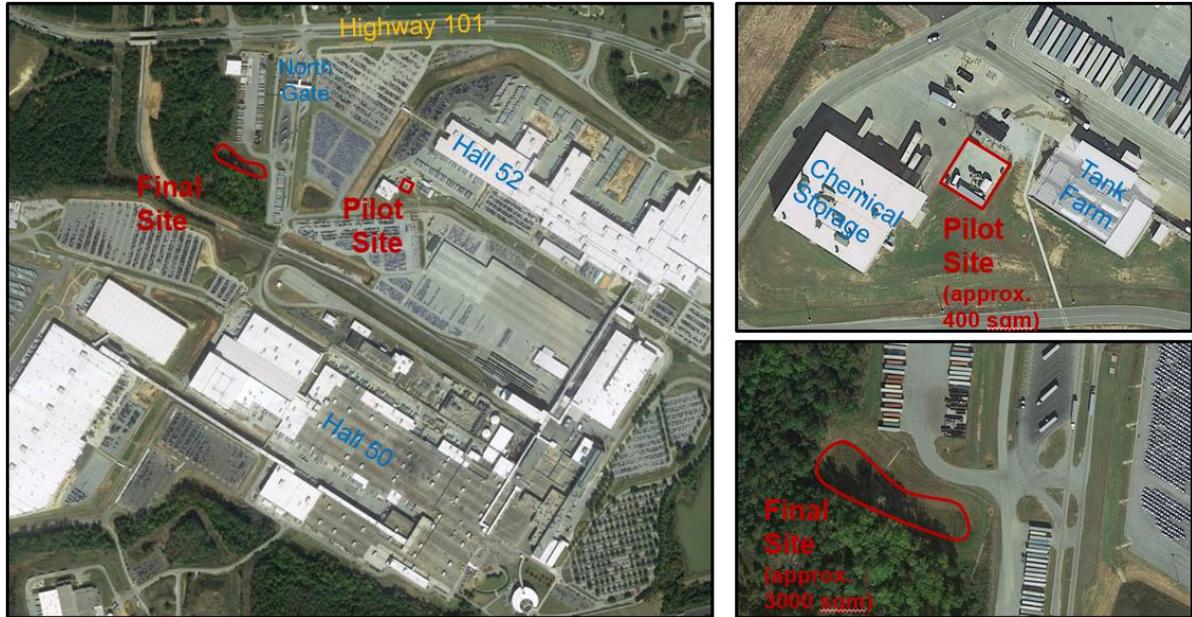


Figure 32: Location Overview [79]



Where  $Q$  is the utilized waste heat from the CHP engine exhaust,  $\dot{m}$  is the mass flow rate of the water flowing through the pipe,  $c_p$  is the specific heat capacity of water, and  $\Delta T$  is the temperature difference between the hot water supply and return temperatures. The volume flow rate is found by setting the mass flow rate equal to the volume flow rate times the density of water,  $\rho$ . This yields the following:

$$\dot{V} = \frac{Q}{\rho c_p \Delta T}$$

With the heat rate found earlier to be 2.36 MMBtu/hr, the density of water at 60 lb/ft<sup>3</sup> for water at a temperature of 200°F [80] and the specific heat of water at 1 Btu/lb-°F, and assuming a  $\Delta T$  of 20°F [13], the volume flow rate can be calculated:

$$\begin{aligned} \dot{V} \left( \frac{ft^3}{hr.} \right) &= \frac{2.36 \text{ MMBtu/hr.}}{\left( 60 \frac{lb}{ft^3} \right) \left( 1 \frac{Btu}{lb - ^\circ F} \right) (20^\circ F)} \\ \dot{V} \left( \frac{ft^3}{hr.} \right) &= 1,970 \frac{ft^3}{hr.} \\ \dot{V} \left( \frac{ft^3}{sec} \right) &= 1,970 \frac{ft^3}{hr.} \cdot \frac{1 \text{ hour}}{60 \text{ minutes}} \cdot \frac{1 \text{ minute}}{60 \text{ seconds}} \\ \dot{V} \left( \frac{ft^3}{sec} \right) &= 0.547 \frac{ft^3}{sec} \end{aligned}$$

The volume flow rate and the cross-sectional area of the pipe can be related using the following equation:

$$\dot{V} = Av$$

Where  $A$  is the cross-sectional area of the pipe and  $v$  is the water velocity. Assuming a standard design water velocity of 5 ft/sec in the pipe, the cross sectional area is found as follows:

$$A = \frac{\dot{V}}{v}$$

$$A = \frac{0.547 \frac{ft^3}{sec}}{5 \frac{ft}{sec}}$$

$$A = 0.109 ft^2$$

The diameter of the pipe is found using the following equation:

$$A = \frac{\pi d^2}{4}$$

$$d = \sqrt{\frac{4A}{\pi}}$$

$$d (ft) = 0.373 ft$$

$$d (in.) = 4.48 in.$$

The pipe diameter is found to be 4.48 inches, however, since piping is specified in whole numbers, this rounded up to the nearest size. A pipe diameter of 5 inches is used to keep calculations conservative. Utilizing RS Means Mechanical Cost Data 2015 which estimates the cost of material, labor, and equipment for installing equipment, a 5 in. Schedule 40, steel pipe would cost \$166/ft [81]. The total cost of installing this piping can be determined by multiplying the cost of pipe per foot times the total distance of the piping. Estimating that one mile of piping is needed (5,280 ft) the total cost of installing the piping can be found as follows:

$$\textit{Piping Cost} = \textit{Unit Piping Cost} \cdot \textit{Piping Length}$$

$$\textit{Piping Cost} = \$166/ft \cdot 5,280 ft$$

$$\textit{Piping Cost} = \$877,235$$

Combining this with the capital cost of the gasification system yields the total installed cost of the project. This is shown in the following calculation:

$$\textit{Total Installed Cost} = \textit{Gasification Capital Cost} + \textit{Piping Cost}$$

$$\text{Total Installed Cost} = \$2,580,000 + \$877,235$$

$$\text{Total Installed Cost} = \$3,456,600$$

The operating cost of the pump must also be determined. This can be found by first determining the pump work with the following equation [13]:

$$\text{Work (hp)} = \frac{\frac{\rho g}{g_c} H \dot{V}}{550\eta}$$

Where H is the head loss in ft.,  $\eta$  is the pump efficiency (assumed to be 80% [13], and  $\dot{V}$  is the volume flow rate of the water for the specified pipe diameter of 5 inches. The diameter of the pipe in feet is 0.417 ft. The head loss is found via the following Darcy equation [82]:

$$H = \frac{V^2}{2g} \left( \frac{fL}{D} \right)$$

Where V is the water velocity, L is the pipe length, and D is the pipe diameter, and f is the Darcy friction factor which is a function of the Reynolds number  $Re_d$ , relative roughness  $\varepsilon/D$ .

The friction factor can be found with the following relationship [82]:

$$\frac{1}{f^{1/2}} \approx -1.8 \log \left[ \frac{6.9}{Re_d} + \left( \frac{\varepsilon/D}{3.7} \right)^{1.11} \right]$$

Where  $\varepsilon$  is the absolute roughness of a pipe material measured in ft. For a commercial steel pipe, this value is 0.00015 ft. The Reynolds number,  $Re_d$ , can be found with the following equation:

$$Re_d = \frac{VD}{\nu}$$

Where V is the water velocity and  $\nu$  is the kinematic viscosity of water found to be  $3.371 \times 10^{-6}$  ft/sec<sup>2</sup>. The velocity of water in the 5 inch pipe can be found with the following equation:

$$V = \frac{\dot{V}}{A}$$

$$V = \frac{4\dot{V}}{\pi D^2}$$

$$V = \frac{4 \left( 0.547 \frac{ft^3}{sec} \right)}{\pi (0.417 ft)^2}$$

$$V = 4.01 \frac{ft}{sec}$$

With a water velocity of 4.01 ft/sec and a pipe diameter of 0.417 ft, the Reynolds number can be found as follows:

$$Re_d = \frac{4.01 \frac{ft}{sec} \cdot 0.417 ft}{0.000003371 \frac{ft^2}{sec}}$$

$$Re_d = 496,003$$

With the Reynolds number found, the friction factor can be determined:

$$\frac{1}{f^{1/2}} \approx -1.8 \log \left[ \frac{6.9}{496,003} + \left( \frac{0.00015/0.417}{3.7} \right)^{1.11} \right]$$

$$\frac{1}{f^{1/2}} \approx -1.8 \log [1.39 \times 10^{-5} + 3.52 \times 10^{-5}]$$

$$\frac{1}{f^{1/2}} \approx -1.8 \log [4.91 \times 10^{-5}]$$

$$\frac{1}{f^{1/2}} \approx 7.75$$

$$f = \left( \frac{1}{7.75} \right)^2$$

$$f = 0.016$$

With the friction factor found, the head loss through the pipe can be determined with the following equation:

$$H = \frac{(4.01 \text{ ft/sec})^2}{2 \left(32.2 \frac{\text{ft}}{\text{sec}^2}\right)} \left(\frac{0.016 \cdot 5,280 \text{ ft}}{0.417 \text{ ft}}\right)$$

$$H = 53 \text{ ft}$$

Including the head loss of two heat exchangers estimated to be 25 ft each, the overall head loss in the system is determined to be 103 ft. With the head loss through the pipe and heat exchangers found, the work required to overcome this loss can be determined:

$$\text{Work (hp)} = \frac{60 \frac{\text{lb}}{\text{ft}^3} \cdot 103 \text{ ft} \cdot 0.595 \frac{\text{ft}^3}{\text{sec}}}{550 \cdot 80\%}$$

$$\text{Work (hp)} = 7.66 \text{ hp}$$

To determine the cost to run this pump, the work will have to be converted from hp to kW. This is shown in the following equation:

$$\text{Work (kW)} = \text{Work (hp)} \cdot \frac{0.746 \text{ kW}}{\text{hp}}$$

$$\text{Work (kW)} = 7.66 \text{ hp} \cdot \frac{0.746 \text{ kW}}{\text{hp}}$$

$$\text{Work (kW)} = 5.72 \text{ kW}$$

The energy cost of running this pump can be found by multiplying the pump power times the operating hours and electricity cost:

$$\text{Pumping Power Cost} = \text{Work (kW)} \cdot \text{Operating Hours} \cdot \$0.06/\text{kWh}$$

$$\text{Pumping Power Cost} = 5.72 \text{ kW} \cdot 7,728 \text{ hrs./yr.} \cdot \$0.06/\text{kWh}$$

$$\text{Pumping Power Cost} = \$2,650/\text{yr.}$$

The pumping power cost will be subtracted from the electricity cost savings to yield the total cost savings:

*Total Cost Savings*

$$= \textit{Total Energy Cost Savings} - \textit{Total O\&M Cost}$$

$$- \textit{Pumping Power Cost}$$

$$\textit{Total Cost Savings} = \$401,753/\textit{yr.} - \$216,276/\textit{yr.} - \$2,650/\textit{yr.}$$

$$\textit{Total Cost Savings} = \$182,880/\textit{yr.}$$

The engineers at the facility are interested in both the payback of a project as well as the internal rate of return to evaluate investment proposals [18]. The payback period is the simplest technique for evaluating capital projects. It is defined as the time period by which an initial investment is recovered in the form of benefits [83]. It is calculated by dividing the initial investment, I, by the yearly net cash flows, C. This is detailed in the following equation:

$$\textit{Payback Period} = \frac{\textit{Total Installed Cost}}{\textit{Total Cost Savings}}$$

For the gasification CHP system, the initial investment is the total installed capital costs found to be \$3,456,600. The yearly net cash flows are the cost savings from installing this system to offset purchasing electricity and natural gas. With a cost savings of \$169,641/yr, the payback period is calculated as follows:

$$\textit{Payback Period} = \frac{\$3,456,600}{\$182,880/\textit{yr.}}$$

$$\textit{Payback Period} = 18.9 \textit{ years}$$

The other technique for evaluating projects involves estimating the profitability of potential investments using the internal rate of return method. The internal rate of return is the discount rate that makes the net present value (NPV) of all cash flows from a particular project equal to

zero [84]. The net present value is the difference between the present value of cash inflows and the present value of cash outflows over a period of time [85]. The formula is shown below:

$$NPV = \sum_{t=0}^n \left( \frac{R_t}{(1+i)^t} \right)$$

Where  $R_t$  is the net cash inflow-outflows during a single period  $t$ ,  $i$  is the discount rate that could be earned in alternative investments, and  $t$  is the number of time periods. Assuming a useful project life of 20 years and a discount rate of 10%, the NPV and IRR can be determined using the NPV and IRR functions in Excel. The results of these calculations are shown below in Table 6:

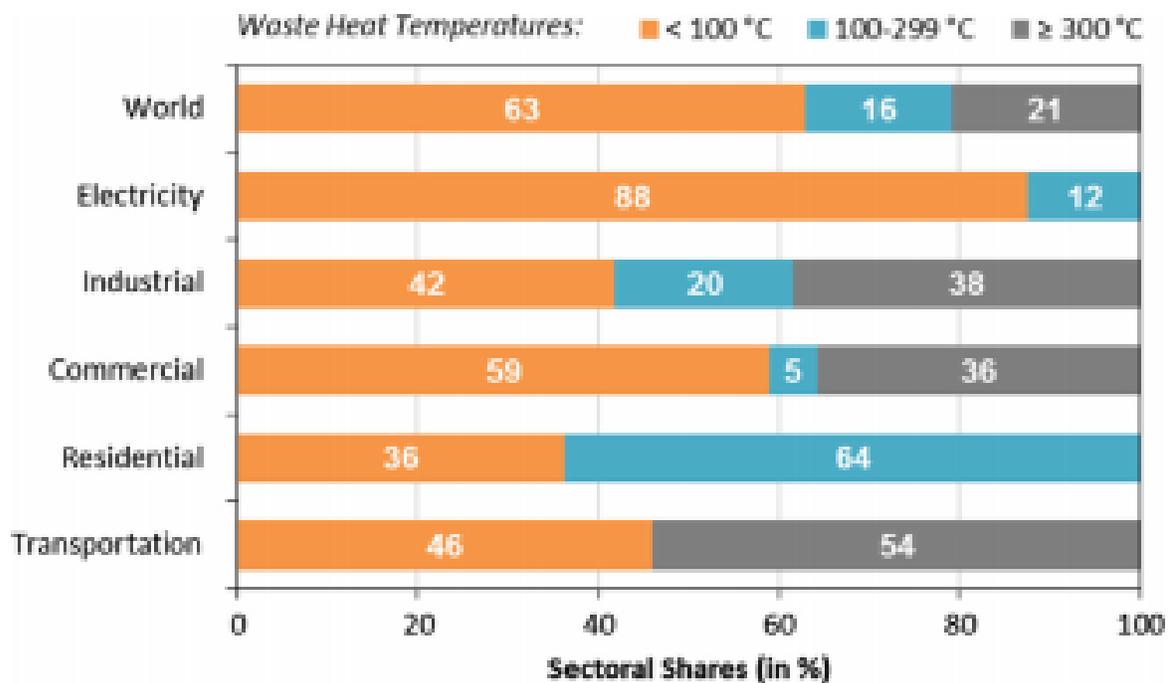
**Table 6: Net Present Value & Internal Rate of Return Calculations**

Time Period	Cash Flows
0	(\$3,456,600)
Years 1-20	\$182,880
Discount Rate	10%
NPV	(\$1,885,998)
IRR	0.54%

The internal rate of return must overcome the hurdle rates that the company has set to justify implementation of a capital project. A hurdle rate is simply the minimum rate of return required by management to justify installation of a capital project [86]. The company has specific hurdle rate of 35% for projects [18], but the IRR of this specific project is only 0.54%.

## CHAPTER 7 – Utilization of Waste Heat for Power Generation

Waste heat can be broken down into three distinct qualities based on the temperature. These qualities are low, medium, and high grade (temperature) waste heat. Thermodynamic cycles are driven by temperature differences between the heat source and heat sink. The higher the temperature of the source, the greater the temperature difference is between the source and sink, thus improving the performance of the system. Therefore, high temperature waste heat is the most beneficial type of waste heat to use followed by medium and low temperature waste heat sources. Figure 34 shows the breakdown of high, medium, and low grade waste heat qualities among the different sectors.



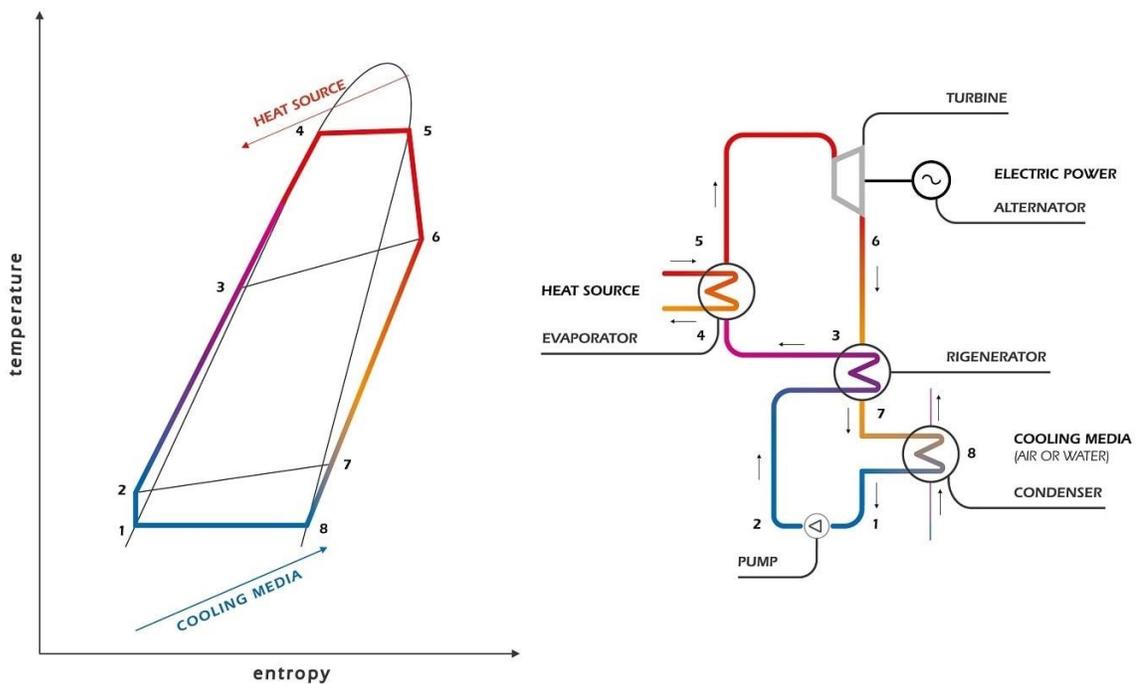
**Figure 34: Sectoral Shares of Waste Heat Distribution [12]**

Low grade waste heat makes up the majority of the world's waste heat at 63% with high grade waste heat following at 21% and medium grade waste heat at 16%. It should be noted that the electricity generation sector has no high grade waste heat. This is because the technology to

capture and reuse this high grade waste heat has already been developed and commercialized. There is a significant need to utilize the low grade waste heat that is currently generated.

## 7.1 - Organic Rankine Cycle

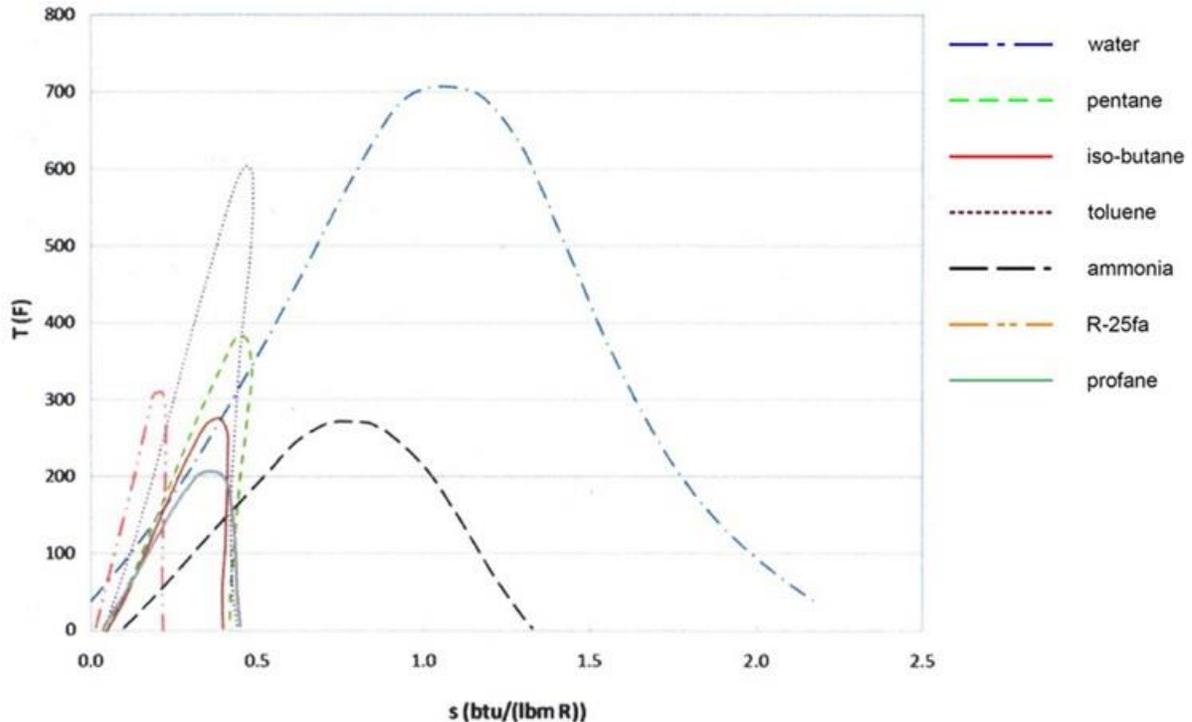
An organic Rankine cycle (ORC) is like a steam Rankine cycle except that it uses organic fluids with low boiling points as working fluids to generate power from low-temperature heat sources [87]. Organic Rankine cycles are the most economical waste heat recovery devices for converting low-grade waste heat to electricity. Low grade waste heat is between 80°F and 400°F [88] and represents 50% or more of the total heat generated in industry [89]. Figure 35 shows what a typical cycle looks like.



**Figure 35: Organic Rankine Cycle Diagram [90]**

The two main advantages of using an organic Rankine cycle are its simplicity and the availability of system components. The working fluid is an organic refrigerant working fluid better suited for low temperature applications than water. Previous studies have focused on the selection of the working fluid, which depends on the application, and showing that the cycle

efficiency is sensitive to the evaporating pressure [89]. Since the selection of the working fluid is dependent on the application, an optimal fluid has not been identified, therefore when designing a system it is important to conduct an in depth study of the various working fluids to find the best one for the application [89]. Figure 36 shows the temperature vs. entropy diagrams for several different working fluids.



**Figure 36: Comparison of Rankine Cycle Working Fluids [91]**

While water is an excellent working fluid for large scale Rankine Cycles with high temperature energy sources, they are not suited to low temperature-low power output applications. This is because the thermodynamic properties of steam lead to multistage, capital intensive turbines as well as complex plant layouts and liquid formation during the expansion [92]. The goal of developing Organic Rankine Cycles is to make it technically feasible and economically attractive to generate power from moderate temperature energy sources, such as biomass, geothermal, and solar energy as well as from industrial waste heat [93]. The criteria for

selecting the proper working fluid involves considering how the chosen fluid will impact the thermodynamic cycle, the performance and cost of components (expander and heat exchangers), the plant layout, and the safety requirements [92]. Many of the working fluids that can be selected for an Organic Rankine cycle are already used in the refrigerating and air-conditioning industries. As such, the guidelines used in these industries can be used for the selection of working fluids for Organic Rankine Cycles. The selected working fluid must meet the following requirements:

- Commercially available at a reasonable specific cost
- Nonflammable
- Nontoxic
- Compatible with materials (lubricating oils, elastomers, metals, etc.)
- Environmentally benign
  - Low Ozone Depletion Potential (ODP)
  - Low Global Warming Potential (GWP)

Unfortunately it is practically impossible to satisfy all of these requirements with an organic fluid suitable for ORC applications [92]. The refrigerating and air-conditioning industries adopted chlorofluorocarbons (CFC's) known as "freons". They were ideal for many applications as they are nonflammable, nontoxic, have a low cost, and good thermodynamic characteristics, but were banned due to their large Ozone Depleting Potential. Afterward, new refrigerants were developed known as hydrofluorocarbons (HFC's) that are nonozone-depleting, nonflammable, recyclable, and had low toxicity. They are used worldwide, but are in the process of being phased out due to their high Global Warming Potential [94]. Another specific requirement for Organic Rankine Cycles is that of thermal stability. This is because

most ORC applications require the working fluid to operate at high temperatures in cyclic conditions, as opposed to application in the refrigerating and air-conditioning industries which operate at much lower temperatures [92]. From a thermodynamic point of view, the ideal working fluid should have:

- Suitable critical point parameters (temperature and pressure) for the application.
- Suitable molecular complexity (number of atoms per molecule) for the application
- and, suitable molecular mass.

Organic Rankine Cycles are made up of four classes of components: (1) the heat exchangers, (2) the expander, (3) the pump, and (4) the generator unit [92]. The heat exchangers are used for the introduction of heat in the primary heat exchanger, the release of heat to the environment in the condenser, and the internal recovery of heat from the hot vapor discharged by the turbine in the recuperator. Because of the low cycle efficiency of ORC's, attention should be made to the design of the heat exchangers. The design must take into account the tradeoffs between increasing and decreasing the surface area of the heat exchange surfaces. Increasing the surface area allows for minimizing the entropy generation and achieving higher performances, but leads to more expensive equipment [92]. The expander is the key component of Organic Rankine Cycles and can vary depending on the size of the plant and the working fluid properties. Expanders can be classified with two categories: (1) turbomachines and (2) volumetric or positive displacement devices. Turbomachines are primarily used in large scale Rankine cycles ranging from 100 kW to 15 MW, while volumetric expanders are used for systems with a power output less than 100 kW. The design of the expander will greatly change based on which working fluid is selected. The pumps used for Organic Rankine Cycles are usually variable speed multistage centrifugal pumps. The generators convert the mechanical

power from the expander into electricity. Additional equipment is necessary to complete the installation of an ORC system. This includes the piping between components, the valves, the bypass connection, and the instrumentation. This equipment can represent between 25-30% of the total installed cost [92]. With a general idea what components are needed to build an Organic Rankine Cycle, the beginning steps of the design process can take place. The key considerations when designing a system include:

- The field of application (solar, geothermal, biomass, waste heat)
- The working fluid
- The cycle configuration
- Reliable thermodynamic and economic optimization

The generic design and optimization process for an Organic Rankine Cycle system consists of three different stages: (1) analysis of the problem, (2) working fluid and cycle configuration selection, and (3) system optimization [92]. A schematic view of this process is shown in Figure 37.

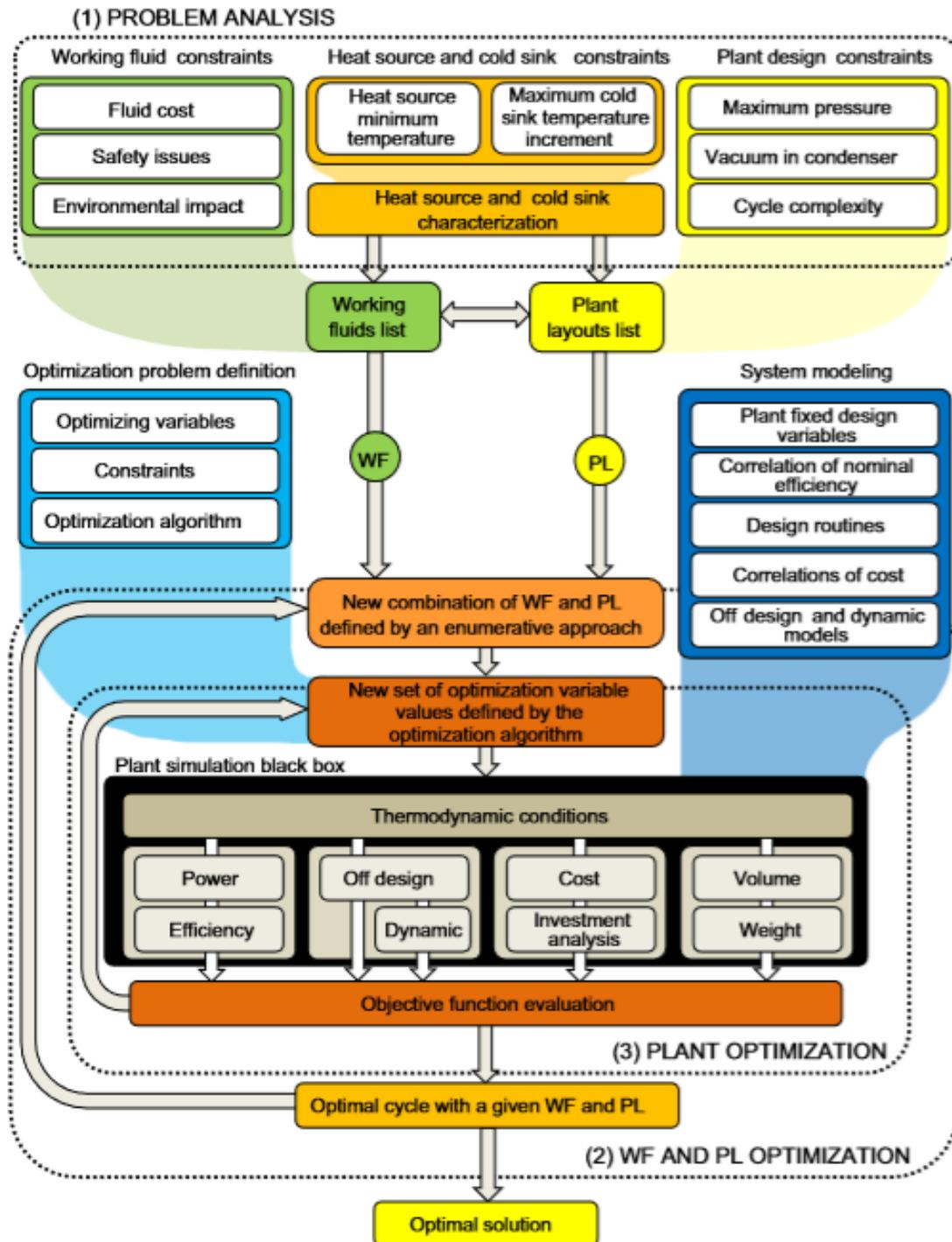


Figure 37: Design and Optimization Process [92]

The problem analysis section involves providing a detailed description of the heat source and heat sink as well as an evaluation of all technical constraints and environmental and safety issues. Technical constraints mainly concern selection of the layout and components, whereas

environmental and safety issues concern the selection of the working fluid. The heat source can be either a liquid or gaseous stream available at a temperature higher than the ambient temperature. A heat-transfer fluid loop is used to transport the heat from the source to the ORC system. This is to avoid hot spots that can cause fluid decomposition. The important parameters to know are: (1) the mass flow rate of the heat source, (2) the heat capacity as a function of temperature, (3) the maximum temperature, and (4) the presence of additional constraints on the minimum temperature of the heat source. Depending on the installation site, the heat sink can be either air or water. The important considerations are (1) the heat sink temperature, (2) the heat capacity, and (3) constraints in the maximum temperature increase due to environmental protection regulations [92]. The most important stage when designing an Organic Rankine Cycle is choosing the correct working fluid and cycle configuration. Working fluids can be selected from various chemical classes such as hydrocarbons (alkanes, alkenes, etc.), refrigerant fluids (partially fluorinated and perfluorinated compounds), and siloxanes. Limiting the choice to well known fluids, the number is around 100 [92]. The thermal stability of the working fluid is an important property to consider as organic fluids tend to decompose around 660°F to 750°F. It is necessary to have the thermodynamic and transport properties of the working fluid, as these properties are needed when analyzing the fundamental cycle, designing the heat exchangers and working components, and detailed dynamic modeling of the expansion device. Without accurate models for the properties, the design process cannot proceed [92]. The cost of the working fluid is an important thing to consider as it can reach 10% of the total installed cost [92].

## 7.2 - Analysis of Reciprocating Engine with ORC

While the economics of a biomass gasification system coupled with a reciprocating internal combustion engine did not prove feasible, there may be an opportunity to improve it by including an organic Rankine cycle after the combustion engine instead of piping the hot water to the facility. Most of the waste heat is available in the engine exhaust and jacket coolant with smaller amounts recovered from the lube oil cooler and the turbocharger's intercooler and after cooler (if so equipped). Heat in the engine jacket coolant accounts for up to 30 percent of the energy input and is capable of producing temperatures between 190 and 230°F. Engine exhaust heat represents 30 to 50 percent of the available waste heat with temperatures ranging from 720 to 1000°F [28]. Since the waste heat from the exhaust has a higher temperature, it will have a higher efficiency when compared to recovering heat from the jacket coolant [95]. As was discussed earlier, a key decision to make when discussing Organic Rankine Cycles was selecting the working fluid. Zou et al. analyzed three different cycle configurations with ten different working fluids. The cycle configurations are 1) recovering exhaust gas waste heat from the engine, 2) recovering exhaust gas and jacket coolant waste heat from the engine with the jacket coolant preheating the working fluid, and 3) recovering waste heat from a specific jacket cooling water circuit which includes a splitter and an exhaust gas heat exchanger. The working fluids studied were: R134a, R245fa, R245ca, R123, pentane, isohexane, hexane, cyclohexane, benzene, and toluene. The working fluids which have high critical temperature such as benzene, cyclohexane, and toluene are more suitable for cycle configurations which only recover exhaust gas waste heat. The working fluid which have low critical temperatures and low evaporating temperatures such as R134a are more suitable for the cycle configuration which uses jacket cooling water to preheat the working fluid. The working fluids which have

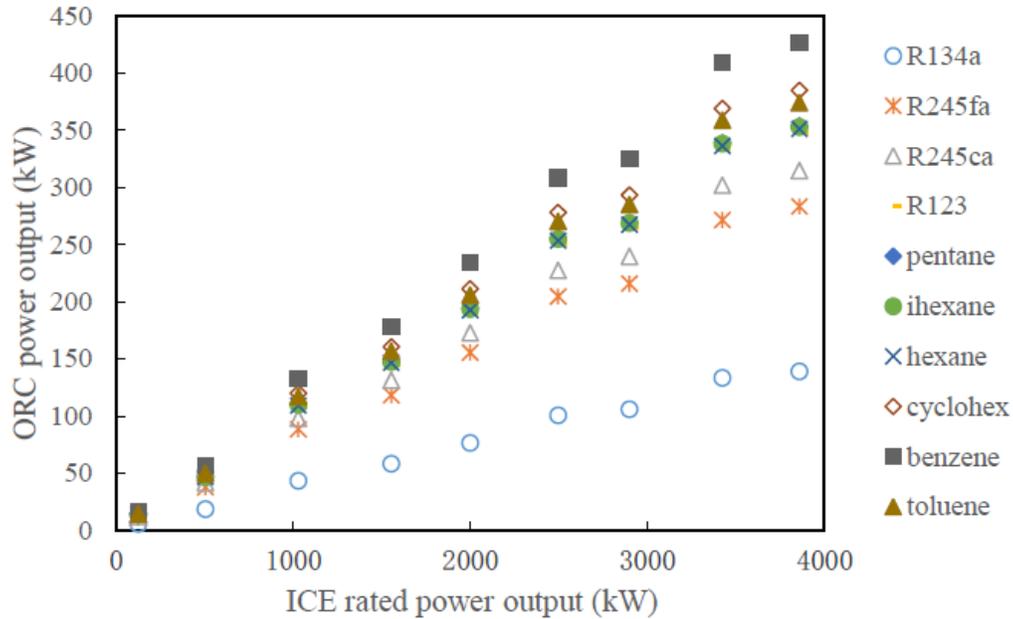
moderate critical temperature and evaporating temperatures such as R245fa, 245ca, R123, pentane, isohexane, and hexane are more suitable for cycle configurations with a specific jacket cooling water circuit including a splitter and exhaust gas heat exchanger system. [95]. With the results of this study coupled with the fact that exhaust gas waste temperatures yield higher cycle efficiencies, it was determined to analyze a system that utilizes the waste heat from the exhaust gas only. The decision now lies with determining the appropriate working fluid from the fluids determined in the study to be appropriate. These fluids are benzene, cyclohexane, and toluene. Since the performance characteristics of these fluids do not vary significantly between fluids, the deciding factor will be the impact on the environment as well as health and human safety. This information is shown in

Table 7 below:

**Table 7: Working Fluid Properties [95]**

Name	T <sub>cri</sub> (K)	P <sub>cri</sub> (kPa)	ODP	GWP (100 yr.)	ASHRAE 34 Safety Group
cyclohexane	553	4,075	0	Very Low	A3
benzene	561	4,894	0	Low	N/A
toluene	591	4,126	0	3.3	N/A

From the table it is clear that benzene is the most suitable fluid because it fulfills the environmental and safety requirements more so than cyclohexane and toluene. With the working fluid selected, the system can be analyzed effectively. The first step is estimating the power output of a system recovering exhaust gas waste heat from the reciprocating engine. This can be done by looking at the power outputs of the system from the study discussed previously. The results are shown in Figure 38 below:



**Figure 38: ORC Power Outputs of ICE Heat Recovery with Ten Working Fluids [95]**

The engine size selected in the previous chapter had a rated power output of 645 kW. To estimate the amount of power output expected by the Organic Rankine Cycle, it is necessary to interpolate between two points on the graph. The two points in question are the second and third points with values of roughly (500 kW, 50 kW) and (1,000 kW, 140 kW) for benzene.

The line between the two points can be determined via the rise over run method:

$$\text{Slope} = m = \frac{\text{Rise}}{\text{Run}} = \frac{140 - 50}{1,000 - 500} = \frac{90}{500} = 0.18$$

By plugging in values to the following equation, a line predicting the performance of an organic Rankine cycle can be created:

$$y = 0.18 * x + b$$

$$50 = 0.18 * (500) + b$$

$$b = -40$$

$$y = 0.18 * x - 40$$

$$y = 0.18 * (645) - 40 = 76 \text{ kW}$$

By interpolating between the second and third points for benzene it can be determined that an Organic Rankine Cycle will have an estimated power output of 76 kW based on an engine power output of 645 kW. While benzene is arguably the best candidate to use for this application, a pressure enthalpy diagram is not readily available to conduct an analysis, therefore a different working fluid can illustrate the principles. Of the remaining working fluids, only halocarbon refrigerants are available minus R245ca: R123, R134a, and R245fa. Table 8 shows a comparison of these refrigerants:

**Table 8: Halocarbon Refrigerant Properties [95]**

Name	T <sub>cri</sub> (K)	P <sub>cri</sub> (kPa)	ODP	GWP (100 yr.)	ASHRAE 34 Safety Group
R123	456.68	3,662	0.012	120	B1
R134a	374.06	4,059	0	1300	A1
R245fa	427.01	3,651	0	950	B1

While R123 has a high critical temperature and low GWP, it has an ozone depleting potential (ODP), which automatically excludes it from being considered. R134a has a high GWP and a low critical temperature when compared to R245fa, therefore, R245fa was selected as the working fluid. Figure 38 can be used to find the estimated power output of an ORC with R245fa as the working fluid.

$$\text{Slope} = m = \frac{\text{Rise}}{\text{Run}} = \frac{90 - 40}{1,000 - 500} = \frac{50}{500} = 0.1$$

By plugging in values to the following equation, a line predicting the performance of an organic Rankine cycle can be created:

$$y = 0.1 * x + b$$

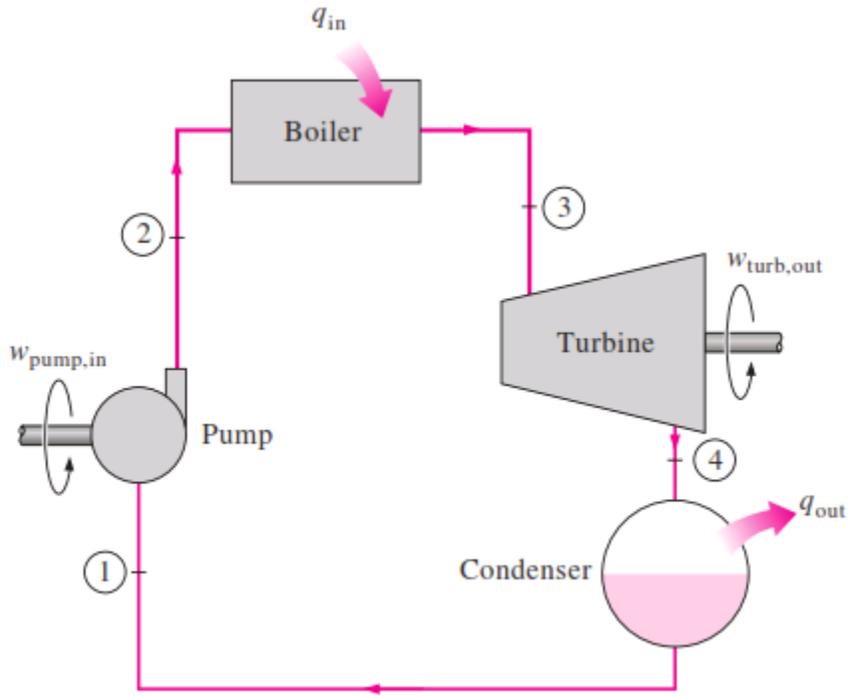
$$40 = 0.1 * (500) + b$$

$$b = -10$$

$$y = 0.1 * x - 10$$

$$y = 0.1 * (645) - 10 = 54.5 \text{ kW}$$

A cycle can be constructed and analyzed using the pressure enthalpy diagram for R245fa to confirm this power output. The pressure enthalpy diagram used was found in the 2013 ASHRAE Handbook: Fundamentals I-P Edition. This can be found in the appendix. Figure 39 is used to show the cycle and various states.



**Figure 39: Rankine Cycle Diagram [96]**

Starting at the inlet to the pump, it is estimated that the saturation temperature at state 1 will be between 100°F and 120°F. Choosing a temperature of 110°F gives a pressure of 40psia. The enthalpy at this state is 46 Btu/lbm. It is estimated that the saturation temperature will be 280°F in the boiler. This means that the pump will increase the pressure to 400 psia with the entropy and temperature staying roughly the same before being heated in the boiler. The enthalpy will increase slightly due to the work of the pump and can be found by adding the work of the pump

to the enthalpy at state 1. The work supplied to the pump can be found via the following equation:

$$w_{pump,in} = v(P_2 - P_1)$$

Where  $v$  is the specific volume of the fluid and is the inverse of the fluid's density. The fluid's density at this state is  $86.5 \text{ lb/ft}^3$ . The work of the pump can be found as follows:

$$w_{pump,in} = \frac{1}{86.5 \frac{\text{lbm}}{\text{ft}^3}} \left( 400 \frac{\text{lb}}{\text{in}^2} - 40 \frac{\text{lb}}{\text{in}^2} \right)$$

$$w_{pump,in} = 4.16 \frac{\text{ft}^3}{\text{lbm}} \left( \frac{\text{lb}}{\text{in}^2} \right) \left( \frac{144 \text{ in}^2}{\text{ft}^2} \right) \left( 1.285 \times 10^{-3} \frac{\text{Btu}}{\text{ft} - \text{lb}} \right)$$

$$w_{pump,in} = 0.77 \frac{\text{Btu}}{\text{lbm}}$$

The enthalpy of state 2 can be found by adding the enthalpy of state 1 to the work of the pump as shown in the following equation:

$$h_{2s} = h_1 + w_{pump,in}$$

$$h_{2s} = 46 \frac{\text{Btu}}{\text{lbm}} + 0.77 \frac{\text{Btu}}{\text{lbm}} = 46.77$$

The efficiency of the pump must also be taken into consideration. Assuming an isentropic pump efficiency of 85% the actual enthalpy of state 2 can be found with the following equation:

$$h_{2a} = \frac{h_{2s} - h_1}{\eta_{pump}} + h_1$$

$$h_{2a} = \frac{46.77 - 46}{85\%} + 46 = 46.91$$

The work of the pump is then found to be  $0.91 \text{ Btu/lbm}$ . State 3 can be determined by following the pressure line for state 2 over to a designated temperature. Since the critical temperature of R245fa is around  $310^\circ\text{F}$ , a saturation temperature of  $280^\circ\text{F}$  was chosen. Since the waste heat

source is around 890°F, it can be expected that the temperature of the superheated vapor will increase to 400°F. The enthalpy at state 3 is found to be 190 Btu/lbm. The heat supplied to the system can be determined via the following equation:

$$q_{in} = h_3 - h_{2a}$$

$$q_{in} = 190 \frac{\text{Btu}}{\text{lbm}} - 46.91 \frac{\text{Btu}}{\text{lbm}} = 143 \frac{\text{Btu}}{\text{lbm}}$$

State 4 can be determined by following a line of equal entropy from state 3 down to the pressure for state 1. The enthalpy at this intersection is found to be 165 Btu/lbm. Assuming an isentropic turbine efficiency of 75% the actual enthalpy at state 4 can be determined with the following equation:

$$h_{4a} = h_3 - \eta_{turbine}(h_3 - h_{4s})$$

$$h_{4a} = 190 \frac{\text{Btu}}{\text{lbm}} - 75\% \left( 190 \frac{\text{Btu}}{\text{lbm}} - 165 \frac{\text{Btu}}{\text{lbm}} \right) = 171.25 \frac{\text{Btu}}{\text{lbm}}$$

Table 9 shows the properties of R245fa for each state.

**Table 9: States of R245fa in ORC System**

State	Pressure (psia)	Temperature (°F)	Enthalpy (Btu/lbm)
1	40	110	46
2	400	110	46.91
3	400	400	190
4	40	240	171.25

With all the states found the work of the turbine and the heat rejected from the system can be found. The turbine work can be found with the following equation:

$$w_{turb,out} = h_3 - h_{4a}$$

$$w_{turb,out} = 190 \frac{\text{Btu}}{\text{lbm}} - 171.25 \frac{\text{Btu}}{\text{lbm}} = 18.75 \frac{\text{Btu}}{\text{lbm}}$$

The rejected heat can be found with the following equation:

$$q_{out} = h_{4a} - h_1$$

$$q_{out} = 171.25 \frac{Btu}{lbm} - 46 \frac{Btu}{lbm} = 125 \frac{Btu}{lbm}$$

The net work of the system can be found by subtracting the pump work from the turbine work.

$$w_{net} = w_{turb,out} - w_{pump,in}$$

$$w_{net} = 18.75 \frac{Btu}{lbm} - 0.91 \frac{Btu}{lbm} = 17.84 \frac{Btu}{lbm}$$

The efficiency of the cycle can be found with the following equation:

$$Efficiency = \frac{w_{net}}{q_{in}}$$

$$Efficiency = \frac{17.84 \frac{Btu}{lbm}}{143 \frac{Btu}{lbm}} = 12.47\%$$

The efficiency of the system can be compared to the Carnot efficiency to determine the highest efficiency that this system can reach. This found by looking at the high and low temperatures in absolute terms. The high temperature is 400°F (859°R) and the low temperature is 110°F (569°R). The Carnot efficiency can then be found in the following equation:

$$\eta_{carnot} = 1 - \frac{T_L}{T_H}$$

$$\eta_{carnot} = 1 - \frac{569^{\circ}R}{859^{\circ}R} = 34\%$$

To compare the estimated net work with the calculated net work, the mass flow rate of the refrigerant needs to be determined. This is dependent on the exhaust gas characteristics of the reciprocating engine. The mass flow rate and the temperature of the exhaust gas were taken from technical data for the GE JMS 320 GS-S.L reciprocating gas engine. Figure 40 shows this engine.



**Figure 40: GE JMS 320 GS-S.L Reciprocating Engine [97]**

The mass flow rate for the engine is 10,500 lbm/hr and the exhaust gas temperature is 887°F. The specific heat of the exhaust gas is the same as the specific heat of air at 0.24 Btu/lbm-°F. It is estimated that the exhaust gas will only be cooled to a temperature higher than the temperature at state 3 of the Organic Rankine Cycle. It is assumed that this exhaust gas outlet temperature is 400°F. With this information, the mass flow rate of the refrigerant can be found. The calculations are shown below:

$$\dot{m}_{\text{refrigerant}} = \frac{\dot{m}_{\text{gas}} c_{p,\text{gas}} (T_{\text{gas,in}} - T_{\text{gas,out}})}{q_{\text{in}}}$$

$$\dot{m}_{\text{refrigerant}} = \frac{10,500 \frac{\text{lbm}}{\text{hr}} \cdot 0.24 \frac{\text{Btu}}{\text{lbm} \cdot ^\circ\text{F}} (887^\circ\text{F} - 400^\circ\text{F})}{143 \frac{\text{Btu}}{\text{lbm}}} = 8,576 \frac{\text{lbm}}{\text{hr}}$$

With the mass flow rate of the refrigerant found, the power output can be compared. This is done with the following equation:

$$W_{\text{net}} = \dot{m}_{\text{refrigerant}} \cdot w_{\text{net}}$$

$$W_{\text{net}} = 8,576 \frac{\text{lbm}}{\text{hr}} \cdot 17.84 \frac{\text{Btu}}{\text{lbm}} = 153,038 \frac{\text{Btu}}{\text{hr}}$$

$$W_{net} = \frac{153,038 \frac{Btu}{hr}}{\frac{3,143 Btu/hr}{kW}} = 48.69 kW$$

The net work of the system is found to be similar to the net work of 48.69 kW found earlier using the Figure 38. The total energy that could be generated by this system can be found with the following equations.

$$\text{Electricity Generated} = P_e \cdot \text{Operating Hours}$$

$$\text{Electricity Generated} = 48.69 kW \cdot 7,728 \frac{hrs.}{yr.}$$

$$\text{Electricity Generated} = 376,290 kWh/yr.$$

The electrical cost savings can be found with the following equation:

$$\text{Electrical Cost Savings} = \text{Electricity Generated} \cdot \$0.06/kWh$$

$$\text{Electrical Cost Savings} = 376,290 kWh/yr. \cdot \$0.06/kWh$$

$$\text{Electrical Cost Savings} = \$22,577/yr.$$

Because installing an Organic Rankine Cycle is an alternative to utilizing the waste heat for process purposes, the economics of an ORC can be compared to the economics of installing a hot water loop from the engine to the energy center.

Reviewing the ICF International's Waste Heat to Power Market Assessment, the capital cost of installing an Organic Rankine Cycle system in the range of 50-500 kW is \$4,500/kW [98]. With an electric generation rate of 48.69 kWe, the calculation to determine the capital cost is shown below:

$$\text{ORC Capital Cost} = \$4,500/kW \cdot 48.69 kW$$

$$\text{ORC Capital Cost} = \$219,113$$

This is only the capital costs for the ORC system itself and does not include the ongoing operating and maintenance costs for the system. The operating and maintenance costs can also be found from the same and are found to be \$0.02/kWh for a system ranging from 50-500 kW [98]. The annual operating and maintenance cost is calculated as follows:

$$ORC\ O\&M\ Cost = 376,290\ kWh \cdot \$0.02/kWh$$

$$ORC\ O\&M\ Cost = \$7,526/yr.$$

The total cost savings can be found by subtracting the total operation and maintenance cost from the energy cost savings. This is shown in the following calculation:

$$Total\ Cost\ Savings = Total\ Energy\ Cost\ Savings - Total\ O\&M\ Cost$$

$$Total\ Cost\ Savings = \$22,577/yr. - \$7,526/yr.$$

$$Total\ Cost\ Savings = \$15,052/yr.$$

Combining the Organic Rankine Cycle with the gasification system yields the following:

$$Capital\ Cost = Gasification\ Capital\ Cost + ORC\ Capital\ Cost$$

$$Capital\ Cost = \$2,579,365 + \$19,113 = \$2,798,478$$

The operating and maintenance costs are as follows:

$$Total\ O\&M\ Cost = Gasification\ O\&M\ costs + ORC\ O\&M\ Costs$$

$$Total\ O\&M\ Cost = \$216,276/yr. + \$7,526/yr. = \$223,749/yr.$$

The total energy costs savings are as follows:

$$Energy\ Cost\ Savings = Gasification\ Energy\ Savings + ORC\ Cost\ Savings$$

$$Energy\ Cost\ Savings = \$299,000/yr. + \$22,577/yr. = \$321,577/yr.$$

The total cost savings are as follows:

$$Total\ Cost\ Savings = Energy\ Cost\ Savings - Total\ O\&M\ Cost\ Savings$$

$$Total\ Cost\ Savings = \$321,577/yr. - \$223,749/yr. = \$97,829/yr.$$

The payback period is as follows:

$$\text{Payback Period} = \frac{\text{Total Installed Cost}}{\text{Total Cost Savings}}$$

$$\text{Payback Period} = \frac{\$2,798,478}{\$97,829/\text{yr.}}$$

$$\text{Payback Period} = 28.6 \text{ years}$$

The NPV and IRR are shown in Table 10 below:

**Table 10: ORC NPV and IRR Calculations**

Time Period	Cash Flows
Year 0	(\$2,806,997)
Years 1-20	\$98,414
Discount Rate	10%
NPV	(\$1,790,132)
IRR	-3.19%

The internal rate of return must overcome the hurdle rates that the company has set to justify implementation of a capital project. A hurdle rate is simply the minimum rate of return required by management to justify installation of a capital project [86]. The company has a specific hurdle rate of 35% for projects [18], but the IRR of this specific project is only -3.19%.

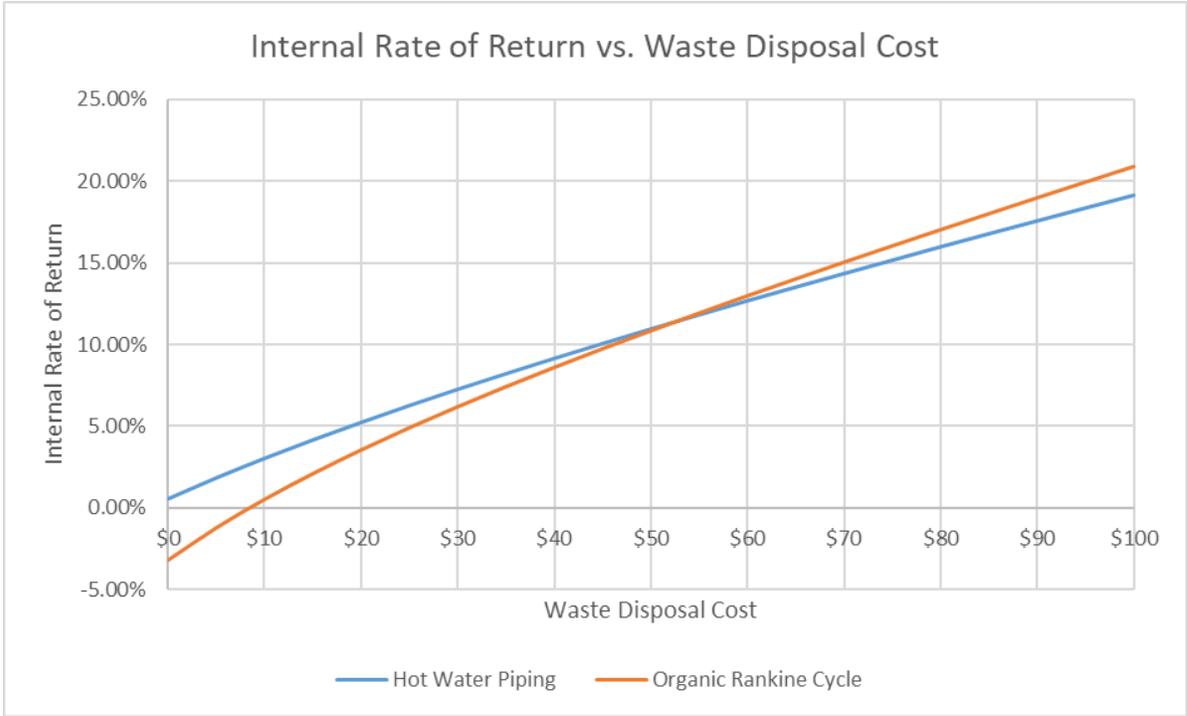
## **CHAPTER 8 – Conclusion & Future Work**

In conclusion, it was determined that the implementation of gasification technology for a combined heat and power application at the automotive assembly facility studied would prove to be infeasible. Although the technological feasibility is there, the economic feasibility falls short. This is due to the electricity, natural gas, and waste disposal costs being too low to justify investment in this project. However, some additional conclusions can be made from this. It can be stated that if this technology were to be investigated in an area that has significantly higher electricity and natural gas costs and the facility in question had a high cost to dispose of their wood waste, then this technology would prove to be feasible. The following tables and figures illustrate how the economics would change when the waste disposal cost and energy costs are increased. Table 11 shows how the economics of the two systems change when the waste disposal costs are increased.

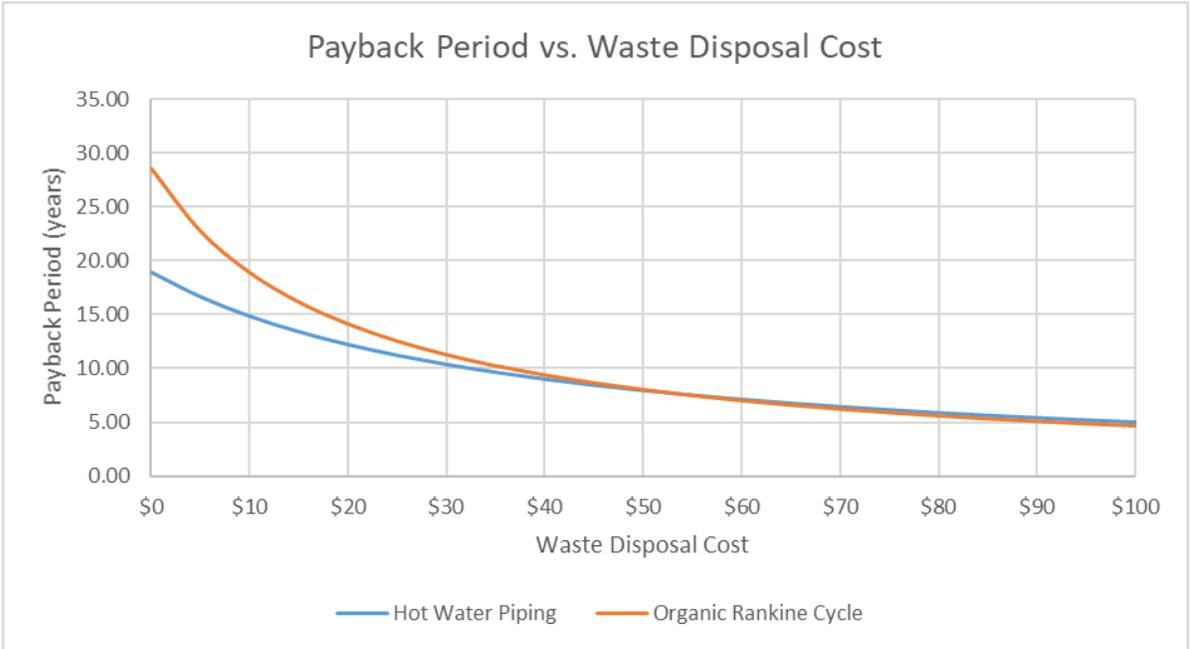
**Table 11: Waste Disposal Cost Variation**

Waste Disposal Cost (\$/ton)	Hot Water Piping		Organic Rankine Cycle	
	IRR	Payback	IRR	Payback
\$0	0.54%	18.90	-3.19%	28.61
\$5	1.83%	16.63	-1.21%	22.78
\$10	3.03%	14.84	0.53%	18.93
\$15	4.16%	13.40	2.10%	16.19
\$20	5.23%	12.22	3.55%	14.15
\$25	6.27%	11.23	4.91%	12.56
\$30	7.26%	10.38	6.19%	11.29
\$35	8.22%	9.66	7.42%	10.26
\$40	9.16%	9.03	8.60%	9.40
\$45	10.07%	8.47	9.74%	8.67
\$50	10.96%	7.99	10.84%	8.05
\$55	11.83%	7.55	11.92%	7.51
\$60	12.69%	7.16	12.98%	7.03
\$65	13.53%	6.81	14.01%	6.62
\$70	14.36%	6.49	15.03%	6.25
\$75	15.18%	6.20	16.03%	5.92
\$80	16.00%	5.93	17.02%	5.62
\$85	16.80%	5.69	18.00%	5.35
\$90	17.59%	5.46	18.97%	5.11
\$95	18.38%	5.25	19.93%	4.89
\$100	19.16%	5.06	20.88%	4.68

Figure 41 and Figure 42 show how the increasing the waste disposal cost increases the internal rate of return and payback period, respectively. The break-even point between the two options is \$52.9/ton. To reach the 35% hurdle rate, the waste disposal cost would have to be \$206/ton for the hot water piping network and \$177/ton for the Organic Rankine Cycle.



**Figure 41: Internal Rate of Return vs. Waste Disposal Cost**



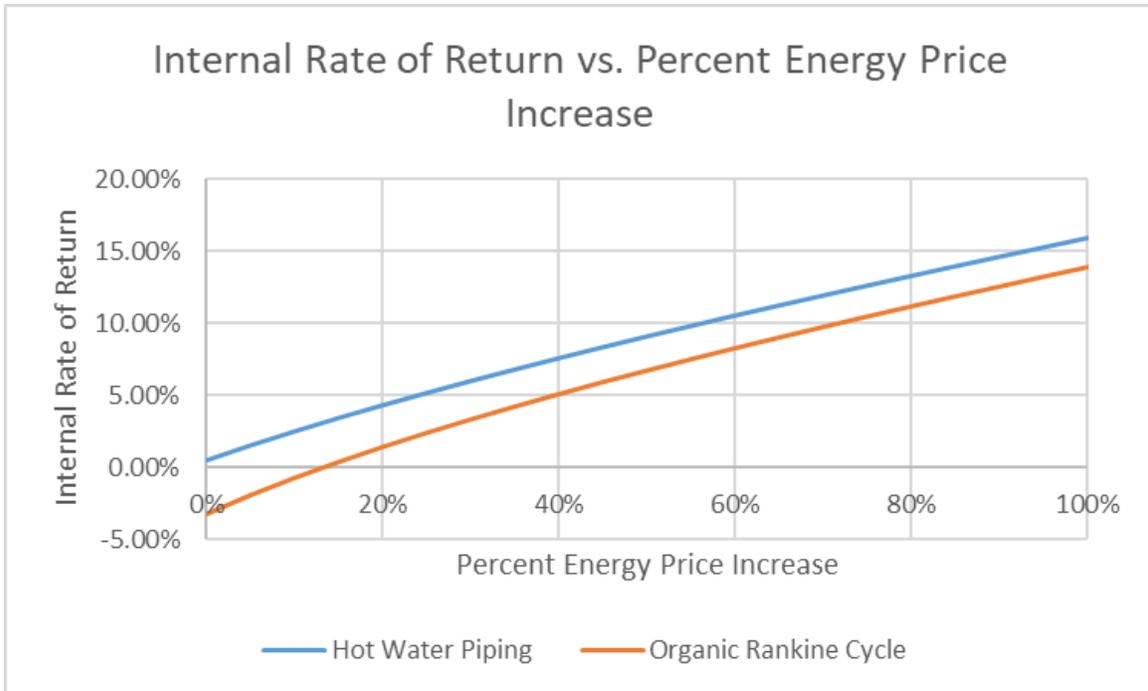
**Figure 42: Payback Period vs. Waste Disposal Cost**

Table 12 shows how increasing the energy prices affects the economics.

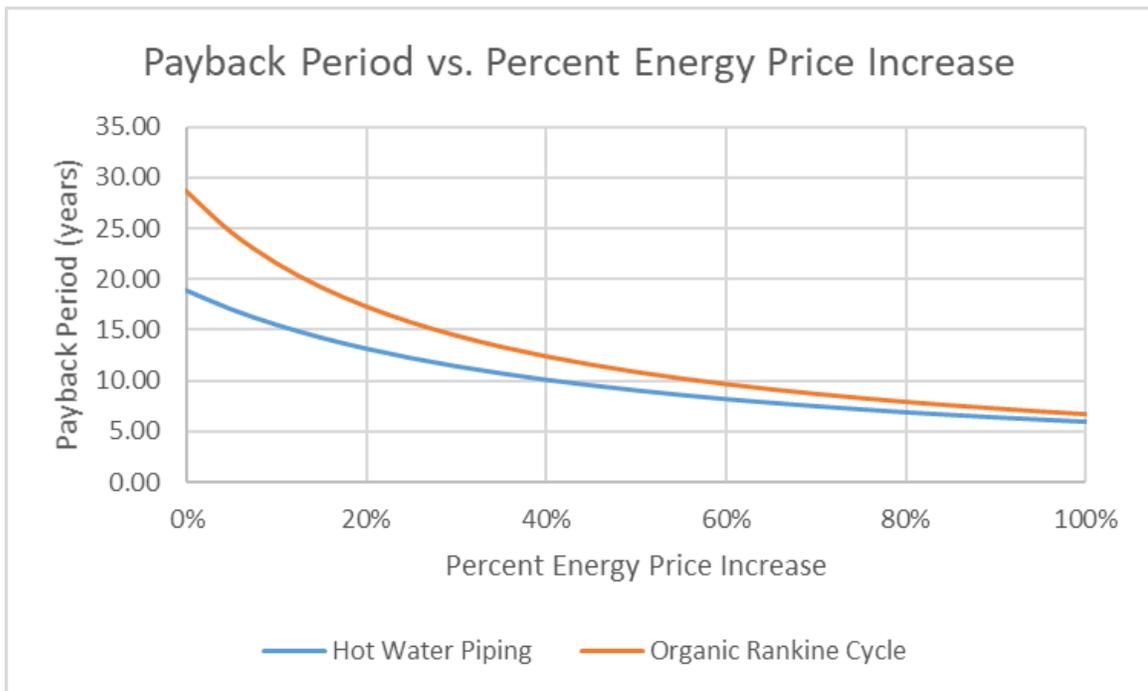
**Table 12: Energy Cost Variation**

Percent Energy Price Increase	Electricity	Natural Gas	Hot Water Piping		Organic Rankine Cycle	
			IRR	Payback Period	IRR	Payback Period
0%	\$0.060	\$4.50	0.54%	18.90	-3.19%	28.61
5%	\$0.063	\$4.73	1.58%	17.04	-1.88%	24.57
10%	\$0.066	\$4.95	2.55%	15.52	-0.69%	21.53
15%	\$0.069	\$5.18	3.48%	14.24	0.41%	19.16
20%	\$0.072	\$5.40	4.37%	13.16	1.45%	17.26
25%	\$0.075	\$5.63	5.22%	12.23	2.42%	15.70
30%	\$0.078	\$5.85	6.05%	11.42	3.35%	14.40
35%	\$0.081	\$6.08	6.85%	10.72	4.24%	13.30
40%	\$0.084	\$6.30	7.63%	10.09	5.10%	12.36
45%	\$0.087	\$6.53	8.40%	9.54	5.93%	11.54
50%	\$0.090	\$6.75	9.14%	9.04	6.73%	10.82
55%	\$0.093	\$6.98	9.87%	8.59	7.51%	10.19
60%	\$0.096	\$7.20	10.59%	8.18	8.27%	9.62
65%	\$0.099	\$7.43	11.29%	7.82	9.01%	9.12
70%	\$0.102	\$7.65	11.98%	7.48	9.74%	8.67
75%	\$0.105	\$7.88	12.67%	7.17	10.46%	8.25
80%	\$0.108	\$8.10	13.34%	6.88	11.16%	7.88
85%	\$0.110	\$8.33	14.01%	6.62	11.85%	7.54
90%	\$0.114	\$8.55	14.67%	6.38	12.53%	7.23
95%	\$0.117	\$8.78	15.32%	6.15	13.21%	6.94
100%	\$0.120	\$9.00	15.97%	5.94	13.87%	6.67

Figure 43 and Figure 44 show the change in rate of return and payback period respectively. There is effectively no break-even point for the two options. To reach the hurdle rate of 35%, the energy prices would have to increase by 258% for the hot water piping network and 275% for the Organic Rankine Cycle.



**Figure 43: Internal Rate of Return vs. Percent Energy Price Increase**



**Figure 44: Payback Period vs. Percent Energy Price Increase**

It can also be extrapolated that looking at any additional energy efficiency or renewable energy projects would yield the same conclusions that the economic would not be in favor of the facility.

This study involved looking at gasifying wood waste for use in a combined heat and power application using a reciprocating engine as the topping cycle while utilizing the waste heat for process purposes or for running an organic Rankine bottoming cycle. Some areas to look at in the future would be gasifying the wood waste and running the gas through the existing gas turbines, utilizing process waste heat to drive an organic Rankine cycle, or running a wood chip boiler steam cycle.

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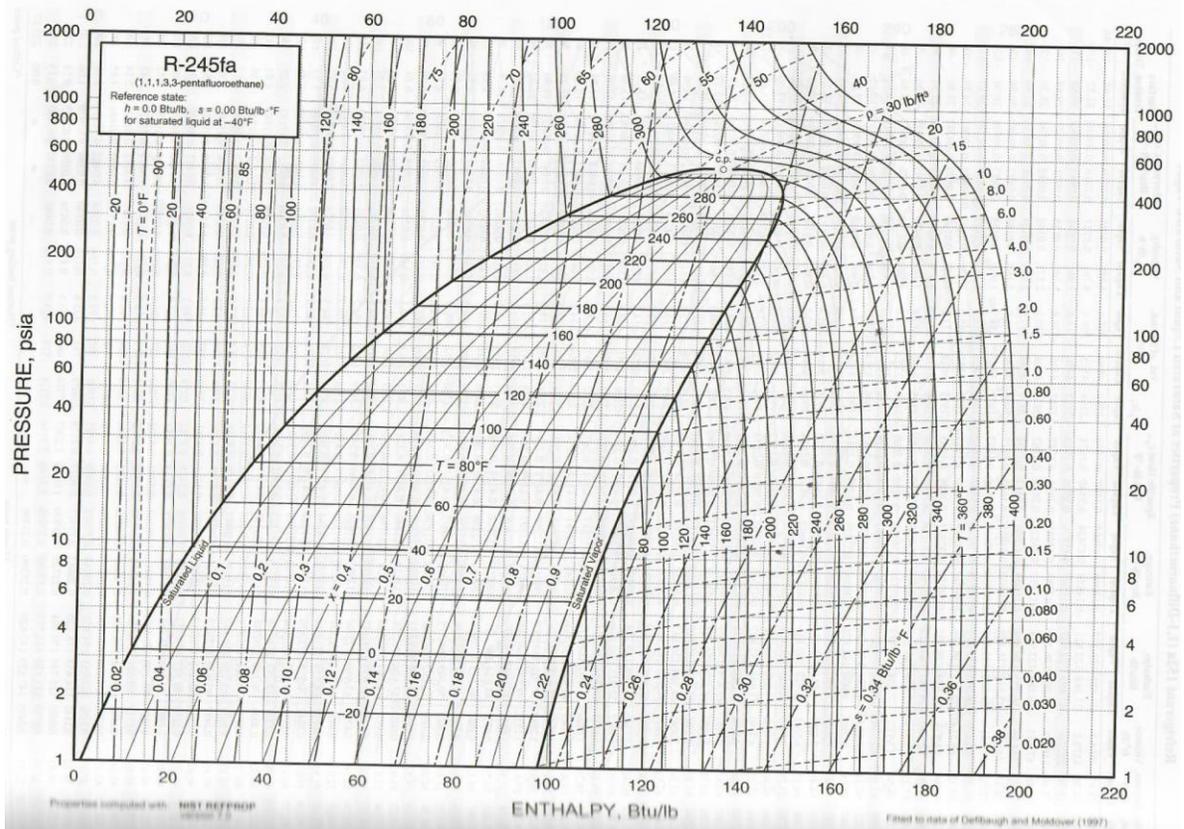
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## APPENDICES

<b>Test Results</b>				
	<b>METHOD</b>	<b>UNITS</b>	<b>MOISTURE FREE</b>	<b>AS RECEIVED</b>
Moisture Total	ASTM E871	wt. %		9.25
Ash	ASTM D1102	wt. %	0.60	0.54
Volatile Matter	ASTM D3175	wt. %		
Fixed Carbon by Difference	ASTM D3172	wt. %		
Sulfur	ASTM D4239	wt. %	0.017	0.015
SO <sub>2</sub>	Calculated	lb/mmbtu		0.037
Net Cal. Value at Const. Pressure	ISO 1928	GJ/tonne		
Net Cal. Value at Const. Pressure	ISO 1928	J/g		
Gross Cal. Value at Const. Vol.	ASTM E711	J/g	20222	18352
Gross Cal. Value at Const. Vol.	ASTM E711	Btu/lb	8894	7890
Carbon	ASTM D5373	wt. %		
Hydrogen*	ASTM D5373	wt. %		
Nitrogen	ASTM D5373	wt. %		
Oxygen*	ASTM D3176	wt. %		
*Note: As received values do not include hydrogen and oxygen in the total moisture.				
Chlorine	ASTM D6721	mg/kg	113	102
Fluorine	ASTM D3761	mg/kg		
Mercury	ASTM D6722	mg/kg	0.009	0.008
Bulk Density	ASTM E873	lbs/ft <sup>3</sup>		
Fines (Less than 1/8")	TPT CH-P-06	wt. %		
Durability Index	Kansas State	PDI		
Sample Above 1.50"	TPT CH-P-06	wt. %		
Maximum Length (Single Pellet)	TPT CH-P-06	inch		
Diameter, Range	TPT CH-P-05	inch		to
Diameter, Average	TPT CH-P-05	inch		
Stated Bag Weight	TPT CH-P-01	lbs		
Actual Bag Weight	TPT CH-P-01	lbs		

**Figure 45: Analytical Test Results of Wood Fuel**



**Figure 46: P-h diagram for R245fa**