ETM
ENGINEERING & TECHNOLOGY MANAGEMENT

Technological Assessment of Emerging Technologies in Conversion of Municipal Solid Waste to Energy

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Abstract

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Abstract

The use of biomass to generate heat, energy, and petroleum substitutes such as bio-oil or bio-crude have showed much promise as a tool for reducing our reliance on imported oil and reducing the world's total carbon output through carbon recycling. This paper is a technology assessment of biomass conversion technologies used at a hypothetical organization Green Tech. This paper outlines the steps on how Green Tech went from defining a problem to performing a gap analysis, defining requirements, identifying selection criteria and finally performing a cost-benefit analysis on three biomass conversion technologies.

1. Introduction

"We can make Oregon the national leader in renewable energy and renewable product manufacturing... Development of renewable energy will lessen our reliance on fossil fuels, protect Oregon's clean air and create jobs." - Governor Kulongoski, 2003[1]

Nothing is more associated with Oregon than its natural resources and how we protect, enjoy and utilize these resources is inextricably connected to the way we generate and supply energy to Oregonians and our economy. Recognizing this, Governor Kulongoski in 2003[1], promoted diversity of renewable energy resources. Because some renewable energy fuels like bio-fuels are freely accessible and are environment friendly, they help stabilize electric rates and reduce our dependence on petroleum/natural gas. Further, investments create jobs, displacing the use of fossil fuel generation and avoiding numerous pollutants and global warming gases.

The use of biomass to generate heat, energy, and petroleum substitutes such as bio-oil or bio-crude have showed much promise as a tool for reducing our reliance on imported oil and reducing the world's total carbon output through carbon recycling. Various combustion and gasification processes have been proven to be effective methods for converting biomass into useful chemical and oil derivatives as well as other carbon products.

For biomass fueled power plants, reliance on forest and agricultural waste means that a continuous supply of fuel may be uncertain. Generation of energy requires large quantities of biomass. It becomes highly important to look for alternate biomass resources and develop a facility to handle multiple biomass fuel types. Municipal solid waste (MSW) is one such product used as a feedstock, which is available abundantly and is cost-competitive with natural gas power generation.

Green Tech, Inc., a renewable energy company, is in the process of expanding its energy generation by including MSW as the feedstock in addition to the homogenous feedstock. Homogenous feedstock comprises of arboricultural activities, yard waste and wood waste. The current technology - conventional fluid bed reactor design however is not designed to accept municipal solid waste (MSW) as the feedstock.

This paper is intended to be an outline of the process that Green Tech used to assess technologies that could be a suitable replacement for it existing process that includes MSW as a heterogeneous feedstock.

2. The Problem

World oil demand is growing substantially faster than production (refinery) capacity. Currently, the U.S. consumes 19.15 million barrels per day of oil, which is more than 25% of the world's total[2]. As a result, it shows that the U.S. produces one fourth of the world's carbon emission, which may be a contributing factor to climate change.

Also, U.S. has spent more than $250 billion annually to import oil [3]. In 2010, it is also estimated that the U.S. imported 10.27 million barrels per day of oil while it produced around 9.69 million barrels of oil per day [4]. As a result, more than 50 per cent of the U.S. oil consumption is imported. By expanding the existing portfolio of energy, the US could be more self-sufficient and provide energy locally.

Burning of fossil fuel has had significant environmental, political, and economical consequences. From environmental aspect, burning fossil fuel generates greenhouse gases (GHG), which consist of carbon dioxide, nitrous oxide, etc. Even though GHGs are beneficial in terms of maintaining earth's temperature, they could be harmful if produced too much. Also governments have to regulate and find the way to control these gases to ensure safety of the people. Economically, people are concerned about fossil fuels. For example, rising of the oil prices in many countries is an obvious reason why people are searching for other alternatives.

Furthermore, Fossil fuel prices are highly volatile. With the conversion from MSW to energy, the energy manufacturers do not have to worry about fluctuating price of fossil fuel since MSW is easily accessible everywhere.

The US spend significant amount of resources disposing of MSW. In 2010, the US spent more than $40 billion dollars to dispose its annual production of 250 million tons of garbage [5]. Also, according to our research, Oregon in particular produced about 2.4M tons in 2008 and disposed 50 percent of its garbage to landfill [6]. However, landfill space in the US is depleting rapidly. The number of operating landfills in the US has declined over the last two decades, falling from 7,924 in 1988 to 1,754 in 2007 [7].

Finally exploring new reserves of fossil fuels has become more risky and costly thus, MSW-to-energy conversion technology could be a solution.

3. Solution:

One solution to this problem is conversion of Biomass into energy products using various processes such as Chemical, Bio-chemical & Thermo chemical conversion process. In this paper, we focus on Municipal Solid Waste (MSW) as a feedstock. The main advantage of biomass conversion is that the conversion process has zero net CO_2 emission [8].

Figure 3-1 – Biomass conversion process [9]

4. Why Biomass?

Biomass is abundant in nature and is freely accessible and can be easily converted into usable energy products in all forms that people need. Thus, help to reduce our dependency on fossil fuel and natural gas. Figure [4-1] shows end products that could be produced by using biomass as a fuel According to a report by Columbia University [10] it shows that almost 90% of total energy consumption comes from fossil fuel and natural gas. Thus, biomass is an excellent alternative for energy production.

Biomass, being a renewable energy source, reduces the costs of operation and maintenance which are major costs of the project other than capital cost. Moreover, renewable energy produces little or no waste products, so it causes little impact on the environment. Finally, renewable energy projects can be economically useful to many areas since it increases the use of local services [11].

By 2008, the U.S. was in second place of the highest-level carbon emission countries, which represents 18.11% of the total[12]. Most scientists believe that wide ranges of biomass resources are beneficial due to its carbon neutral nature.

MSW, a biomass energy source, is easily accessible everywhere and can be directly combusted into energy with minimal processing. The technology presents the opportunity for both electricity production and an alternative to landfilling. Further MSW facilities are paid by the fuel suppliers to take the fuel (known as a "tipping fee").

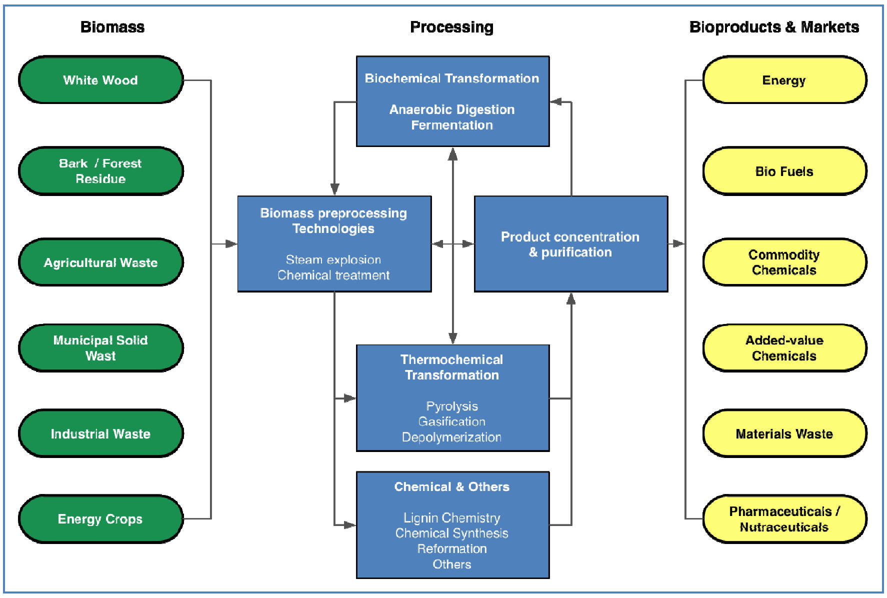

Figure 4-1 - Biomass sources, biomass processes, and bio-products markets [13]

5. Current State / Company Overview

Green Tech Inc. is a renewable energy company generating electricity using homogenous biomass in the Portland metro area. Homogenous feedstock comprises of arboricultural activities, yard waste, processed wood and wood from forest. The plant with a current capacity of 100 ton per day converts the homogenous biomass using conventional fluid bed reactor technology into energy.

Conventional fluid bed reactor is a thermo-chemical conversion process, which provides a medium in which rapid heating of the biomass particle takes place [14]. Adding an inert medium to the bed, the technology provides a controlled fluidized environment and uniform temperature over a wide range of biomass feed rates[14].However Green Tech Inc. is facing certain challenges to use the same technology to process MSW.

- Burning of waste with partial supply of oxygen produces synthetic gas (also called as Syngas), which is mainly composed of carbon monoxide and hydrogen. The gas needs to be cleaned or purified before further processing.
- The process requires upfront processing of feedstock.
- The output is sensitive to input meaning the conventional process rely on high calorific value material
- The current process is not optimized and designed to handle a heterogeneous feedstock like MSW.
- The conventional conversion facility is not self-sustaining. Green Tech cannot use the gases emitted during the process to heat the reactor.
- The current process is very inefficient in term of conversion of energy from waste to electricity.

Thus it is very important for Green Tech to look for a technology that satisfies company's goals and strategy.

6. Future State

Due to a number of problems that the company is currently facing, it needs effective and affordable solution to solve and improve the present operating system. To achieve an optimal MSW-to-energy system, there are a couple of requirements that the company is targeting.

1. The new technology should be easily integrated into the existing system.
2. The adopted technology should be able to process Municipal Solid Waste effectively so as to generate better profits and have additional revenue stream in terms of tipping fees.
3. The selected technology should reduce or eliminate the process of feedstock preparation. By eliminating feedstock preparation process, it saves the company time and cost of operation.
4. The integrated technology should be efficient in terms of enhancing output products. In other words, it should be able to produce several by-products that are marketable such as bio-oil, bio-char, and other chemicals.

The next section illustrates the possible by-products from the considered technologies.

6.1. Bio Oil

Bio-oil is a complex oxygenated compound comprised of water, water-soluble compounds such as acids, esters, and water-insoluble compounds. It is a dark brownish viscous liquid resembling fossil crude oil [15].

Bio-oil can be used as a substitute for fossil fuels to generate heat, power, and chemicals. Boilers and furnaces can be fueled by bio-oil in the short term whereas turbines and diesel engines can be fueled by bio-oil in longer term. Plus, transportation fuels like methanol liquid can be drawn from bio-oil by using the bio-oil as a feedstock instead of the biomass. Furthermore, there is a wide range of chemicals that can be extracted or derived from the bio-oil such as resins, acetic acid, sugars, feedstock chemical industry, etc. [16].

Bio-oil has potential uses as a fuel for production of heat and electricity so it should be marketed to energy industries. It may also have additional higher value as a feedstock for green chemical industries.

6.2. Bio Char

Bio-char is a solid material, which is a by-product of Pyrolysis. It is rich in carbon and can endure in soil for thousands of years.

It can be utilized in two main applications. First, it can store unwanted CO_2 generated by combustion and decomposition of woody biomass and agricultural residue in the soil. As a result, it reduces GHG emissions, which are the cause of climate change. Also, it enhances soil fertility by providing sufficient nutrients for plant growth and water retention. Therefore, Bio-char offers promise for its climate benefits and soil productivity [17].

Based on its capability to absorb $CO_2$and improve soil fertility, the potential market could be from agricultural industries to energy industries.

6.3. Slag

Slag, a by-product of the gasification process, occurs in several forms depending on its cooling process.

Air-cooled slag which is a black glassy rock can be processed into bricks, synthetic gravel or asphalt, and other materials. On the other hand, slag becomes rock wool if compressed air is blown through a stream of molten slag. Rock wool looks similar to gray cotton candy, and is light. It is a efficient insulation material, twice as effective as fiberglass. Since it is lighter than water and very absorbent, it could effectively be used to help contain and clean oil spills in the ocean. Cleanup crews could spread rock wool over and around an oil spill. The rock wool would float on the water while soaking up the oil [18].

Based on what slag is capable of, it can potentially be marketed to construction and water treatment organizations.

7. Methodology

The research was done in three phases to answer the question "What technology is most efficient for processing municipal solid waste (MSW) to energy?" 1. Intensive literature review to identify all technologies that can be used to process MSW to energy; 2. Establish evaluation criteria at higher level and filtering technologies based on these criteria; 3. Apply cost benefit analysis method to determine the most suited and capable technology for providing a successful, long-term project at Green Tech Inc. Figure 7-1 shows the process followed during our research.

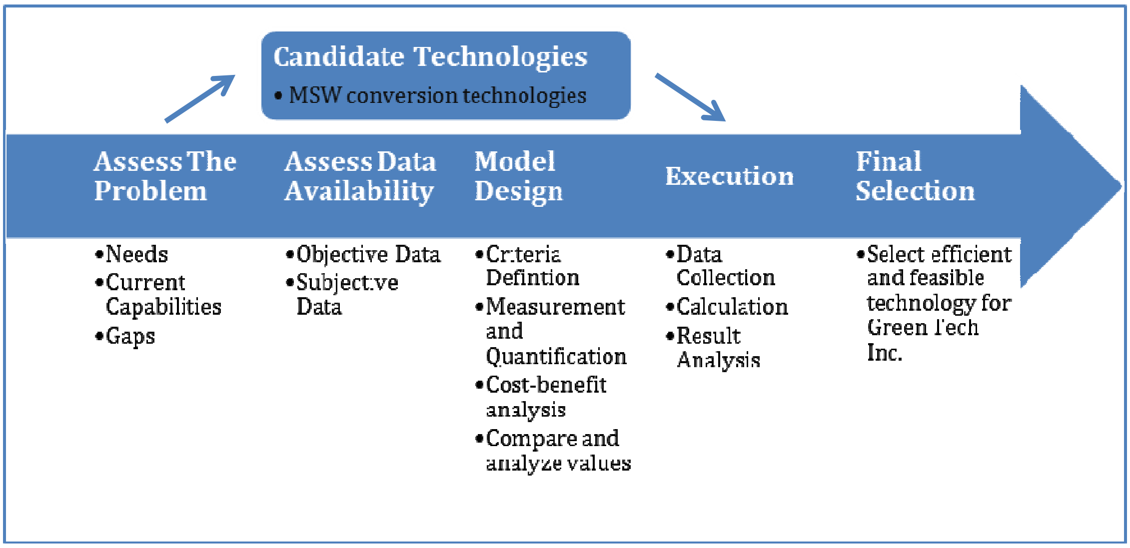

Figure 7-1 – Research Process

8. Gap Analysis

8.1. Technical

With the increase in governmental regulations over the years, it has never been so important to minimize greenhouse gas emissions from industries. A new bill however has relaxed these emission control regulations until 2014, after which emission values are expected to be either par or less than the current limit. Similar to the gas emissions is the ash formation, which should be less than 3 percent. Ash is a non marketable by-product and disposing it is a problem. Thus it is in the best interest for Green Tech Inc. to incorporate a technology that either produces the same or less than the current emission capability.

Municipal solid waste landfills are the largest source of human related methane in the United States and it accounts for 34 percent of these emissions. Thus the plant should be capable of diverting more waste from landfill, and produce energy at minimal cost.

Further, the company currently produces about 685KWh/ton of electricity, however rest of the byproducts produced are negligible and is not marketable. Thus the new technology should have a potential for additional revenue stream in terms of tipping fee and more marketable by-products.

Finally, the technology selection should be such that the conversion process accepts the waste with minimal or no preparation and manage to process irrespective of feedstock's moisture content. Currently feedstock preparation involves drying and grinding biomass into smaller particle size. Also it's essential to utilize heterogeneous feedstock such as medical waste, hazardous/toxic materials and still produce multiple useful products. Table 8-1 shows all technical gaps.

Requirements	Capabilities	Gaps
Minimal carbon emission	With in the EPA mandated emission limit CO-0.299lb/ton CO_2 – 1970lb/ton [19]	Technology not proven with the MSW to maintain emission rate with – in current limit.
Minimal waste going to landfill	Can convert waste into energy (electricity). In 2008, about 50% total waste was land filled [16].	
Increase production efficiency & product mix	Currently generating 685kWh/ton [20]of Biomass electricity & byproducts are negligible.	Technology needs to be proven for commercialization which can increase the electricity generation by at least 15% or improves / introduces new marketable by product.
Reduce (less than 3%) or eliminate ash formation	Current ash content 5 to 20%	No proven technology that reduces ash content to less than 3%, no proven technology which does not utilize pre processing.
Should be insensitive to input waste	Current system is capable of processing feedstock irrespective of the type of biomass but yield varies with calorific value of the input waste.	No proven technology that can utilize hazardous/toxic materials, medical wastes, asbestos, tires, etc – with closed loop system.
No feedstock preparation	Feedstock drying and grinding in to smaller particle size.	No Proven reactor design that can take feedstock without any preparation
The process should take heterogeneous feedstock	Can process homogeneous feedstock	

Table 8-1 – Technical Gaps

8.2. Organizational

There are several requirements that the organization is pursuing.

First, the organization wants to add additional revenue streams. It is very significant from every organization's point of view as they need to survive in today's competitive environment. So they try to find the ways to generate profits as much as they could. There are several ways to do so. The utilization of MSW as a feedstock provides additional revenue stream in the form of tipping fees. Also, Green Tech currently doesn't have any business relationship established with waste management companies. Thus it is crucial to develop good relationship with waste management companies and secure access to waste so as to compete with other competitors.

The new technology which will be adapted to utilize MSW should be easily integrated into existing infrastructure and process. The requirement to select a technology should be easily retrofittable with minimal equipment change or process change. Moreover, the organization wants the minimal investment and technologies which has proven emission level by EPA regulation. It is obvious for every company that paying less is better, but they have to ensure that whatever technology they want to adopt is approved by involved regulator.

Finally, the organization wants an effective storage and transportation of by-products. This is required because the current plant does not have an effective storage yet for by-products that will come out from the process. Plus, by-products such as bio-oil, bio-char, and syngas require effective transportation

Requirements	Capabilities	Gaps
Additional revenue stream	Access to waste in Portland Metro Area.	Increasing competition – need to develop relationship with waste management companies.
New technology should be easily integrated into existing infrastructure & process	The existing systems can be easily upgraded to increase efficiency	Uncertainty in governmental regulations
Minimal investment & technologies which has proven emission level by EPA regulation	Need to prove candidate technologies that do not violate EPA standards.	
Need an effective storage & transportation of by-products	Currently can handle gas output effectively.	No existing storage facility & transportation infrastructure

Table 8-2 – Organizational Gaps

8.3. Personal

As part of the plant retrofit project to incorporate MSW, re-training the existing and new employees on the processes and procedures becomes necessary. Existing employees have knowledge of the current processes/procedures that can be tailored to incorporate the updated system or procedures. The scope of the training overhaul will be taken into consideration depending on the technology that is implemented.

Further, personnel safety needs to be evaluated; training employees on how to properly handle bio-oil becomes necessary, as bio-oil has known carcinogens. Employees need to have a good understanding of the toxicity levels and appropriate controls that need to be in place to protect plant personnel [21]. Employee training needs to incorporate updated safety information regarding handling of all MSW process outputs (bio-oil, char, and slag.)

Requirements	Capabilities	Gaps
Training existing employees on new process and technology	Employees have knowledge of existing processes	Train employees on new technology.
Health and Safety of employees in conversion process	Know safety policy/process for existing technology.	Bio-oil has known carcinogens - update policy /process for handling.

Table 8-3 – Personal Gaps

9. Technology Selection

9.1. Technology Requirements

Using the current biomass conversion at Green Tech as a baseline and the output from the gap analysis, technology requirement were developed to identify a future state. The technology requirements were used as primary screening parameter to identify potential candidate technologies. Below in table 9-1 is a list of technology criteria that was derived from the gap analysis.

Requirement	Description
Should process heterogeneous feedstock	The current biomass process only supports wood waste as a feedstock. Since the evaluation is identifying MSW as a feedstock, the new reactor design should be able to support heterogeneous feedstock.
Should be easily integrated into existing system/process	In order to minimize major capital investment, retrofitting the plant design is necessary. The future state should be able to leverage existing processes and some of the existing equipment.
No or minimum feedstock preparation	The current process requires extensive feedstock preparation, which includes feedstock grinding and feedstock drying to eliminate excessive moisture. Future reactor design should either eliminate or minimize feedstock preparation.
Should generate 15% more electricity than current output	If future reactor design can generate electricity, the output should have a net increase.
100% carbon conversion process	The future reactor design should recycle excessive waste and or production to act as a fuel source.
Reduce (less than 3%) or eliminate ash formation	Current state produces ASH as a byproduct that is not marketable. Future reactor designs should either eliminate or re-use byproducts.
Output should be insensitive to input	The current process is sensitive to input. Future reactor designs should be able to accepts heterogeneous feedstock an produce multiple outputs.
Increase production efficiency & product mix	Expanding the product mix will act as additional revenue sources for Green Tech.

Table 9-1 – Technology Requirements

9.2. Technology Selected for Evaluation

Sixteen biomass technologies that are proven to process MSW were identified that met some or all of the technical requirements were used as a base for further consideration [22][23][24][25][26][27][28].
Table 9-2 lists all selected technologies that were considered for evaluation.

C#	Technology	C#	Technology
1	Updraft Gasification	**9**	Circulating Fluid Bed Reactor
2	Downdraft Gasification	**10**	Biomass Catalytic Cracking
3	Circulating Fluid Bed Reactor	**11**	Aerobic Digestion
4	Plasma Arc Gasification	**12**	Anaerobic Digestion
5	Vacuum Pyrolysis	**13**	Fermentation
6	Ablative Fast Pyrolysis	**14**	Hydrolysis
7	Rotating Cone Pyrolysis	**15**	Micro Turbine Technologies
8	Bubbling Fluidized Bed Reactor	**16**	Esterification

Table 9-2 - Biomass technologies that were selected for evaluation

In order to complete the evaluation, we adopted nine (Appendix 1) evaluation criteria. The criteria were established as minimum screening parameters, with the objective that each technology would be required to meet most or all of the criteria in order to be further considered for future procurement. The criteria were structured to assess the feasibility and viability of a MSW conversion plant that meets all the established requirements defined in the gap analysis.

9.2.1. First Level Evaluation Matrix

Candidate Technologies	C 1	C 2	C 3	C 4	C 5	C 6	C 7	C 8	C 9	Total
Updraft Gasification	1	0	0	1	1	0	1	1	1	**6**
Downdraft Gasification	1	1	1	0	1	0	0	1	1	**6**
Circulating Fluid Bed Reactor	1	1	1	0	1	0	0	1	1	**6**
Plasma Arc Gasification	1	1	1	1	1	1	1	1	0	**8**
Vacuum Pyrolysis	1	0	1	1	0	1	1	1	0	**6**
Ablative Fast Pyrolysis	1	0	1	0	1	0	0	0	1	**4**
Rotating Cone Pyrolysis	1	0	1	0	1	0	0	0	1	**4**
Bubbling Fluidized Bed Reactor	1	0	1	1	1	0	1	1	1	**7**
Circulating Fluid Bed Reactor	1	0	1	1	1	0	1	1	1	**7**
Biomass Catalytic Cracking	1	0	1	0	1	0	0	1	0	**4**
Aerobic Digestion	1	0	0	0	0	0	0	0	1	**2**
Anaerobic Digestion	1	1	0	1	0	0	0	1	0	**4**
Fermentation	1	0	0	0	0	0	0	0	1	**2**
Hydrolysis	1	0	0	0	0	0	0	1	0	**2**
Micro Turbine Technologies	1	1	0	1	0	1	0	0	1	**5**
Esterification	1	0	1	0	0	0	0	1	1	**4**

Table 9-2.1 - Biomass technologies that were evaluated by the criteria

9.3. First Level Criteria Technology Selection

After evaluating sixteen biomass technologies through the criteria process, three technologies were selected for further analysis. Below is a description of each technology that will be further evaluated using cost benefit analysis.

9.3.1. Plasma Arc Gasification

Plasma Arc Gasification is a waste disposal technology that turns garbage into usable by-products without burning it by using electrical energy and the high temperatures created by an electrical arc gasifier. Temperatures as high as 7200°F - 12,600°F are reached in the arc column. At this range of temperature, most types of waste are broken into basic elemental components in a gaseous form. The organics of waste solids (carbon-based materials) are converted to a synthesis gas (syngas) whereas inorganic materials and minerals produce a rock-like glassy by-product (slag) [29].

There are three main by-products of plasma arc gasification:

1. Syngas: a mixture of hydrogen and carbon monoxide. Most of the produced syngas could generate the electricity that powers the plant. The remaining could be sold to utility companies [30].
2. Slag: a solid residue resembling obsidian. Once molten slag is cleaned of contaminants, it can be funneled into brick or paving stone molds and then air-cool into ready-to-use construction material [30].
3. Heat: Heat from the molten slag helps maintain the temperature within the furnace. Some of the heat from gases can be used to convert water into steam, which in turn can turn steam turbines to generate electricity [30].

The plasma arc gasification has been considered as an effective waste-to-energy technology because of several facts. First, it is capable of breaking down all kinds of MSW due to its high-temperature operation. Second, it requires minimal or no feedstock preparation. Moreover, it produces useful by-products that could be applicable. Finally, it is an environmentally friendly waste-to-energy technology that produces less greenhouse gas than other thermal conversion technologies since there is no burning process occurred [31]. The technology is in early stage of development and we notice that there are only two manufacturers in the U.S. – Westinghouse [32] & Geoplasma [33]

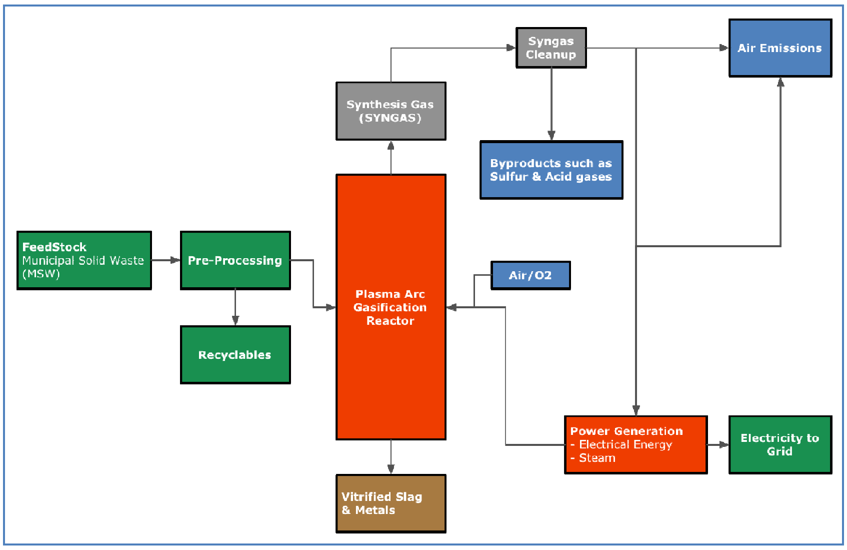

Figure 9.3.1 - Plasma Arc Gasification Process [29]

9.3.2. Fluidized Bed Reactor Pyrolysis

Fast Pyrolysis is a process similar to CFB. Here small particles of biomass waste (less than 2-3mm) are rapidly heated to high temperatures (500-550°C) in the absence of oxygen, vaporized, and then condensed into liquid fuel. Products of the process are typically 70wt% of liquid bio-oil, 15% solid char and remaining non-condensable gases (NCG). Most importantly, the process has no waste since both Pyrolysis Oil and Char have significant commercial application and value, while non-condensable gases are recycled and produce approximately 75% of the energy required for the pyrolysis process. Because of their long history of service and inherently simple operating design, this type of reactor is considered to be very reliable and virtually trouble free as a system capable of conducting fast pyrolysis of biomass.[21]

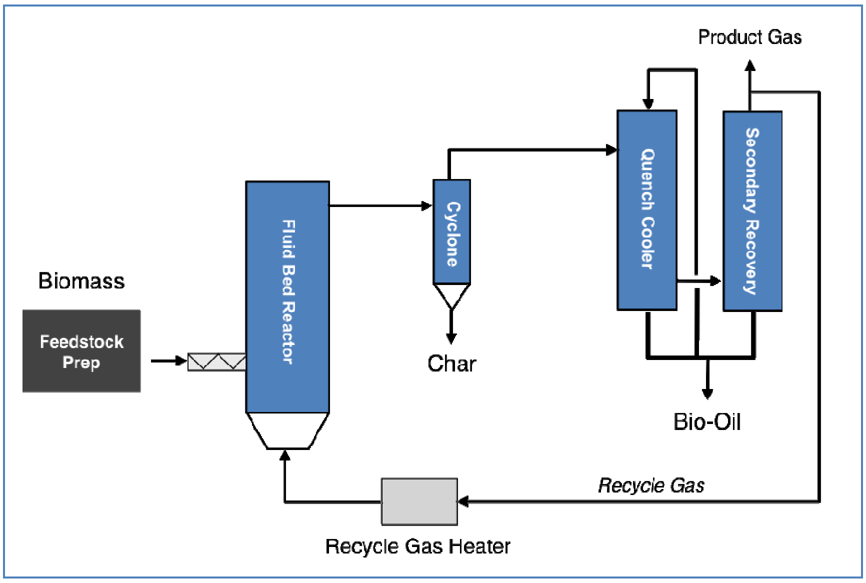

Figure 9.3.2 - Fluidized Bed Reactor Pyrolysis

9.3.3. Circulating Fluidizing Bed Reactor Pyrolysis

Fast Pyrolysis is a process by which small particles of biomass waste (less than 2-3mm) are rapidly heated to high temperatures (500-550°C) in the absence of oxygen, vaporized, and then condensed into liquid fuel.

Circulating bed reactor (CFB) operates similarly to traditional fast-pyrolysis reactor designs in converting MSW to bio-oil and other minor byproducts. The design is slightly more complicated as the process involves moving large quantities of sand into the reactor. Sand flow rate is also 10-20 times greater than the biomass feed rate significantly increasing the energy cost to operate CFB reactor designs.

Feed size needs to be taken into consideration with the CFB system designs. Particles only reside in the high heat transfer pyrolysis zone for only 0.5-1 seconds before it is entrained over to the char combustion section. For relatively large particles this would not be enough time to transport heat to the interior of the particle. Consequently, if larger feed particles are used, the oil yield will be reduced due to combustion of incompletely pyrolyzed particles.[21]

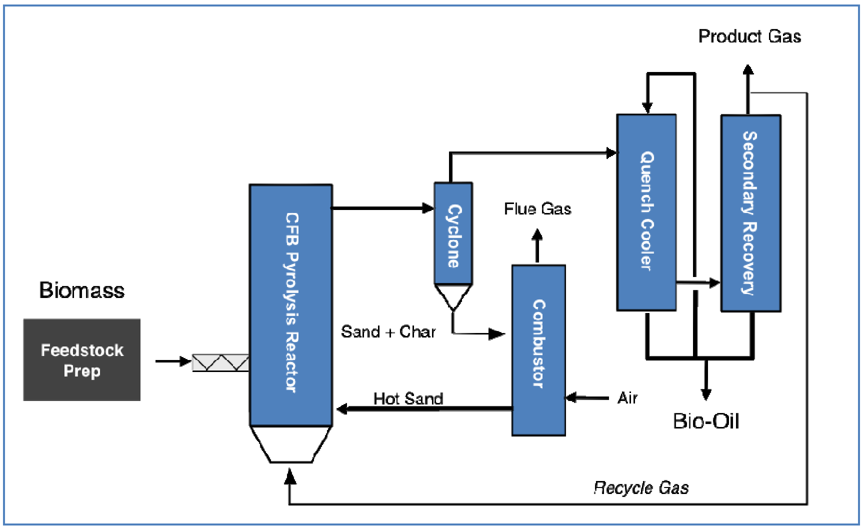

Figure 9.3.3 - Circulating Fluidized Bed Reactor Pyrolysis

10. Second Level evaluation - Economic Analysis

The second level evaluation was to do cost benefit analysis on all three candidate technologies selected in the previous section; this involved calculating NPV, IRR and Payback period and selecting the most efficient one. In order to perform the financial analysis we made couple of assumptions after which initial investment and operating cost was calculated for each technology. Appendix [2, 3, 4] lists all general, production and financial assumptions.

10.1. General Assumptions

Plant and financial assumptions are listed in appendix 2. The plant is assumed to operate during 317 scheduled operating days with an 85 percent utilization rate. The utilization rate is a crucial factor as it determines how much feedstock is needed and the quantity of outputs that can be produced and sold. The operating time parameters include annual days of downtime, annual operating hours, onstream percentage and downtime costs. Further, the plant fuel will be derived from the outputs of each technology. The maintenance costs for the plant are assumed to be 2 percent of the total equipment cost.

10.2. Capital Costs

Using similar papers from NREL[27][34][35][36][28] and companies that are using the above mentioned technologies, each major piece of equipment was sized and estimated [37][38]. For non-standard equipment, other methods such as comparison with other similar equipment were employed. Installation charges were applied based on the economic analysis performed by the companies [37][38]trying to use these technologies and most recent NREL papers[34][36][27][28][35]. Appendix 3 provides break-up for equipments required to retrofit each technology.

A contingency factor of 20 percent was applied to project the total equipment costs. This factor was designed to account for the uncertainty in the analysis and if any miscellaneous equipment left out of the analysis. Thus the total equipment cost summed all equipment cost, its installation charges and the contingency factor.
Using this total equipment cost, the total project investment (TPI) was derived using the bottom-up costing approach. Table 10-2 outlines all the costs used.

Description	Cost		
	Plasma Arc Gasification	**Fluidized Bed Reactor**	**Circulating Fluid Bed Reactor**
Total equipment cost	$11,766,000.00	$2,704,000.00	$3,054,000.00
Site development cost/warehouse	$0.00	$270,400.00	$305,400.00
Total Installed Cost (TIC)	$11,766,000.00	$2,974,400.00	$3,359,400.00
Installation cost (20% of equipment cost)	$2,353,200.00	$594,880.00	$671,880.00
MISC start up cost (5% of Total Installed Cost)	$588,300.00	$148,720.00	$167,970.00
Project Contingency (20% of TIC)	$2,353,200.00	$594,880.00	$671,880.00
Total Project Investment (TPI)	**$14,707,500.00**	**$4,312,880.00**	**$4,871,130.00**

Table 10-2 – Capital Costs

10.3. Revenue

Appendix [4, 5 and 6] shows the revenue generated for first year. For simplicity purpose we assumed that the feedstock processed for five years will be constant @ 30,600t/year.

Plasma Arc: Electricity selling price was derived based on the current selling price by BPA [39] in Oregon which is about $ 47.00 per MW. The slag price was assumed to be $1.21 per kilo gram based on analysis done by city of Marion, Iowa [40]. The total revenue generated by Plasma Arc for one year is 6.8M; this is based on the net electricity output of 865 kWh [33].

The selling price of Bio-Oil was assumed to be $ 50.50/barrel & $.21/kg for Bi-Char [37]. Fluidized bed reactor with yield of 70% Bio-oil[35]& 15 % [35]Bio-Char is estimated to generate the total revenue of $8.9M for each year. Circulating fluidized bed reactor with the yield of 75% Bio-Oil [35] and 10% Bio-char [35] is estimated to produce total revenue of 9.3M. Appendix [4, 5 and 6] lists all important assumption made for revenue calculation.

10.4. Operating Costs

Labor Costs

The wages were decided according to the personnel. A Payroll burden of 33% was included for calculations. It was assumed to require 16 personnel for plasma arc gasification process, 17 for fluid bed reactor process and 18 for circulating fluid bed reactor process during all scheduled operating hours.

Maintenance Costs

The maintenance costs for the plant are assumed to be 2 percent of the total equipment cost.

Insurance Costs

The insurance costs for the plant is assumed to be 11 percent of total initial investment. Property insurance premiums were based on 0.4% of asset value for buildings and 0.7% of the building contents value.

Taxes and Depreciation

For the biomass plant, taxes paid on net cash flow (minus depreciation) were incorporated to determine NPV, IRR, and Payback Period. The model developed for this project assumed that federal taxes are paid according to Internal Revenue Service (IRS) Form.

Double declining depreciation of capital over the useful operating life of 15 years is assumed for the purpose of reporting taxable income to the IRS. No special financing and grant programs or accelerated depreciation are used in the analysis, nor are production credits or employment credits.

To obtain the final total expenses, we sum all of the operating costs represented above with the depreciation and loan interest for each technology. As a result, Plasma Arc Gasification by calculation has the most expensive operating costs ($307,735), which are approximately twice as much as the other two technologies ($139,564 and $152,947).

10.5. Financial Analysis Results

The economic viability of all three technologies was evaluated based on Cost-benefit analysis comparing Net Present Value (NPV), Payback Period, and IRR for all three technologies. Appendix [4, 5 and 6] shows the financial analysis for all three technologies. A life of 15 years was considered for all three technologies.

Retrofitting Plasma arc gasification technology at Green Tech Inc. shows total revenue of $6.8 million with a net profit of $360K. However the technology shows a longer payback period than 5 years with a negative 17 percent internal rate of return. The net present value (NPV) for the project is negative $10 million.

However going with the fluidized bed reactor Pyrolysis technology involves a capital cost of $4.3 million producing a net profit of $2.4 million including the revenue due to tipping fee. The time recovery period for the investment would be 2.37 years with a 31 percent rate of return, a value greater than hurdle rate of 7 percent. The Net Present Value (NPV) is positive with a value of $2.5 million. The circulating fluid bed reactor technology, on the other hand shows similar results with a closer profit of $2.7 million compared to the fluidized bed reactor with a payback period of 2.34 years.

Candidate Technologies		NPV	Payback period	IRR
		NPV>0	Min # of years	IRR>7%
A	Plasma Arc Gasification	($10,252,291.82)	> 5 Years	-17.11%
B	Fluidized Bed Reactor Pyrolysis	$2,542,582.64	2.37 Years	31.44%
C	Circulating Fluidized Bed Reactor Pyrolysis	$2,974,404.44	2.34 Years	32.13%

Table 10-5 – Financial Summary

Due to the closeness in values between fluidized bed reactor and circulating fluid bed reactor technology, incremental cost analysis method was used to select the most suitable and feasible one. According to its results, circulating fluid bed reactor was found to be a good option for Green Tech Inc. as the extra amount invested earns a return that exceeds the IRR.

	Alt. B	Alt. C	Alt. C-Alt. B
Initial cost	($4,312,880)	($4,871,130)	($558,250)
Net annual income	$2,364,167	$2,772,185	$408,018
IRR on total cash flow	31.44%	32.13%	67.54%

Table 10-6 – Incremental Cost Analysis

11. Conclusion & Future Research

The research process sufficiently helped Green Tech to establish a technology assessment method to select a technology that can be procured for implementation and provide a sound profit for the organization. This paper outline the steps in how Green Tech went from defining a problem to performing a gap analysis, defining requirements, identifying selection criteria and finally performing a cost-benefit analysis on three technologies that met all or majority of the defined criteria.

It is important to note that in order to make a conclusion about what technology that was suitable, a hypothetical organization was needed to define the research boundaries. Since boundaries were set, majority of the decision making process focused on identifying a technology that was cost effective and met the technical requirements that were defined early on. Structuring research in this method had a positive output that allowed Green Tech to make a technology decision, but was limited to assessing technology from other perspectives. Using environmental, organizational, and other perspectives might have yielded different results.

After reviewing 16 different waste conversion technologies that process MSW, we were able to come up with 3 different technologies that are in the best interest of Green Tech. Further based on cost benefit analysis, circulating fluid bed pyrolysis technology was proposed which is environmental friendly with a net zero CO_2 emission and has no ash as the by-product. Also, with minimal investment, the technology can be easily retrofitted to existed process.

Future research on this topic could be expanded to include the following:

- Adding additional criteria for more granular definition of the technology.
- Use alternative models such as analytic hierarchy process (AHP) and compare the results. This would validate other important factor to selecting technology and not only selecting a technology from a financial perspective. Other perspectives such as environment and political impacts can be taken into consideration.
- Perform a 15 year cost analysis rather than the current 5-year cost model. Expanding the cost analysis to 15 year might yield different results in the final technology selection.

12. Next Steps

Identifying a suitable alternative to the current biomass technology at Green Tech is the first step. In order to implement the technology selected through the technology assessment process, several additional steps need to be performed and need further evaluation:

1. **Determine license fees for technology**. Pyrolysis technology is a patented process owed by Dynamotive [41] and needs to evaluated and considered whether additional license fees need to be taken into consideration as an additional procurement or operational cost.

2. **Identify vendors who manufacture the reactors.** Research of all vendors who manufacture circulating fluid bed reactors. Other components that were identified for replacement need vendors identified.

3. **Get exact quote for equipment.** The current cost estimates defined in section 11.2 are based upon published papers and technology assessments done in various locations throughout the US. Establishing relationships with vendors and getting exact quotes for the equipment is necessary to get an exact cost projections. The cost model needs to be adjusted accordingly.

4. **Identify strategic partners**. It is necessary to develop the appropriate relationship for both feedstock inputs (MSW) and biomass process outputs. These partnerships are critical to Green Tech as there is a need for constant supply of MSW and the sale of output as bio oil has a limited shelf life.

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Appendix 1 (Baseline evaluation criteria)

C#	Criteria	Description
C1	Process MSW (heterogeneous feedstock)?	The current process currently only supports homogenous feedstock comprised of arboricultural activities, yard waste, processed wood and wood from forest products. The need is to expand and retrofit the plant to expand by processing MSW as MSW will be a source of revenue.
C2	Generate electricity? If yes, >685kwhr/ton	The current process supports the generation of electricity and is a current source of revenue for Green Tech. The new MSW technology should support additional electricity generation.
C3	Produce bio-oil/Bio-char?	Current process output currently is only electricity. By diversifying output to bio-oil, and bio-char, Green Tech. will have additional revenue sources.
C4	Technology proven for MSW?	Reactor designs should be able to support MSW. This criterion allows Green Tech to take advantage of a new revenue source (MSW) and diversify its feedstock.
C5	Easily integrated to existing system	To minimize initial capital investment, procuring a system and that can be retrofitted into the existing system is critical. Leveraging existing systems, like chillers, quencher, and other plant components will minimize overspending.
C6	Need feedstock preparation?	Minimal or no feedstock preparation is critical to minimizing the investment in additional processing equipment and the space needed to process the feedstock. Since MSW can vary in size, this is critical factor to processing various feedstock sizes.
C7	Can process medical waste, hazardous waste etc.	This is not a critical must-have criterion, but might prove to be beneficial as this may be a business differentiator and set Green Tech apart from competitors.
C8	Carbon emission level less than or equal to current level?	Existing regulation does not specify a maximum carbon emission level, but rather than wait until regulation is imposed, Green Tech should select a technology that has minimal carbon emissions.

C9	Minimum Investment <$4M	Green Tech. is a small corporation with limited funds. Retrofitting the existing plant will cut down on initial capital investment. Doing a cost benefit analysis will identify the most suitable technology for procurement and implementation.

Appendix 2 (General Assumptions)

Plant Assumptions	Plasma Arc Gasification	Fluidized Bed Reactor	Circulating Fluid Bed Reactor
Plant Capacity(tpd)	100		
Plant Availability (85%)	317days/yr		
Dry Feedstock consumed (ton/year)	30,600		
Yield(%Electricity/%Slag)	84/16		
Plant Operating Fuel	Electricity	Pyrolysis Oil	
Plant Life (years)	15		
Study Period (years)	5		
Maintenance Cost (%Equipment Cost)	2%		
Financial Assumptions			
Hurdle Rate	7%		
Tax Rate	30%		
Tipping Fees ($/ton)	$58		

Table 11-1 – Plant and Financial Assumptions

Appendix 3 (Equipment Cost)

PLASMA ARC GASIFICATION			
Equipment	**Qty**		**Cost**
Plasma ARC	1	$9,000,000.00	$9,000,000.00
Heat Exchanger	1	$2,266,000.00	$2,266,000.00
Utility Interconnect	1	$500,000.00	$500,000.00
Total equipment cost			$11,766,000.00

FLUIDIZED BED REACTOR PYROLYSIS			
Equipment	**Qty**	**Unit cost**	**Cost**
Feed stock Handling and drying	1	$1,000,000.00	$1,000,000.00
Fluidized bed - Pyrolysis System	1	$750,000.00	$750,000.00
Quench cooler	2	$352,000.00	$704,000.00
Heat recycle to gas heater	1	$250,000.00	$250,000.00
Total			$2,704,000.00

CIRCULATING FLUIDIZED BED REACTOR PYROLYSIS			
Equipment	**Qty**	**Unit Cost**	**Cost**
Feed stock Handling and drying	1	$1,100,000.00	$1,100,000.00
Fluidized bed - Pyrolysis System	1	$1,000,000.00	$1,000,000.00
Qunech cooler	2	$352,000.00	$704,000.00
Heat recycle to gas heater	1	$250,000.00	$250,000.00
Total equipment cost			$3,054,000.00

Appendix 4 (Plasma Arc gasification – Financial Summary)

PLASMA ARC GASIFICATION					
Plant Assumptions		**Financial Summary (Year 1)**			
Plant Capacity (tpd)	100	**Revenues**	**FY2012**	**Cash Flow**	
Plant availability (85%)	317 days/year	Electricity	$1,243,620.00	Cash from Sales	$6,797,520.00
Dry feedstock consumed (ton/year)	30,600	Slag	$5,553,900.00	Non operating other income	$1,774,800.00
Yield (%Electricity/%Slag)	84/16	Total revenue	$6,797,520.00	Sub total cash received	$8,572,320.00
Plant operating fuel	Electricity				
Plant life (years)	15	Direct cost of sale	$5,066,280.00	Cash Spent on Operations	$6,156,985.00
Study period (years)	5			Net Cash Flow	$2,415,335.00
Maintenance cost (% Equipment cost)	2%	Gross margin	$1,731,240.00		
		Other Income (tipping Fees)	$1,774,800.00		
Investment		Total Gross profit	$3,506,040.00	**Cost-Benefit Analysis**	
Capital cost ($)	$17,060,700.00	Gross margin%	25.47%	Rate of Return (IRR)	-17.11%
Production				Payback Period	> 5 years
Net Electricity Production (KWHR/ton)	865	**Expenses**		NPV(RR=7%)	-$10,252,291.82
Slag production (kgs/ton)	150	Operating cost/expense	$2,991,429.00		
		Depreciation expense	$1,568,796.00	**Financial Assumption**	
Net Electricity Production (MW/year)	26460			Hurdle Rate	7%
Slag Production (Kgs/year)	4,590,000	PBITDA	$514,611.00	Tax rate	30%
		EBITDA	$2,083,407.00	Tipping Fees ($/ton)	$58
Price Assumption:		Taxes incurred	$154,833.00		
Electricity Selling price ($/MW)	47	**Net profit**	$359,778.00		
Slag selling price($/Kg)	1.21	Net Profit/Sales	5.30%		

Appendix 5 (Fluidized Bed Reactor – Financial Summary)

FLUDIZED BED REACTOR PYROLYSIS					
Plant Assumptions		Financial Summary (Year 1)			
Plant Capacity (tpd)	100	**Revenues**	**FY2012**	**Cash Flow**	
Plant availability (85%)	317 days/year	Bio-Oil	$8,205,846.00	Cash from Sales	$8,892,510.00
Dry feedstock consumed (ton/year)	30,600	Bio-Char	$686,664.00	Non operating other income	$1,774,800.00
Yield (%Bio-Oil/%Bic-Char)	70/15	Total revenue	$8,892,510.00	Sub total cash received	$10,667,310.00
Plant operating fuel	Pyrolysis Oil				
Plant life (years)	15	Direct cost of sale	$5,224,118.00	Cash Spent on Operations	$7,320,548.00
Study period (years)	5			Net Cash Flow	$3,346,762.00
Maintenance cost (% Equipment cost)	2%	Gross margin	$3,668,392.00		
		Other Income (tipping Fees)	$1,774,800.00		
Investment		Total Gross profit	$5,443,192.00	**Cost-Benefit Analysis**	
Capital cost ($)	$4,312,880.00	Gross margin%	41.25%	Rate of Return (IRR)	31.44%
Production				Payback Period	2.37 Years
Bio-Oil (Barrels/ton)	5.31	**Expenses**		NPV(RR=7%)	$2,542,582.64
Bio-Char(Kgs/ton)	136	Operating cost/expense	$2,065,810.00		
		Depreciation expense	$396,576.00	**Financial Assumption**	
Bio-Oil (Barrels/year)	162,486			Hurdle Rate	7%
Bio-Char(Kgs/year)	4,161,600	PBITDA	$3,377,382.00	Tax rate	30%
		EBITDA	$3,773,958.00	Tipping Fees ($/ton)	$58
Price Assumption:		Taxes incurred	$1,013,215.00		
Bio-Oil selling price($/Barrel)	50.5	**Net profit**	$2,364,167.00		
Bio-Char selling price($/Kg)	0.17	Net Profit/Sales	26.59%		

Appendix 6 (Circulating Fluidized Bed Reactor – Financial Summary)

CIRCULATING FLUDIZED BED REACTOR PYROLYSIS					
Plant Assumptions		**Financial Summary (Year 1)**			
Plant Capacity (tpd)	100	**Revenues**	**FY2012**	**Cash Flow**	
Plant availability (85%)	317 days/year	Bio-Oil	$8,777,304.00	Cash from Sales	$9,234,743.00
Dry feedstock consumed (ton/year)	30,600	Bio-Char	$457,439.00	Non operating other income	$1,774,800.00
Yield (%Bio-Oil/%Bio-Char)	75/10	Total revenue	$9,234,743.00	Sub total cash received	$11,009,543.00
Plant operating fuel	Pyrolysis Oil				
Plant life (years)	15	Direct cost of sale	$4,983,467.00	Cash Spent on Operations	$7,260,062.00
Study period (years)	5			Net Cash Flow	$3,749,481.00
Maintenance cost (% Equipment cost)	2%	Gross margin	$4,251,276.00		
		Other Income (tipping Fees)	$1,774,800.00		
Investment		Total Gross profit	$6,026,076.00	**Cost-Benefit Analysis**	
Capital cost ($)	$4,871,130.00	Gross margin%	46.04%	Rate of Return (IRR)	32.13%
Production				Payback Period	2.34 Years
Bio-Oil (Barrels/ton)	5.68	**Expenses**		NPV(RR=7%)	$2,974,404.44
Bio-Char(Kgs/ton)	90.6	Operating cost/expense	$2,065,810.00		
		Depreciation expense	$396,576.00	**Financial Assumption**	
Bio-Oil (Barrels/year)	173,808			Hurdle Rate	7%
Bio-Char(Kgs/year)	2,772,360	PBITDA	$3,960,266.00	Tax rate	30%
		EBITDA	$4,356,842.00	Tipping Fees ($/ton)	$58
Price Assumption:		Taxes incurred	$1,188,080.00		
Bio-Oil selling price($/Barrel)	50.5	**Net profit**	$2,772,186.00		
Bio-Char selling price($/Kg)	0.17	Net Profit/Sales	30.02%		