Bio-Power from Low Value Biomass Through Torrefaction

Interim Report

for

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CONTACT
Ravi Malhotra
Executive Director
Email ravi@iCASTusa.org

Phone (303) 462-4100
www.iCASTusa.org

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Introduction

This report is the interim report on iCAST's (International Center for Appropriate Sustainable Technology) progress to date on the Bio-Power from Low Value Biomass through Torrefaction Project funded by the Colorado Department of Agriculture's (CDA) Advancing Colorado's Renewable Energy (ACRE) Program. The outline of this report is in accordance with the CDA's interim report format.

Work completed to date and any relevant findings:

Since the inception of the project, iCAST has developed teams to complete initial design work for a torrefaction facility and is currently working on validating the design assumptions and increasing the efficiencies of the design. The team has completed the following tasks:

- Coordinating team members including:
  - Colorado State University Chemical Engineer Senior Design Team lead by Dr. Gordon Smith
  - University of Colorado Senior Engineering Design Team Lead by Dr. Angela Bielefeldt
  - iCAST staff also recruited several interns for the project with backgrounds including business, engineering, and finance.
- The project teams developed 2 preliminary reports including a technical and financial analysis of the project. (Appendix A & Appendix B)
- The team has started to verify and improve upon the initial design through the following analyses:
  - Financial Analysis (Appendix C)
  - Mass Energy Flow (Appendix D)
  - Physical Properties (Appendix E)
- The team identified and engaged with stakeholders for comments and feedback on the project and design. Stakeholders included universities, torrefaction equipment manufacturing companies, utilities, and other bio-energy industry partners.

Preliminary findings

Overall the findings of the project indicate the technologies that exist on a larger scale pose several challenges on a smaller scale. Technical challenges include finding equipment that has a small capacity while still maintaining the efficiencies of a large scale plant.

In addition, financial challenges arose from the initial cost analysis. The findings indicate the cost of torrefied biomass is well above the going market price for energy on a BTU/lb basis. In other words, the final product could not compete in todays energy market. The team is looking into more cost effective ways to produce the product as well as calculating a monetary value for the "renewable" aspect of the fuel as opposed to market alternatives such as coal.

Problems being encountered and/or mitigating circumstances;

The major problem encountered in this project has been contacting equipment manufacturers. As torrefaction for bio-energy is a relatively new industry, there are few companies that manufacture the equipment, most of which are located outside the United States. It has been difficult to engage with the companies as well as get valuable information on their torrefaction plants. To mitigate this issue, iCAST has consistently followed up and has been getting increased responses and valuable data from the companies. In addition, iCAST has looked to industry partners to gather valuable information as well.

Next steps

The next steps of the process are as follows.

- Validate the initial plant design, costs, efficiencies, and financial feasibility.
- Perform final analysis on
    - Equipment Costs
    - Operating costs including:
        - Feedstock
        - Fuel
        - Energy
        - Labor
        - Transportation
    - Government Incentives
    - Market Analysis
- Develop a final plant based on final analysis and industry feedback.
- Develop and deliver project deliverables including;
    - Plant design
    - Process Flow Diagram
    - Plant specifications
    - Cost model
    - Final recommendations

Any anticipated changes to project timeline.

At this time there are no anticipated changes to the project timeline.

Solid Fuels Generation by Torrefaction of Woody Biomass

DRAFT

Austin Archer
Brittany Bellefeuille
Joe Dauner
Justin Rogers
Sarah Williams

ABSTRACT

The goal of this project was to develop a process that used local resources in the production of biofuels. Four processes were compared based on economics, environmental considerations, technical feasibility, process safety, and social aspects: torrefaction, pyrolysis, gasification, and anearobic digestion.

Initially, the desired feedstock was manure and straw waste from beef feedlots. With the basis of a 100,000 cow feedlot, it was assumed that sixty pounds of manure per cow are produced each day. This is approximately ninety percent water by weight. Successive calculations led to a feed rate of 300 tons/day.

Torrefaction, pyrolysis, and gasification were determined to be technically feasible but not economically viable because their products would not be energy dense enough for market viability. Anaerobic digestion is a better solution for waste control than for fuel production. Based on these conclusions the feedstock was changed to woody biomass from logging residue. This feedstock was chosen because woody biomass is a prevalent feedstock in current research and the ease of acquiring it.

Woody biomass feedstock can be obtained from a logging company's residuals. Calculations were based on the assumption that a typical logging operation in Colorado can clear 1500 trees per day and that a pine tree provides an average of 0.75 yd^3 of slash, totaling approximately 100 tons of feed per day. It was assumed that the wood slash can be acquired at no cost.

Torrefaction is the process chosen for further development because the product is the most economically feasible. Torrefied biomass can be co-fired with coal. The equipment necessary for torrefaction of this feedstock were selected and sized. Price quotations were obtained if available. The estimated total cost of equipment is $3.5 million, the estimated total capital investment is $13.9 million, and the estimated operating cost per year is $4.1 million.

At this time there is not a market for torrefied wood. If the product is sold at the current price of raw biomass, $260/ton, operating costs will exceed net profits. However, because torrefied wood is significantly higher in energy density and burns more efficiently, it should have a higher market value. If the product is sold for $380/ton, the operating costs will be covered. Currently, renewable energy credits have little impact on the economics of the process, but their contribution is highly variable and may increase in the future.

PROJECT FEASIBILITY

The first step of the project was to research a variety of processes. The processes considered were torrefaction, pyrolysis, gasification, and anaerobic digestion. They were compared based on costs, environmental considerations, technical feasibility, safety, and social aspects. Torrefaction was determined to be the desired process and was chosen for further design. Key characteristics of all processes considered are discussed below.

Torrefaction

Torrefaction is the heating of material to between 200 and 300 °C under atmospheric pressure in the absence of oxygen, distinguished by its low heating rate of less than 50 °C/min. When biomass is torrefied, approximately 70% of the mass is retained as a solid biochar while retaining 90% of the original energy content.

The only torrefaction production plant ever to exist was a demonstration plant operated by a French company called Pechiney. It was opened in 1988 and torrefied wood from the surrounding forest near La Val de Cere, France. This plant was shut down in the early 1990's for economic reasons. Since then, a few processes have been proposed for the torrefaction of biomass but none have reached commercial scale [Bergman, 2005], [Arcate, 2002].

The Energy Research Center of the Netherlands (ECN) has done a significant amount of biomass torrefaction research, focusing on wood. Their research included data gathered from the Pechiney plant and other studies. The information below is mostly based on the research done at ECN.

Costs:

The cost of the torrefaction process depends on how the process is heated, whether or not it runs autothermally (without the use of utility fuel), whether or not it is integrated with pelletisation, and the size of the process.

Pelletised, non-torrefied, biomass has been used for biomass co-firing in coal-fired power stations [EIA, 2010]. Unfortunately, this material has about half the energy density of conventional coal, and has inferior combustion characteristics. If torrefied product is co-fired or gasified as a replacement for conventional coal, its price must be competitive with coal. In Colorado, the price of coal at the end of 2010 was about $37/ton, or $1.76/GJ [EIA, 2010].

Bergman et. al. have done a rough economic analysis of stand-alone torrefaction, stand-alone pelletisation, and combined torrefaction and pelletisation (TOP) processes. The analyses were done in 2005 using euros as the currency. All prices have been adjusted to 2010 dollars ($1.20/euro in 2005, 12% inflation since then [FRBSL, 2010], [BLS, 2010]). These analyses took into account a process producing 60 kton/year of torrefied wood (about 100 kton/year of feedstock) for the stand-alone torrefaction and TOP processes. The stand-alone pelletisation process was taken as a 80 kton/year process. Note that the biomass being torrefied in these scenarios is wood.

For stand-alone torrefaction, the total capital investment was estimated to be $8.5-16.5 million, with production costs of $74-$104/ton of product. For stand-alone pelletisation, the total capital investment was $7.9 million with production costs of $73/ton of product. The TOP process had an estimated total capital investment of $9.9 million with production costs of $67/ton of product [Bergman, 2005], [Bergman TOP, 2005]. If torrefaction is performed on a commercial scale, pelletisation must be incorporated.

The return on investment calculated by Bergman et. al. assumes an energy price of $9.81/GJ or $229/ton. The price that is more likely to be encountered in Colorado is $1.75-$2.75/GJ, or $41-$65/ton [EIA, 2010]. Given a similar size facility (60 kton/year of product annually, or about 100 kton/year feedstock), this gives significantly lower returns on investment. In fact, these prices lead to negative returns on investment for all three processes. However, due the passage of Colorado H.B. 1001, the use of renewable energies used in Colorado is mandated to go up, which could produce demand for torrefied biomass at a higher price [State of Colorado, 2010]. Unless the price of the product could be sold for increases, these processes are economically infeasible.

The table below summarizes the costs of the three processes. The numbers involved depend heavily on exact process parameters and are subject to variation. The ROI calculated from these numbers reflects the most optimistic estimate and a 40% tax rate.

Process	Pelletisation	Torrefaction	TOP
Capital Investment (millions of dollars)	7.9	8.5	9.9
Operating Costs (dollars per ton)	73	74	67
Return on Investment (%)	-3.6	-3.8	-0.7

Environment:

The chief attraction of torrefaction is its environmental benefits. Whether directly combusted, co-fired with conventional coal, or gasified, the process itself is carbon neutral. Any thermal pre-treatment of biomass would require some utility fuel, probably natural gas, though its use could be reduced through the combustion of some torrefaction gases. Additionally, raw biomass could be combusted to heat the torrefier and heater [Bergman, 2005], [Basu, 2011].

Biomass has a diversity of chemicals associated with it. Besides solid product and torrefaction gases, a number of condensable organics are produced. The gases are predominantly carbon monoxide and carbon dioxide. The organics are predominantly acetic acid, methanol, 2-furaldehyde, hydroxyaceton and a small amount of others. Some lipids also are also formed, and some reaction water from the decomposition of the biomass (predominantly hemicellulose) [Bergman, 2005].

Some of the organics that are released can be combusted with the torrefaction gases. Combustibility of torrefaction gases is important, as it reduces the net emissions of the process. It can be considered carbon neutral if run autothermally. That is, if the energy requirements of the drying and torrefaction processes are satisfied by burning torrefaction gases. If torrefaction gases can’t be combusted, or the energy provided by their combustion is insufficient, the process will need to be heated by either natural gas or combusting some of the raw feedstock (if mitigating emissions is of vital importance) [Bergman, 2005]. Unfortunately, any torrefaction gases that aren’t combusted go to flue gas.

Torrefaction demands that feedstock be dried. Thus, water use for the process would be very low.

Technical Feasibility:

The purpose of torrefaction is to reduce the amount of energy in the biomass only slightly, while significantly reducing the mass. Virtually every type of biomass that has been torrefied exhibits some degree of energy densification on a mass basis. Typically, 30 percent of the mass is lost during torrefaction, while only 10 percent of the energy is lost.

It is unlikely the manure would be a useful torrefaction biomass. Its high moisture content, combined with the relatively low hemicellulose and cellulose content, makes it a poor candidate. The decomposition of hemicellulose is the primary source of mass reduction. Wheat straw has plenty of hemicellulose, cellulose, and lignin, the three chemicals that are most relevant to the process, making wheat straw a viable candidate [ERCN, 2010], [Bridgeman, 2008].

Since torrefaction has been done for so long, torrefaction equipment is available. “Torrefiers” have been built for general biomass torrefaction purposes, including Wyssmont’s Rotary Turbo Dryer, which is a popular option among woody biomass torrefaction facilities [Wyssmont, 2010]. Several manufacturers and vendors provide size reduction equipment, briquetters and pellet mills, and all other equipment necessary for the process. The enhanced grindability of the material provided by torrefaction should make the pelletisation process easier.

A key concern of the torrefaction process is densification. In order to effectively transport the torrefied product, it must be compressed by briquetting or pelletisation. Results on the success of densifying torrefied biomass have been mixed. One of the goals of torrefaction is to make grinding less demanding. It may be possible to produce strong pellets if the torrefied product is pressed while still near torrefaction temperature. Higher temperatures may keep the lignin malleable enough to form strong pellets [Chen, 2010]. If not, addition of a binding agent may be necessary. The most important process parameter when considering densification is the torrefaction temperature. If it’s too high, the lignin could decompose. The process should be hot enough to decompose hemicellulose, while cool enough to soften, but preserve, the lignin [Bergman, 2005].

Safety:

The most dangerous aspects of torrefaction are associated with the high temperatures and possibly the gases released during the process. These dangers are no greater than for most chemical processing plants. At torrefaction temperatures, none of the components of the feedstock combust. Noxious gases released would have to be carefully controlled. Another possible safety concern is the moving parts in the system. The drying process and torrefier would likely depend on the use of a moving bed. The crusher (whether a large hammer mill or a jaw crusher) could also present safety concerns. For the most part, the process is relatively simple, demanding only 3-5 operators for a 60 kton/year process [Bergman, 2005], [Bergman TOP, 2005].

Social Aspect:

The concept of using biomass for energy has been around for a long time, and has had support for decades. The last ten years have seen a large boost in public awareness for the need for renewable energy. The specific concept of torrefaction seems to be mostly unknown to the general public. The need for a biomass thermal pre-treatment facility may not be immediately apparent to everyone, and the added step may convince some that it's not worth it at all.

Pyrolysis

Pyrolysis is the process of burning material in the absence of oxygen and is usually performed between 500 and 800 °C. It can control waste and pollution and can create both solid and liquid fuels. One potential feedstock for pyrolysis is biomass.

Costs

One of the most important factors to consider is the economic feasibility of pyrolysis. Most research is focused on the production of an oil product that is used as a substitute for different fuel oils. A European market study for crude pyrolysis oil assigned it a delivered cost of $6.8078 to $10.9461 per GJ [EMSB 2006]. The biochar product was estimated at an average of $2.6767 per GJ. A typical high heating value (HHV) is 17 MJ/kg [EMSB] for the oil and 12150 Btu/lb [Lehmann 2009] for the char.

A Canadian company called Dynamotive Energy Systems performs pyrolysis on plant biomass and their largest plant has a capacity of 200 tons of feedstock per day. Using the assumptions previously specified for plant capacity and production rate, and assuming an oil fraction of 0.65 [Fast and Stucley] as well as Dynamotive's claimed efficiency of 0.8 [Dynamotive 2010], 0.0569 megatons of raw oil are produced per year, and 0.0175 megatons of solid char per year. At an average selling price of $8.877 per GJ for oil, sales are approximately $ 7.795 million per year [EMSB] . Assuming a solid yield of 0.2 [Dynamotive 2010] the total sales for biochar is $1.2 million per year. Total capital investment was determined with an estimate from Dynamotive which reported $30 million per megaton of installed capacity. With our capacity at 0.003 megatons per day our total capital investment for the plant is $32.85 million.

Many studies and projects have determined that the remaining products can be recycled to power the pyrolysis plant. Generally these can supply at least 75% of the required energy [EMSB]. An estimate of 5 operator shifts per day gives a direct wages and benefits estimate of $466,667. This leads to an operating cost of $581,640 per year. The return on investment for a plant this size that is producing only biocrude oil is 0.113. If biochar is also sold the return on investment could be close to 0.134.

Environment

Since they are considered carbon neutral, pyrolysis products can replace a portion of traditional carbon based fuel and lower the output of carbon dioxide. The three energy dense products are syngas, biocrude oil, and solid biochar. Process emissions are negligible; however, product emissions can be significant. Biochar is expected to have significantly lower CO_2 and SO_x emissions than traditional coal, but the NO_x emissions may be equal to those of coal or slightly higher. For this reason it is desirable to co-fire the biosolid with coal. Bio-oil has lower CO_2 and SO_2 than traditional diesel. Specific numbers for emissions depend on the desired product, the quality of feedstock, and the method of pyrolysis.

Pyrolysis of biomass is desirable because it does not require food crops as feedstock. Of the three energy-dense products, bio-oil has the greatest fuel potential. Additionally, the syngas could be used for electricity and biochar could be co-fired in coal power plants.

Technical Feasibility

Pyrolysis is a proven and effective process. It has consistent results and is widely researched, piloted, and demonstrated. It can be easily implemented because, once built, it is not complicated to operate and can likely be scaled up to be integrated into existing energy generating facilities. Pyrolysis plants are relatively uncomplicated and easily implemented.

When performed effectively, pyrolysis creates valuable fuels. A majority of current research focuses on utilizing the liquid portion for biocrude oil. It can be about 50-60% as efficient as traditional diesel oil [BPR] and can also be further refined to be even more energy efficient. The solid biochar and the combustible gas are useful as well.

The mass balance of pyrolysis depends heavily on process design and feedstock quality. According to two separate studies, the bio-oil portion tends to be around 60-70% of the total product, on a mass basis, if pyrolysis is optimized for oil [Fast and Stuckey]. The Wisconsin biorefinery states that the remainder of the product is 13-25% solid that can be used for biochar, and 10-20% combustible gas. As mentioned previously the gas is typically recycled for heating the pyrolysis. The fast pyrolysis used by the biorefinery has a yield of about 72% of the mass fed to the pyrolyzer.

Safety

There are few safety issues in performing pyrolysis. It is run at high temperatures, but lower than those of gasification. The hopper feeder is somewhat dangerous due to the moving parts but should not be considered a major threat. No hazardous byproducts are formed and many of them are potentially useful. Depending on which energy source is desired (char, oil, or gas), the remaining portions could be made into paint fillers or ink.

Social Aspect

The main political benefit to pyrolysis is that it is considered a carbon neutral process. If sold to utilities, whether as liquid fuel, gas, or charcoal to be co-fired with coal, the products can be incorporated into their percentage of renewable energy (carbon credits). The federal government is clearly an advocate because NREL is currently focusing on biomass pyrolysis as a main area of their biomass research [TCC 2009]. They have they capability for fast pyrolysis using a fluidized bed reactor. As they continue to research and develop liquid fuels, namely from bio-oil, they also plan to focus on stabilizing and upgrading bio-oil for transport and fuels.

Gasification

The process of gasification involves heating a carbon containing material to temperatures in the neighborhood of 1000 °C and exposure to low oxygen concentrations. This produces a syngas composed mainly of hydrogen (the desired product), carbon dioxide and carbon monoxide. The leftover solids consist mostly of metallic oxides. Gasification is often performed on the products of torifaction or pyrolysis to improve gas yields.

Costs

A local Cattle company, JBS Five Rivers, plans to install gasifiers at their Weld County site (Kruner, CO) [Cattle Network]. Various values they've given for the cost and capacity of their proposed system will be analyzed.

They are installing three, 4,200 lb/hr units that cost $425,000 each. From this, their operation is estimated to contain 50,000 cattle. Thus, the scale-up cost of this gasification facility is approximately $2,550,000, and is taken as the freight on board cost. Therefore, the total capital investment is $13,500,000. The JBS feed lot is building three separate gasifier units; therefore, if we estimate that each unit requires one, full time operator, the direct wages and benefits required for our scale-up is approximately $840,000 per year. The operating costs can then be estimated to be $1,000,000.

The amount of hydrogen gas produced from the process is estimated to be 3.5 MM SCF/day [Engler 1975] . The delivered price of hydrogen is $1.00 per pound [Vehicle 2002] . Thus, the annual revenue from selling the hydrogen produced from this system is approximately $3,000,000.Thus, for the scale-up process, the ROI is calculated to be 0.089. This value does not include the cost of condensing the hydrogen, nor the potential revenue gained from selling the residual ash.

Another example of a gasification system is provided by an economic analysis of a gasification process performed in 1974 by the Department of Chemical Engineering at Kansas State University [Engler 1975] . They looked at a gasifaction system designed to accomodate 200,000 cattle, so their numbers will be divided in half for our analysis. In 1974 dollars, their estimated total capital investment was $6.5 million. Normalizing for the size of the gasification capacity, this is estimated to be $15,200,000 in today's dollars. In 1974 dollars, their estimated operation costs was $2.2 million. Normalizing for the size of the gasification capacity, this is estimated to be $5,200,000 in today's dollars.

They estimated their production of hydrogen gas to be 5.20 MM SCF/day. If the delivered price of hydrogen is again taken to be $1.00 per pound, the annual revenue from selling the hydrogen is approximately $4,500,000.

This, unfortunately, produces an ROI value of -0.028. This value is considered to be less accurate than the one calculated above since it was produced by manipulating values from the 1970s.

Environment

In many farms implementing a gasification process, the syngas produced is used for heating buildings rather than selling on the market. This reduces, by about a half, the amount of heating gases that would otherwise be used [Wilson 2009] .

The desired product from gasification is hydrogen gas; however, other gasses produced in large quantities include CO and CO_2, both of which pose an environmental risk. Other compounds that can appear in small quantities include H_2S, COS, NH_3 and HCN depending on the sulfur and nitrogen content of the feed [Higman 2008]. These gases also pose environmental risks.

The gasification process does not require the addition of water. Generally, the feed needs to be dried before it can be gasified.

Issues such as noise and odor, public support, permit requirements and life cycle analysis are a largely unknown factor at this time. In this preliminary analysis, no examples of public disapproval of biomass gasification plant construction were found. Similarly, no significant information regarding required permits or life cycle considerations was found.

Technical Feasibility

In order to achieve gasification, the feed needs to reach temperatures of 1,000 to 1,600 °C. Often, pyrolysis is performed on the feed first before gasification to improve yields. Because of these high, long sustained temperatures, a significant amount of energy is required for gasification compared to other techniques.

The major gasses produced from gasification are hydrogen, carbon monoxide and carbon dioxide. The ashes produced are composed of many different oxide salts (discussed below) and can be used as a fertilizer [Wilson 2010] . The only products with absolutely no economic value are carbon monoxide and carbon dioxide.

Many different processes exist for gasification. The most complicated are continuous processes with many moving parts needed for large operations, and the least complicated are the batch processes which require far less equipment and are generally found on individual farms. Therefore, as the size of the operation increases, the complexity of the process equipment increases.

Since gasification processes are being used on many farms, feedlots, dairies and poultry farms across the United States, and since many companies specialize in designing and installing these systems, the process equipment is reliable and easy to implement.

Safety

The syngas produced contains a few harmful compounds. One that is produced in significant quantities is carbon monoxide. Other potentially dangerous compounds produced in much smaller quantities include H_2S, HCN (hydrogen cyanide), COS, NH_3, and others depending on the specific process and feed characteristics.

The left over ash is composed of K_2O, CaO, MgO, Na_2O and many other oxides [Higman 2008] . Many of these compounds exothermically react with water; therefore, the ash poses a danger if exposed to large amounts of water or inhaled.

Digestion

There are two types of digesters: Aerobic and anaerobic. Aerobic digestion has only solids as its product. It also does nothing to limit the emission of methane and other greenhouse gasses. Anaerobic digestion is likely to produce a valuable commodity (biogas) in addition to a solids product. Anaerobic digesters, therefore, are better suited for this project’s design criteria.

Costs

Cost estimates with the 100,000 cow size facility.

Assumes that heating the digester is provided by direct burning of biogas or by heat generated from an energy generator.

The yield of the digester is approximately 30.6 SCF of methane per cow per day

There are two ways to arrange large scale usage of biogas. The first option is a three way cooperation between a energy producer, an agricultural producer, and a digester operator. The agricultural producer is paid for raw biogas and then purchases energy from the utility. The second option is to upgrade the biogas to natural gas and sale to the national market. Due to the size of this project, on-farm power generation should be run by an energy utility as the energy generated would be on the order of a natural gas power generating station.

The analysis numbers are taken from a summary report of dairy manure digesters that use biogas. This report covered 95 anaerobic digesters and the minimum, average, and maximum capital costs are below. All values are taken from the Dairy Digesters study [Liebrand]

	Min	Average	Max	
Digester cost ($)/cow	194	536	1557	
Total cost ($)/cow	299	848	1959	
Digester, no energy generation ($ Million)	19.4	53.6	155.7	Total Capital Investment
DW&B+Maintanace Estimates ($/year, $4-7/cow)	400,000	550,000	700,000	
Operating Cost ($ Million/year)	0.40	0.55	0.70	

The Sale price of methane was taken from the US energy Administration website average for last year. The sale price of the methane is below.

Assumed Production of (methane) in Biogas with Impurities	30.6	ft^3/(cow*day)
Biogas	1,117	Million ft^3 / year
Cost to Upgrade (Scrub) to Natural Gas	3.88	$/(1000 ft^3)
Annual Cost to Upgrade to natural gas	4,333,572	$/year
Sales Price Average	4.0	$/(1000 ft^3)
Net Annual Income	134,028	$/year

The ROI for the average capital cost case is 0.0015. The ROI calculation does not include anything about the valuing reduction in odor or in improved manure handling.

Some common traits of biogas allow it to be applied with flexibility. If a producer has very large heating costs it could be reduced by using biogas as a direct heating source. Digester gas consists of 50-70% methane with carbon dioxide and a small amount of ammonia, hydrogen sulfide and volatile intermediates released from digestion [Miner, 2000]. Sulfur can be removed by iron gauze. The heating value of biogas is 500-550 Btu/ft^3 [Miner, 2000]. Biogas is limited to in-place use as its conversion to a liquid takes place at too high of a pressure or too low of a temperature to make use in mobile equipment practical.

Environment

The major benefit of digestion is that greenhouse gas is retained, limiting greenhouse gas emissions. Methane emissions are reduced to negligible amounts [EBIA, 2007]. Ammonia and sulfur are pollutants produced in the gas which require removal by a simple liquid stripping or adsorption processes. If the gas is flared then there is no carbon retention value. The un-quantified factor in environmental concerns is the endorsement of concentrated animal feeding. Digesters represent an endorsement of large scale concentrated agricultural practices. This leaves a small scale producer (~200 cows) at a significant disadvantage to a large scale producer.

Permits and approval for digesters can be a significant hurdle to project implementation [Keske, 2009]. The public review period is difficult if large opposition to a waste processing project is coordinated. Co-digestion permitting is difficult for Colorado because of the “stigma associated with being labeled a ‘waste energy facility’ on permitting applications.” This results in a large NIMBY effect by people not wanting to reside next to a waste processing facility [Keske, 2009].

Life cycle analysis for digesters ranks above pond digestion. Digestion ranks below the heat treatment of manure (pyrolysis) due to the large amount of solids that still have to be dealt with post digestion. While some of the solids can be sold most are spread on cultivated fields at very little profit. This practice is a mainstay of manure treatment, but digestion results in a very low energy density solid and thus has a large expense for transportation.

Land use for digestion is better than current pond treatment methods which require ten times more land. Also, a digester requires less area for large uncovered waste ponds.

Water use is high in digesters. Digesters must have a high water content, wtih approximatly 10% solids content. Depending on how quickly manure is placed in the digester, water is added. After digestion is complete, before releasing the water, it has to be monitored for biological and chemical oxygen demand. Another water treatment solution uses a two stage digestion consisting of an organic leach and a typical digester system [Keske, 2009]. The organic leach removes significant organic solvents prior to moving to the digester and these volatiles are then separated as biogas from the water, and the water for the leachate is recycled [Keske, 2009].

Technical Feasibility

Technical feasibility for digesters is extremely high as many have been built all over the world. Energy balance on the digester indicates a positive production of energy with the combustion of biogas for energy. The heat energy is used to maintain the temperature of the digester and to provide on farm energy. European digesters indicated an energy use of 28 MJ/dry ton of cow manure to a production of 5.6-8.8 GJ/dry ton [EBIA, 2007]. The energy input in was primarily from transportation of wastes to and from the digester.

Mass out of the digester is generally applied as a fertilizer after chemical characterization. Solids experience 50-60% reduction in volume [Janelle, 2005]. The only downside of mass reduction is the need for potential chemical levels to be monitored prior to agricultural application. Monitoring is only for quantification of nutrient levels and not for contamination issues [EBIA, 2007].

Process equipment is expensive for digesters. Permanent flow channels and facilities for sludge handling is a custom design for each facility. In addition, heating is required in the winter. The equipment and processes can be simple or extremely complex depending on the goals and customization. Multi-stage digestion and experimental design add expense as well as the opportunity for greater gas production. Equipment used in initial designs reviewed in the literature indicated that cheap digester covers had to be replaced after failure in the first few years. This indicates that a trend to more reliable and expensive initial construction generally provides a stronger return on investment. The reliability of the process and equipment depends very heavily on the operators. If equipment is maintained and evaluated regularly then operation can be simple. Operation of gas generators is considered adequate when used for 80% of the scheduled time. Digestion is a waste treatment operation, so down time is not possible since the manure keeps coming. Gas is flared during generator down time to avoid the need for large storage capabilities.

Implementation is given a low score as each project requires a long lead time and is almost always more successful if initiated by the operator. The implementation requires significant farm facility modification. Startup is not considered an obstacle to operation as microbes are readily available naturally or can be seeded from a local waste treatment facility. Gas production can be optimized during the startup time while not interfering with the waste treatment aspect of the digestion.

Safety

Safety elements were only considered above and beyond normal manure handling issues as producers are already adept at dealing with manure. The most significant issue for safety is that biogas is an asphyxiate, thus anyone working around or in a digester has to be provided an adequate oxygen source. The second element of consideration is using a combustible gas. This is dealt with by proper planning and equipment evaluation during digester and generator design.

As indicated earlier, gases like ammonia and sulfur have to be removed prior to energy generation or flaring. Concentration of nutrients in solids may be above levels that are directly applicable to agricultural land. Solids and waste water have to be monitored. Pathogen reduction of the solid fiber is found on 2 to 3 orders of magnitude allowing a broader scope of application [Mattocks, 2000]. The nutrient/fertilizer content of the manure is not reduced only concentrated.

Social Aspect

Local support for digesters can be quite variable. Residential neighborhoods that do not already have a large agricultural presence nearby are resistant to inclusion of waste material close by. While agricultural communities generally welcome the local energy production of a digester. Transportation of large quantities of waste never appeals to residential areas. Areas that have an odor issue can be sold a digester as an odor mitigation tool. The issue of co-digestion with other waste products provides significant barriers if the additional waste products are potential hazards or perceived as potential hazards.

Mainstream support for digestion is adequate. As biogas energy generation is considered a green technology digestion can ride the wave of public support. Generation of energy on a local level is considered a good trend by the general public. Western reliance on local tools and resources plays heavily in favor of doing it yourself attitude that is required for successful digester operation.

The Need For Renewable Energy

Alternative fuel incentives have dramatically increased in recent years. Drive for implementation of renewable energy comes from an economic standpoint as well as through political and social initiatives. Rising prices of fossil fuels, the desire for national energy security, and the welfare of the environment all play crucial roles in the demand for new energy sources. Fossil fuel alternatives include nuclear, geothermal, hydroelectric, solar, wind, and biomass. Currently these make up only fifteen percent [Trends, 2010] of the energy consumption in the United States. As technologies continue to develop, biomass is becoming an attractive option for a source of renewable power. A variety of feedcrops can be included in the definition of biomass. Most biofuel crops are considered “carbon neutral” because the carbon that is released into the atmosphere when they are burned is carbon that was captured by those plants relatively recently. It is often the case that power generation facilities of a certain locality can be retrofitted to incorporate biomass that is locally available.

Logging and farming operations in Colorado produce millions of tons of residual biomass every year. Usually this biomass represents a waste stream that is either left behind or control burned. One proposed use of such material is as energy to supplement fossil fuels. Unfortunately raw biomass is significantly less energy dense than traditional coal and it does not burn at a temperature high enough to be a viable alternative to coal. Transportation is cumbersome because it is heavy, absorbs moisture readily, and disintegrates quickly. It is also difficult to grind in order to reduce particle size. In the case of woody biomass, material properties can be improved through the process of torrefaction followed by pelletization, improving its characteristics. Once the process is complete, torrefied wood pellets have better properties for transportation and handling. Additionally, by designing a torrefaction facility alongside a logging operation, the product would retain more of its value because one of the transportation steps would be removed.

Torrefaction and Pelletisation: Process Description

Overview

Torrefaction is a thermal pre-treatment process for biomass to be used as fuel. Sometimes referred to as “mild pyrolysis,” torrefaction is the heating of biomass in the temperature range of 200 to 300 °C in the absence oxygen [Bergman]. These conditions cause the biomass to decompose and produce various volatiles. The solid product is referred to as torrefied wood, or more generally, torrefied biomass. Historically, the process has been characterized by slow heating rates and long reaction times of over an hour.

Though the process was first reported with respect to woody biomass in the 1930’s, the process received little attention until the 1980’s, when torrefied wood was considered a reducing agent for metallurgical applications. A pilot-scale demonstration plant was built in Pechiney, France to torrefy wood for metallurgy, but it was dismantled in the early 1990’s [Bergman].

The torrefaction process has seen another revival in the last ten years as a pre-treatment method to upgrade biomass for use as fuel. Raw biomass has been used as fuel for some time, but it has properties that dramatically inhibit its potential as an energy source. The energy density of raw biomass is significantly less than that of coal. In addition to relatively low calorific value, it is also very hard to grind, and is hygroscopic. These attributes make it a difficult fuel to transport, store, and burn. Torrefaction addresses all of these problems [Bergman].

Figure [1] shows a simplified mass and energy balance for the torrefaction process. Typically, 70% of the original biomass is retained as solid product, with 90% of its original energy content, increasing energy density by about 30%. The other 30% is converted to torrefaction gases, which contain approximately 10% of the biomass’s energy. In contrast, traditional pyrolysis produces energy yields of 55-65% in even the most advanced applications.

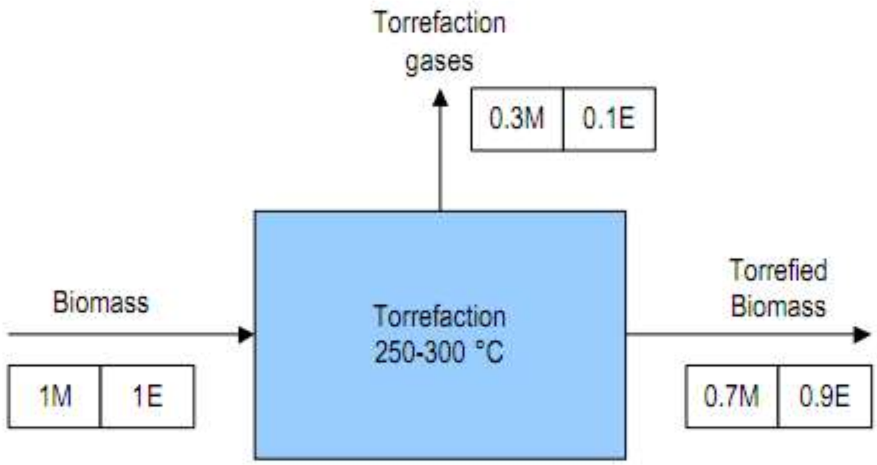


Figure [1] [Bergman]

Though untreated wood chips have been used as fuel before, even the use of "raw" biomass virtually always involves some minor processing. The biomass must be dried, and after drying, it is often densified to form pellets or briquettes. The "pelletised" product has a higher energy density, on a volume basis, than untreated biomass. Like torrefied biomass, this product has superior grinding characteristics and improved transport properties owing to their reduced volume [other Bergman].

However, despite ongoing research to improve "biopellet" properties for large-scale power production, there is still concern about their durability and biological degradation. Biopellets must be kept in controlled environments because if exposed to water, they disintegrate. There are also problems involving severe dust formation. Biopellets are also subject to significant variation in feedstock, leading to lack of uniformity in overall product and difficulty establishing homogeneous pellets when dealing with mixed feedstocks [other Bergman].

Biomass must be ground prior to pelletising and prior to co-firing in large-scale power production applications. Both processes demand the drying of biomass prior to processing. Since torrefaction improves the grinding characteristics, and pelletising improves volumetric energy density, the two processes compliment each other very well. Figure [2] provides a basic flow diagram of the overall torrefaction and pelletisation (TOP) process. As shown in the figure, torrefaction is placed between drying and grinding. The processes further compliment each other at the unit operation level because the torrefied product (which will be hot coming out of the reactor) is more easily ground and densified at higher temperatures, reducing power demands on the densification unit [other Bergman].

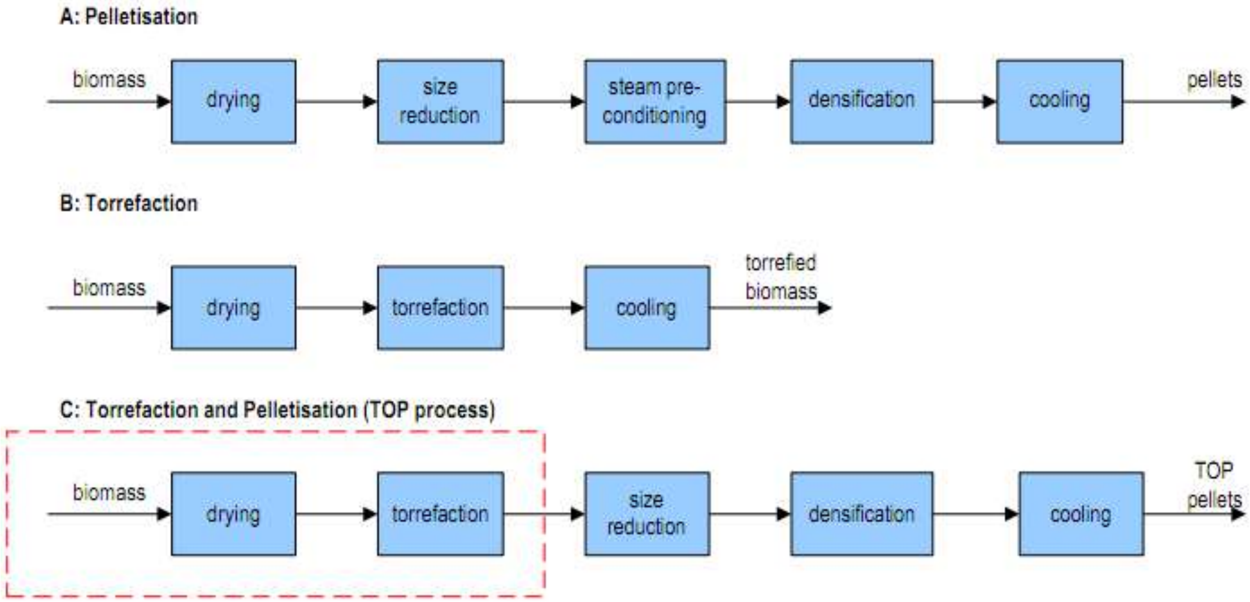


Figure [2] [Bergman]

Our Process

We are interested in taking logging residue (sometimes referred to as demolition wood) from logging sites in Colorado. Typically, logging companies use only the trunks of felled trees. Needles, twigs, and most branches are stripped [real cost]. These residues are usually burned on-site. Instead of simply burning this biomass, we would like to torrefy and pelletise it. This requires that our process be somewhat compact, and all the equipment involved should be either skid-mountable or otherwise portable.

A number of variations of the process outlined above have been proposed. Several groups have used raw feedstock to provide heat and power to their torrefaction and/or pelletisation processes. Others have used a portion of their torrefied product to provide heat and power. One thing all torrefaction operations have in common is that they burn torrefaction gases for heat in an effort to reduce fossil fuel use. Torrefaction gases, consisting mostly of water, also contain a number of volatile organics with combustion value.

Due to complications that arise from having several combustion systems, we have ruled out the use of raw biomass for heat. Additionally, based on Bergman's analysis of torrefaction off-gases, their combustion value is likely to be very low, and will provide only a small amount of the heat necessary for the operation. Therefore natural gas will be necessary to heat the system.

The wood is torrefied by contact with hot gases. Some of the torrefaction gases are recycled, heated in a heat exchanger by combustion of utility fuel, and sent back to the torrefier. Hot flue gas is used to provide the heat. After passing through the heat exchanger, the flue gas is sent to dryer, where it will provide the more mild heat necessary to dry the biomass. Solid feed will be reduced to chips prior drying. It will then be torrefied, followed by grinding and pelletising. Since densification takes place as a single unit operation, many of the design considerations center on the torrefaction gas recycle loop. Figure [3] shows the torrefaction process flow diagram, including gas recycle and heat exchange.

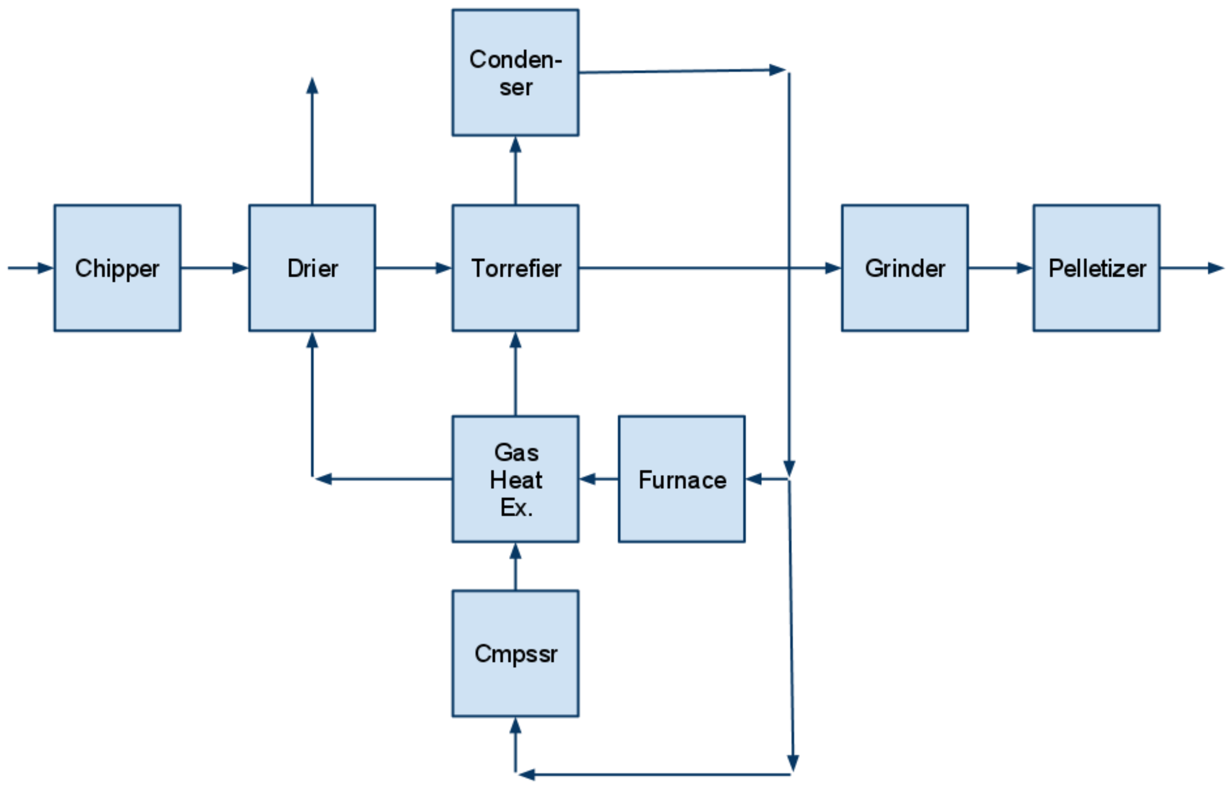


Figure [3]

Aspen Plus Design

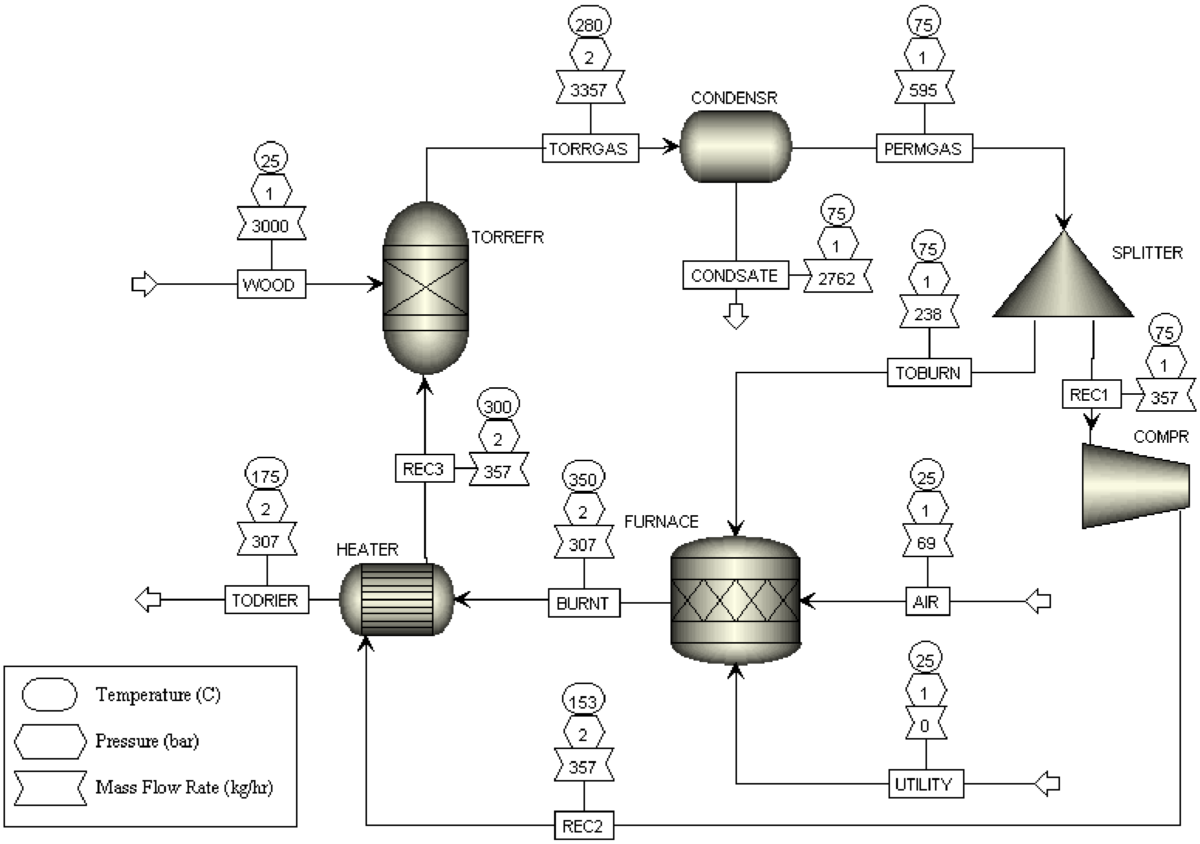


Figure [4]

An Aspen Plus model was developed to help size key pieces of equipment. Because the design recycles torrefaction gases, where some of the gas supplements the furnace and some is used to heat the torrefier, the equipment involved in this loop were best sized by modeling them. The model only examines equipment in the gas recycle loop because the sizes of other pieces of equipment--such as the chipper, grinder, drier, etc--only depend on the feed rate, which is assumed to be fixed. The Aspen model also helps predict optimal an recycle ratio, air and utility-fuel flow rates, and condensate composition.

Details of each process step:

Feedstock

Process 150 acres per job

1 acres/day

1500 trees/day

¾ yd^3 slash/tree

1125 yd^3 slash / day (unbundled)

Compression ratio of a John Deere bundler 80%

Bundled Density is 19 lbs/ft^3 or 8.6 kg/ft^3 [Peterson 2005]

The plant will take the slash, tree branches and tops that are normally left behind or burned by a full sized mechanical logging site. Since this is usually a discarded byproduct of the logging industry, it is believed that the feedstock will be free. It is assumed that: there are 1500 trees per acre, a typical logging company can process an acre a day, and a typical tree provides three fourths of a cubic yard of slash. The density of the slash varies greatly on many factors such as the tree species and many factors of the logging [Peterson, 2005]. With such a wide range of densities, an average was taken. The feedstock was calculated to be 100 tons per day, or 1125 cubic yards per day. Our project starts after the loggers have removed the slash from the trees.

Chipping

With a feed rate of 1125 cubic yards per day or 140 cubic yards per hour, a chipper was needed for the first step of the process. The chipper is assumed to be fed by a log loader between truck loads or any other free equipment that the logger has on hand.

Drying

With chips from the feed measuring 1”x1”x1” and with a flow rate of approximately 100 tons per day, the chips will need to be dried before entering the torrefaction unit. A drying unit operating at elevated temperatures will be necessary for our purposes. A facility that dries biomass over a course of weeks would be prohibitively large to have at a logging site. The chips enter at 45 wt% water, and will need to be dried to 10 wt% water. The dryer will produce 10,000 pounds of exhaust water per hour and 15,000 pounds of dried product per hour.

Torrefaction

The torrefier will reduce the mass of the feed by approximately 70%. Although the mass entering the dryer should have a moisture content of no more than 10%, most of the mass lost in the torrefier is water. This is because water is produced by the devolatilization and decomposition of polymers in the biomass. The biomass will enter the torrefier at approximately 110 °C, so will have to be heated up. For this reason, the torrefier is divided into two regions: heating and torrefying. It is assumed that the only mass lost during heating is water. The temperature of the biomass will increase to 280 °C in the heating region, after which torrefaction begins. This model is based off of the dryer/torrefier hybrid model produced by Idaho National Labs.

The torrefiers will be a moving bed reactor with solids moving down the tube, and hot gases flowing counter-currently upward. A single large torrefier would demand an excessive footprint, therefore more production lines involving multiple torrefiers will be needed.

Condenser

The gases evolved from the torrefiers are composed of, in decreasing order, water, carbon dioxide, and carbon monoxide , with trace amounts of various organics. Before the gases are sent to the furnace and heat exchanger, the water and organics need to be removed. The water is condensed and removed so that energy is not wasted heating water in the furnace. Many of the organics are condensed with the water and may need treatment.

Furnace

Heat is provided to the torrefiers by a furnace burning a utility gas (methane), suplemented by the torrefaction gas (by combustion of carbon monoxide). Idealy, the process will achieve autothermal opperation, and no utility gas need be used. Oxygen for combustion is supplied by an air feed.

Heat Exchange

Heated gases from the furnace are sent to a heat exchanger, where they heat the other half of the torrefaction gases. The now heated torrefaction gasses are sent back to the torrefier.

Grinding

In order to be suitable for co-firing with coal, torrefied biomass should resemble coal as much as possible. This means it must be ground and densified to a product with a similar particle size, density and heating value. The conventional method is to reduce the size of torrefied biomass using a grinder and then send it to a pelletizer which creates a product that is more energy dense and easier to transport and handle. To determine equipment specifications for a grinder a torrefier ouput of about 40 to 50 tons per day was calculated. If the grinder runs for eight hours each day, one should be purchased that has a capacity of five to six tons per hour.

Pelletizing

Pelletization is the process of reducing the bulk volume of the torrefied biomass for increasing the energy density [Mani 2010]. The hot lignin is the primary binding agent in pelletized biomass [United States 2010]. The process flow for the pelletizer is the same as the grinder at 40 to 50 tons/day. This means the capacity of the pelletizing process is targeted at 5 to 6.25 tons/hr of ground warm biomass. In addition to a pelletizing some method of cooling the fresh pellets must be used since hot pellets all placed in a pile will decompose rapidly if they are warm. Thus a cooling means will be employed. Cooling on a conveyor will be utilized, as the pellets are to be transported immediately the cool time on a slow moving conveyor is approximately 3 seconds. With the need to use a conveyor to hoist pellets into a truck bed the cooling time will happen without need for an additional cooling step.

Pellets standards have been developed by the Pellet Fuels Institute and have been nominated to be included in the Standards Development Process with the EPA [Pellet Fuels Institute]. The table below indicates the minimum fuel standards which our process is designed to meet. The measurement of fines Inorganic ash and chloride are all fuel standards that need to be analyzed for each produced pellet. As the selling of raw biomass pellet industry has no problem meeting these standards the torrefaction process will not pose any foreseeable problems.

TABLE 1 PFI Fuel Grade Requirements

	Residential/Commercial Densified Fuel Standards See Notes 1 & 2		
Fuel Property	PFI Premium	PFI Standard	PFI Utility
Normative Information - Mandatory			
Bulk Density, lb./cubic foot	40.0 - 46.0	38.0 - 46.0	38.0 - 46.0
Diameter, inches	0.230 - 0.285	0.230 - 0.285	0.230 - 0.285
Diameter, mm	5.84 - 7.25	5.84 - 7.25	5.84 - 7.25
Pellet Durability Index	≥ 96.5	≥ 95.0	≥ 95.0
Fines, % (at the mill gate)	≤ 0.50	≤ 1.0	≤ 1.0
Inorganic Ash, %	≤ 1.0	≤ 2.0	≤ 6.0
Length, % greater than 1.50 inches	≤ 1.0	≤ 1.0	≤ 1.0
Moisture, %	≤ 8.0	≤ 10.0	≤ 10.0
Chloride, ppm	≤ 300	≤ 300	≤ 300
Informative Only - Not Mandatory			
Ash Fusion	NA	NA	NA
Heating Value	NA	NA	NA

Post Processing

It is assumed that cooled hard pellets with a density of about 800 kg/m^3 are produced. The most economical way to deal with the product is to minimize storage between unit operations. Thus a set of belly dump trailers will be used for day storage and transport of the pellets. Typical capacities of belly dump trailers range from 20 to 25 cubic yards per trailer [Truckers]. Given a volumetric flow rate of 60 to 75 cubic yards per day of densified biomass, a minimum of three trailers will be needed each day. Due to limitations in haul and processing time of trailers, a total of six trailers should be purchased to account for buffering capacity of product transportation scheduling.

Distribution of the pellets was from a storage facility was not explicitly considered in this process as location specific and market details will drive this decision. The cost of bagging and tranportation of the product from the distribution facility was estimated by assistance from iCAST. The cost were 30 $/ton each for packaging and transportation.

EQUIPMENT

Chipping

A Rotochopper MC266 - Mobile diesel powered wood grinder/processor was sized to accommodate a feed rate of 200 cubic yards per day. It processes the slash into 3”x3”x1” chips, and uses a conveyor belt to move the process chips to the next station. It can be transported from site to site by a truck that can haul a fifth wheel trailer. The trailer is 50’ 3” long, 102” wide and 13’ 5” in height. This piece of equipment was quoted at $250,559.

Drying

An Onix ONL-126 was sized to dry the chips. It is a rotary dryer that uses natural gas to supply heating. The estimated cost per wet ton to run the ONL-126 is $10.73. The footprint of the machine is 150’ by 50’, but can be broken down into different parts for transportation. This piece of equipment was quoted at $1,012,000.

Torrefaction

The torrefier is based off the design recommended by the Energy Research Centre of the Netherlands (ECN) and outlined by Idaho National Labs. A vertical tube will be charged with dry wood chips supplied by a hopper feeding through a rotary airlock. Hot gases will flow up the column through the packed bed of chips, providing heat necessary for sustained torrefaction at the bottom and cooling as it flows up. Solid reaches the bottom and falls through an exit hopper, another rotary airlock, and onto a screw-conveyor.

The processing option with the lowest footprint involves the use of four torrefiers, all designed for a throughput of two tons per hour. Based on a torrefier with a 1.2 meter diameter operating at a torrefaction temperature of 300 °C, the following torrefier dimensions can be determined:

Table 1

Flow Rate (kg/hr)	2000
Diameter (m)	1.2
Incoming Solid Temperature (°C)	110
Incoming Gas Temperature (°C)	300
Height (m)	3.4
Volume (m^3)	3.2
Residence Time (min)	22
Length-to-Diameter Ratio	2.8
Heat Required (kW)	930
Pressure drop (psi)	20

Sizing calculations for the torrefier are provided in the enclosed spreadsheet. The torrefiers will see consistent, but low concentrations of organic acids in torrefaction off-gases, so all equipment associated with their construction should be stainless steel.

Estimates place the cost of a torrefier around $111,000 per torrefier.

Condenser

To condense water from the torrefaction gases, a shell and tube heat exchanger can be used, with cooling water flowing on the tube side, and torrefaction gases flowing on the shell side and water condensing on the tubes. The equipment selected for this operation is the Exergy 00486-8. The model was selected based on its heat exchanger area (0.70 m^2) compared to the predicted heat exchanger area given by the Apsen Plus model (0.65 m^2).

Furnace

Grinder

The most widely used piece of equipment for the grinding step is a hammer mill. Hammer mills operate by feeding material through a hopper into a grinding chamber and crushing it by spinning rotors with attached hammers at a high speed. Once the particles are reduced in size they are filtered through a mesh screen. Milling chambers often range from 24 to 48 inches in diameter, with a width of 10 to 18 inches [Hammer Mills]. The weight of the machine, assembled size, and power required vary based on the system. The model selected for the proposed design is a Schutte Buffalo Hammermill 15 Series Model 1580. It has the following specifications:

- Weight: 6700 lb
- Shaft speed: 1800 RPM
- Power Required: 150 HP
- Rotors: 24" diameter
- Screen area: 1680 in^2
- Approximate assembled area: 108 ft^2

Price estimates for this model has been difficult to obtain, though similar equipment can be purchased for around $10000 to $20000.

Pelletizing

Initial options for the production of densified biomass.

- Example Buhler RWPR 900 at 5 tons/hr or 4535 Kg/hr
    - $425000 initial price estimate for the machine and options
    - Replacement of the die ring 25000$ every 2 years
- Product is 6 or 8 mm diameter pellets
    - Both are appropriate for pellet stoves
- Flow rate is 5 tons/hr
- pellet size is 6-8 mm diameters
- Requires a cooling step
    - the cooling of the pellets is accomplished by 3 seconds in open air
    - As we are loading directly into semi-truck trailers then cooling will be finished by the time that loading happens

Biomass product is a wood pellet with the highest density of product available.

Post Process

Per the above recommendation, a set of 6 belly dump trailers should be sourced. An estimate of the cost is approximately $40,000 per trailer, for a total of $240,000. Also a method of loading is required. A conveyor belt to a set of parked empty trailer is recommended with pricing to be in the $100,000 target range all post processing equipment.

Equipment Table

Unit Operation	**Name of Product**	Power Required (hp)	Total Power (HP)	Fuel Diesel (Gallons/hr)	Cost of Equipment ($)	Maintences/year costs? estimates
Gas Heat Ex.	Exergy 00486-8		0		6000	
condenser	Exergy 00486-8		0		6000	
Chipper	Rotochopper MC 266 FP		0	247.5	250559	
Dryer	Onix Corp. ONL-126		0		1012000	
Torrefiers (4)		5364	5364		111000	
Grinder	Schutte Buffalo Hammermill 15 Series Model 1580	150	151	0	20000	
Pellitizing	Pellet mill RWPR 900-NA	450	450	0	425000	12000
Hoppers (8)			0			
Airlocks (8)	Meyer HDX 6-vane 12" round		0			
Trailers for transportation (6 belly dump trailers)	used equipment estimate		0		250000	
Compressor	Atlas Copco XAS 375 DD6 com2/com3	147.5	147.5		313991	
Furnace	Industrial Combustion LND-420 (P)		0			
Totals			**6113**	**247.5**	**2394550**	**12000**

Energy Balance and Utilities

Energy balance calculations were done on the basis of 12 ton/hr feed rate into the dryer. The balance equations used are based on recommendations and methodology used by Idaho National Labs in the design of their pilot scale moving-bed torrefaction unit. In their system, the drying and torrefying operations are combined into a single reactor. In our system, drying takes place separately from torrefying. The essential heat transfer calculations are very similar. For all of these calculations, it is assumed that each biomass chip is a cube that is one inch on each side. In general, this will be the *maximum* size of a biomass pellet; most will be smaller than this. Heating times, then, are probably slightly overestimated.

For the drying process, it is assumed that chips will enter the drier at approximately room temperature. Heat demand was modeled as being part of two regimes. The first calculates the heat and time necessary to bring the particles up to drying temperature, and assumes that no mass is lost during this period. In the second regime, biomass is drying, and it is assumed that its temperature stays constant during this period. The time necessary to heat a single pellet up to drying temperature is given by Equation 1.

$$\frac{T - T_e}{T_0 - T_e} = e^{-\left(\frac{hS}{\rho CV}\right)t}$$

The heat required to raise the temperature of the biomass is

$$Q_h = m_p C_p \Delta T$$

It is assumed that water will begin evaporating as soon as the mass is at the drying temperature. The dryer is specified to reduce moisture content to approximately 10%. Equation 3 is used to determine how long it will take to evaporate the water.

$$\frac{M - M_e}{M_0 - M_e} = e^{-kt}$$

Where *k* is given by

$$\ln(k) = -2200\left(\frac{1}{T}\right) + 2.76$$

The heat necessary to dry the biomass is simply the mass of water multiplied by its heat of vaporization.

The torrefiers were sized an a very similar basis. However, further considerations were made in order to determine an ideal geometry for the torrefier. Just like the drying equations, these equations are based on Idaho National Laboratory's calculations. The time necessary to heat biomass up to torrefaction temperature is given by Equation 5.

$$\frac{T - T_f}{T_0 - T_f} = e^{-\left(\frac{hS}{\rho C_p V}\right)t}$$

The time required to reduce the mass during torrefaction is given by

$$\frac{m - m_e}{m_0 - m_e} = e^{-kt^n}$$

Throughout the torrefaction process, the bulk density changes due to changes in moisture and volatiles content. We write the bulk density as a function of its constituent compositions.

$$\rho = \frac{1}{\frac{X_w}{\rho_w} + \frac{X_v}{\rho_v} + \frac{X_s}{\rho_s}}$$

In addition to the solid biomass, considerations must be made for the flow of gas through the reactor, and their provision of heat for the solids. Since the purposes of the flowing gases is to heat the solids, a heat demand for the biomass must first be considered. The heat necessary to torrefy the biomass is given by

$$Q_P = m_p C_p \Delta T + m_p w h_{fg}$$

The heat provided by the hot gases is given by

$$Q_a = m_a C_{p,a} \Delta T_a$$

Equation 8 is set equal to equation 9 in order to form a steady state energy balance.

A sample calculation for drying time, torrefying time, and heat requirements are provided in Appendix ().

Economics

The product produced is a densified biomass pellet.

- Less than 8% water content
- 40 lbs/ft^3 or 640 Kg/m^3
- 19-22 MJ/kg or 42,000 BTU/lb [Bergman 2005]
  - Coal compares at 25-30 MJ/Kg

The overall costing method used the Lang method for estimating Chemical plant capital costs [Seider 2010]. The freight on board (FOB) cost of all equipment is presented in the prior table. The total cost was estimated by the following equation.

$$Ctci = 1.05 * fLtci * \Sigma \frac{Ii}{Ibi} * Cpi$$

- 1.05 is used as a delivery correction for the 5% cost of delivery of equipment
- Ctci is the total capital investment with the 15% working capital included
- fLtci is the Lang factor for a solids-fluids processing plant at 5.03.
- Ii/Ibi is the correction of cost indecencies for the plant from when the current Lang factors were published in 2000. Using an estimate based on the ten year jump of 1.1
- Cpi is the total FOB cost of the equipment specified.

The economics of the following process are made with the following assumptions.

- 3 operators to run per shift and only 1 shift per day
    - This is due to limits of logging during the daylight and expected flow rates of biomass. The cost of using operators was estimated at 35$/hour for Wages and Benefits [Seider 2010].
- The yield of product to initial biomass is 40% (by wt)
- The operation is only producing product for 75% of the time
    - The remainder of the time is spent on moving the equipment (once per year) and maintenance
- The selling price range is from 260 to 520 $/ton
    - Based on a low end of raw biomass pellets selling at 260 $/ton [Confluence Energy]
    - Converting on the difference in energy density from raw wood pellets to torrefied wood pellets gives and equivalent price for torrefied biomass of 300 $/ton.

Total Capital Investment	13,911,499	
Product Produced per year	11,250	[tons/year]
Fuel Cost	2,283,188	[$/year]
Power Cost	618,972	[$/year]
Utilities Cost	400	[$/year]
Operator Cost	315,000	[$/year]
Technical assistance to Manufacturing	180,000	[$/year]

Bagging Costs (30$/ton)	337,500	[$/year]
Sales/Transportation (30$/ton)	337,500	[$/year]
Total Costs	4,072,560	[$/year]
Net Profit at $260/ton	-1,147,560	[$/year]
Net Profit at $360/ton	-472,560	[$/year]
Net Profit at $380/ton	202,440	[$/year]
Net Profit at $450/ton	989,940	[$/year]
REC Value (20 MJ/ton) (14$/MWh)	875	[$/year]

The prior information shows that the cost of using a torrefied process demands a higher sale price than using raw biomass pellets. The conversion for the higher energy density of the torrefied biomass pellets indicates that even at the energy content price of 300$/ton there is not a positive operation cost. Also, when compared with the cost of coal at approximately 100$/ton and a higher energy density there is a sizable cost difference. The calculation of renewable energy credits, based on the Chicago exchange value of 14$/MW hr shows that the fuel product cost difference is not recovered significantly by the REC, based on the Connecticut exchange [CCFX]. The annual amount of REC credit is only 1000 $/year. The economic result is in line with the estimations discussed in the feasibility report.

BIBLIOGRAPHY

Arcate, J.R. Torrefied Wood, an Enhanced Wood Fuel. *Bioenergy 2002* [Online] 2002. http://www.techtp.com/recentpapers/BE2002.htm (accessed Dec 3, 2010).

Basu, P.; Butler, J.; Leon, M.A. Biomass co-firing options on the emission reduction and electricity generation costs in coal-fired power plants. *Renewable Energy* [Online] 2011**.** *36*, 282-288. http://www.sciencedirect.com/ (accessed Oct 8, 2010).

Bellefeiulle, David. Rocky Mountain Timber and Tree. Phone Interview.

Bergman, P.C.A.; Boersma, A.R.; Zwart, R.W.R.; Kiel, J.H.A. *Torrefaction for biomass co-firing in existing coal-fired power stations*. Energy Research Center of the Netherlands. Petten, Netherlands, 2005.

Bergman, P.C.A. *Combined torrefaction and pelletisation: The TOP process*. Energy Research Center of the Netherlands report. Petten, Netherlands, 2005.

Biomass Pyrolysis Research [BPR]. United States Department of Agriculture. April 2010. <http://www.ars.usda.gov/Main/docs.htm?docid=19898>

Bureau of Labor Statistics (BLS). Inflation Calculator. http://www.bls.gov/data/inflation_calculator.htm (accessed Dec 1, 2010).

Bridgeman, T.G.; Jones, J.M.; Shield, I.; Williams, P.T. Torrefaction of reed canary grass, wheat straw and willow to enhance solid fuel qualities and combustion properties. *Fuel* [Online] 2008. *87*, 844-856. http://www.sciencedirect.com/ (accessed Sept 16, 2010).

Cattle Network. "Colorado Companies' 'Gasifier' May Use Manure's Mojo." The Associated Press. Web. 20 May 2010. <http://www.cattlenetwork.com/Colorado-Companies---Gasifier--May-Use-Manure-s-Mojo/2010-05-20/Article_Latest_News.aspx?oid=1082999&fid=CN-LATEST_NEWS_>.

CCFX. Chicago Climate Exchange. http://www.ccfe.com/ccfe.jsf. April 17, 2011

Chen, W.; Kuo, P. A study on torrefaction of various biomass materials and its impact on lignocellulosic structure simulated by a thermogravimetry. *Energy* [Online] 2010. *35*, 2580-2586. http://www.sciencedirect.com/ (accessed Sept 16, 2010).

Confluence Energy. Kremmling, Colorado Pellet mill, www.confluenceenergy.com. February 2011.

Dynamotive Energy Systems. 2010. <http://www.dynamotive.com/>.

Engler, Cady R., Walter P. Walawender, and Liang-Tseng Fan. "Synthesis Gas from Feedlot Manure. Conceptual Design Study and Economic Analysis." *Environmental Science & Technology* 9.13 (1975): 1152-157. Print.

Energy Information Administration (EIA). Coal FAQs. http://www.eia.doe.gov/ask/coal_faqs.asp (accessed Dec 1, 2010).

Energy Research Center of the Netherlands (ERCN). Phyllis: The composition of biomass and waste. http://library.williams.edu/citing/styles/acs.php (accessed Sept 16, 2010).

European Biomass Industy Association (EBIA). “Anaerobic Digestion”. 2007. Web http://www.eubia.org/108.0.html.

European Market Study for BioOil (EMSB). Climate Change Solutions. 15 December 2006.

Fast Pyrolysis. Energy Center of Wisconsin. 2004-2010. http://www.biorefine.org/proc/fastpyro.pdf

Federal Reserve Bank of St. Louis (FRBSL). Economic Research. http://research.stlouisfed.org/fred2/data/EXUSEU.txt (accessed Dec 1, 2010).

Fusselman, Steve, Alan Darby, and Fred Widman. *Advanced Gasifier Pilot Plant Concept Definition*. Rep. Canoga Park, CA: Pratt & Whitney Rocketdyne, 2006. Print.

Higman, Chris, and Maarten Van Der. Burgt. *Gasification*. Amsterdam: Gulf Professional Pub./Elsevier Science, 2008. Print.

Institute of science and Society. “The biogas Economy”. 2010. Web http://www.i-sis.org.uk/theBiogasEconomyArrives.php.

Janelle, Robbins H. *Understanding Alternative Technologies for Animal Waste Treatment: A Citizen's Guide to Manure Treatment Technologies*. Waterkeeper Alliance, 2005. Print.

Keske, Catherine. *Economic Feasibility Study of Colorado Anaerobic Digester Projects*. Publication. Colorado Governor’s Energy Office, Aug 28th, 2009. Print.

Lehmann, J. and S. Joseph (eds.). 2009. Biochar for Environmental Management: Science and Technology. Earthscan, London & Sterling, VA.

Liebrand, Carolyn Betts, and K. Charles Ling. “Cooperative Approaches for Implementation of Dairy Manure Digesters”. USDA rural development. research Report 217.

Mani, Sudhagar. Grinding & Pelleting Economics. GA, Athens. 05 Mar. 2011. *The University of Georgia*. Agricultural Engineering Technology Conferance, 11 Sept. 2009. Web.

Mattocks, Richard P. "Waste Treatment: Anaerobic and Aerobic: Benefits, Costs and Operating Experience at Ten Agricultural Anaerobic Digesters." *Animal, Agricultural and Food Processing Wastes*. By Mark A. Moser. St. Joseph: American Society of Agricultural Engineers, 2000. 346-52. Print.

Miner, J. Ronald., F. J. Humenik, and Michael R. Overcash. "Anaerobic Treatment." *Managing Livestock Wastes to Preserve Environmental Quality*. Ames: Iowa State UP, 2000. 135-86. Print.

Netherlands. Energy Research Centre of Netherlands. ECN Biomass. *Combined Torrefaction and Pellitisation: The TOP Process*. By P.C.A. Bergman. July 2005. Web. 2011.

2 Netherlands. Energy Research Centre of Netherlands. ECN Biomass. *Torrefaction for biomass co-firing in existing coal-fired power stations: "BIOCOAL"*. By P.C.A. Bergman, A.R. Boersma, R.W.R. Zwart, J.H.A. Kiel. July 2005. Web. 2011.

“Hammer Mills.” *www.pacceram.com*. Web. 13 Mar. 2011.

Pellet Fuels Institiue. North American Trade Association. 2011. http://pelletheat.org/, March 2011.

Peterson, Douglas R. *The Real Cost of Extracting Logging Residue*. Tech. Lumberjack RC&D, 2005. Print.

“Renewable Energy Trends in Consumption and Electricity.” U.S. Energy Information Administration. August 2010. <http://www.eia.doe.gov>

Ro, K.S. et Al. *Pyrogasification of Blended Animal Manures to Produce Combustable Gas and Biochar.* International Symposium on Air Quality and Manure Management for Agriculture. 2010. <http://asae.frymulti.com/azdez.asp?JID=1&AID=32676&CID=isaq2010&T=2>

Seider, Warren D. JD Seader, Daniel R. Lewin, and Soemantri Wildagdo. *Product and Process Design Principles: Synthesis, Analysis, and Evaluation 3rd edition.* Wiley 2010.

Serio, et. Al, *Pyrolysis Processing of Animal Manure to Produce Fuel Gases*. Advanced Fuel Research, Inc. East Hartford, CT. 2002.

State of Colorado Legislature. H.B. 1001: Concerning incentives for the installation of new distributed renewable energy generation facilities in Colorado. http://www.leg.state.co.us/CLICS/CLICS2010A/csl.nsf/fsbillcont3/47C157B801F26204872576AA00697A3F?Open&file=1001_enr.pdf (accessed Dec 3, 2010).

Stucley, Colin. *Australia’s First Commercial Pyrolysis Bio-Oil Project*. Renewable Oil Corporation. Surrey Hills, Australia. November, 2007. <http://www.renoil.com.au/Bioenergy%20Aust%20Conf.%202007%20%20session3%20-%20for%20publication.pdf>.

Thermochemical Conversion Capabilities (TCC). National Renewable Energy Laboratory. November 2009. <http://www.nrel.gov/ >.

"Trailers, Used Trailers." *Trucker.com*. Web. 11 Mar. 2011.

United States. Idaho National Laboratory. Department of Energy. *A Review on Torrefaction Process and Design of Moving Bed Torrefaction System for Biomass Processing*. By Jaya Shankar Tumuluru, Shahab Sokhansanj, and Christopher T. Wright. Aug. 2010. Web. Feb. 2011.

Wilson, Kelpie. "Frye Poultry Manure Gasifier." *Mother Earth News*. 5 Mar. 2009. Web. 14 Oct. 2010. <http://www.motherearthnews.com/Energy-Matters/Biochar-Poultry-Manure.aspx>.

Wyssmont Company Website. Wyssmont Turbo Dryer. *Wyssmont*. http://www.wyssmont.com/product_detail.php?section=Dryers&id=1 (accessed Oct 1, 2010).

"Vehicle Technologies Program: Fact #205: February 25, 2002 Hydrogen Cost and Worldwide Production." *Vehicle Technologies Program*. U.S. Department of Energy. Web. 05 Nov. 2010. <http://www1.eere.energy.gov/vehiclesandfuels/facts/favorites/fcvt_fotw205.html>.

DRAFT

Report for

Mobile Biochar Production Process

to

International Center for Appropriate and Sustainable Technology (iCAST)

April 28th, 2011

Benjamin Miller, Kelly Albano, Deena Garland

Herron Kennedy, William Nabours

For CVEN 4434/5434

Dr. Angela Bielefeldt

University of Colorado at Boulder

Contents

Introduction

The purpose of this Assessment is to explain how the Bio-Buff Consulting team will design a biomass to biochar process through a mobile torrefaction system. The biomass to be used will come from sawmill residue from Delta Timber, located in Delta Colorado. The process will have to be efficient, economical, and mobile. The goal is to create a biochar that can be readily used as a fuel supply at power plants in order to replace coal. In this assessment we will first offer background information on both the local environment as well as the torrefaction process. The assessment begins with an analysis of the background on the local area, local power needs and coal supply, as well information on various stakeholders. We will then discuss the regulations and tax incentives associated with constructing a mobile torrefaction unit in Delta County.

We will then analyze four different design alternatives. These include batch versus continuous reactor, autothermal versus non-autothermal process, pelletization versus briquetting of the final product, and various forms of air pollution control. We will then conclude which alternatives to use in our final design. These design decisions were made by considering key decision criteria outlined by iCAST that included: variable operation rates, flexible capacities, product compatibility with coal co-firing, mobile or semi-mobile, and self-powered. Each respective decision matrix will be discussed within each section.

In the Design portion we will go into further detail on each of the design components including cost, dimensions, and other relevant specifications. The total Capital and Operations and Maintenance costs, including tax incentive will be tallied at the end. The possible selling price for the final product will be estimated based on the region’s local economy and the feasibility and Return on Investment of the entire project will be calculated.

Delta Timber Background

The city of Delta is located on the Western slope of Colorado, and is the largest city in Delta County. As of 2000 the population consisted of 6,400 people and 2,569 total households (U.S. Census Bureau, 2009). The picture below shows the city and the surrounding area.

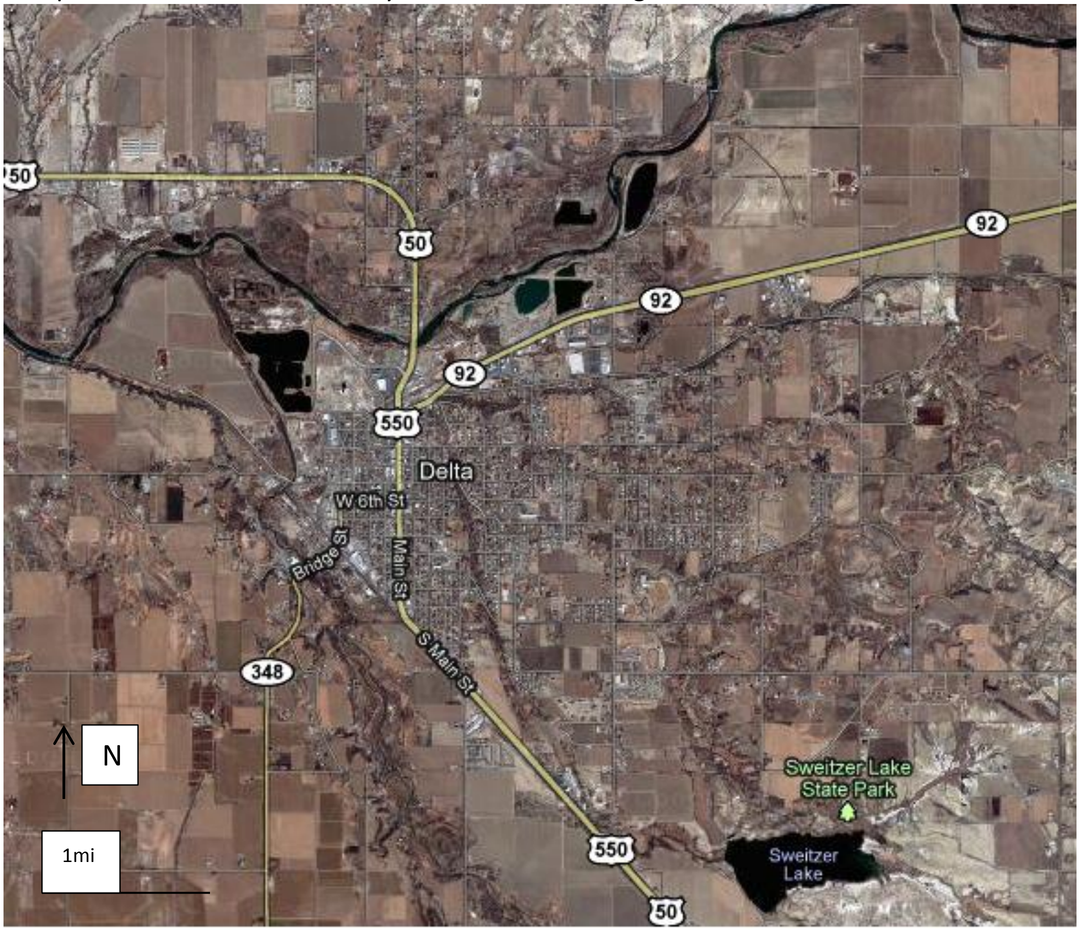


Figure 1 Aerial view of Delta, Colorado (Google, 2011)

Delta Timber's primary product is lumber to be sold for home construction. The annual sales are estimated to be between five and ten million dollars (Manta, 2008). It is located off of highway 92, just short of Delta, Colorado and includes the sawmill itself as well as a smaller building used as an outlet store. An aerial view of the mill is shown below. The company deals primarily with aspen trees but also with a certain amount of conifer trees. Live aspen trees tend to be made of very slow burning wood and have a high moisture content ranging from seventy percent in dry seasons to around ninety-five percent for quaking aspen (Hee, 2010). Live conifer wood is slightly drier on average but still retains an average moisture content of seventy-five percent (Umbanhowar, 2008).

Figure 2 Aerial view of Delta Timber (Google, 2011)

The Delta Timber Company is currently considered a zero waste company, as they have found a market for all of the waste that the mill produces. This arrangement not only lessens the mill's environmental impact but also provides additional income. Table 1 below summarizes the secondary products that the mill produces and what industries typically purchase them. It is from these secondary products that we will divert materials to use as biomass. The density of the products can be assumed to be between 6750 to 10800 kg/yd^3 (Forest2Market, 2011).

Table 1 Delta Timber's Secondary Products (iCAST, 2011)

Product	**Amount (cubic yards per day)**	**Market**
Planar Shavings	370	Animal bedding industry
Bark	30-60	Landscape and soil amendment markets for composting
Sawdust	90-150	Used for restoration products in oil and gas industry Animal bedding industry
Mulch	250-300	Playground cover Landscape and restoration products
Broken Logs	2.4	Sold locally as firewood

Delta Timber receives around five to six dollars per cubic yard of secondary product with the purchaser paying all shipping fees. This income comes to about $3700 to $5300 per day. The products are shipped to about eight different states along the Rocky Mountain Range, which allows the assumption that the average shipping distance is around 300 miles. (iCAST, 2011)

The environmental impact most of these products is minimal. The wood products that are used for landscaping, playground cover, and composting are open to the atmosphere and decay naturally. The decay rate of aspen wood varies significantly with the specific aspen species and the local climate. In many cases the presence of decaying aspen wood can have a positive effect on the surrounding soil. Decaying mulch and compost adds nutrients to the soil preventing crusting of the soil surface too improvement the movement and absorption of water. For dryer areas, mulching can prevent moisture from being lost through evaporation, and also keep the soil colder in the summer and warmer in the winter, allowing for a more consistent temperature year round. This can make the use of mulch essential for some farming industry applications. (Kluepfel, 2010)

Products going to the animal bedding industry are either composted or sent to a landfill after being used. The sawdust being used for the oil and gas industry is also most likely landfilled after use.

Local Power Background

In looking for potential customers for the torrefied biomass, it is important to understand the energy needs of the local area. The chart below states the energy output of local coal-fired power plants within 90 miles from the sawmill, as well as their location compared to Delta Timber and the West Elk Coal Mine.

Table 2 Power Plants Located in Delta County (CO, Power Plants, CO Power Plants) (Google, 2011)

City	Power Output (kW)	Distance from Sawmill	Distance from Mine
Delta	4989	2	40
Montrose	113,100	23	62
Mesa	3,000 18,600	54	81
Gunnison	86,400	86	98
Grand Junction	66,000	40	79
Nuclea	114,000	75	116

Because the only potential customers of our final product are coal fired power plants, the only two plants we can consider selling to be Grand Junction's Cameo Station and Nuclea's Nuclea station.

The picture below shows Delta County with Delta Timber Shown in green, the two power plants shown in yellow, and the West Elk Coal Mine shown in red.

Figure 3 - Aerial view of Delta County, Delta Timber shown in green, power plants shown in yellow, and West Elk Mine shown in red (Google, 2011)

The Grand Junction, which is located around 40 mi from the saw mill, is owned by the Public Service Company of Colorado and created as the world's first solar/coal hybrid plant (Scott, 2010). The project was run jointly by both Xcel Energy and Abengoa Solar and the total solar usage reduces the coal consumption by 2 to three percent and accounts for about one megawatt of the output power (Scott, 2010). The coal consumption of Cameo Station is around 300,000 tons annually (U.S. Department of Energy, 2007). Although the total solar energy used is far from a significant fraction of the power usage, it still is a strong indication that the local community is open to accept alternative forms of power, making this plant our primary potential customer. Also, Cameo is the closest plant to Delta Timber, making the transportation costs much smaller. Because of this, Cameo is considered to be the primary potential customer for the final product.

The other potential customer is the city of Nuclea. Nuclea Station is owned by Tri-State Generation and Transmission (U.S. Department of Energy, 2007). It is located farther away from the sawmill than Cameo but has a much higher energy output. The estimated amount of coal for Nuclea is 650,000 tons per year (U.S. Department of Energy, 2007). Nuclea would be the second choice for potential customer for the final product.

The West Elk Mine, owned by Arch Coal, is located a mere forty miles away from the sawmill along highway 133. Because of its close proximity it is likely that any power producer within range of the sawmill would obtain its coal from here. The mine, in 2009, outputted 4.2 million tons of coal although it typically produces closer to 6.5 million tons. This lag is most likely due to a decrease in local industry activities causing a smaller power demand in the area. The open market price in Colorado for coal from West Elk Mine is around $35 a ton. The project, as of May 2010, had around 350 employees after laying off 100 employees in June 2009. (Browning, 2010)

There are direct Union Pacific railroad routes from the West Elk Mine to Delta , Grand Junction and Nuclea (Sonrisa Publications, 2006). It can be assumed that the current method of coal transportation of coal to each of the plants is by coal train.

Because coal production is a large part of the local economy, it is important to carefully assess the community views during the course of this project. In the past, Delta County's coal mining community has opposed Clean Air Act laws that threaten to cut down on the use of coal locally (Lohmeyer, 2010). Because we are essentially creating a coal replacement, it is likely that the project would not gain much local support. This is especially true because the local community has already suffered through a round of layoffs from the West Elk mine (Browning, 2010). Because the City of Grand Junction has shown to already be open to alternative energy, it is likely that the community is far enough outside of the impact of the coal economy to be accepting of yet another alternative fuel source.

Biochar Benefits and Current Torrefaction Practices

The goal of the project is to produce a torrefied bio-char end-product which can be substituted/co-fired for or alongside coal in current coal fired power plants. These goals require the bio-char to be similar enough to coal so the combustion process creates similar results to that of coal.

Because the torrefaction process removes moisture and other undesired products such as low energy volatiles, the caloric value of organics is increased nearly to that of coal as seen in figure 6. Seeing that the BTU/lb of torrefied wood is very similar to that of coal (9,600 to 12,000 BTU/lb versus 8,000 to 11,000 BTU/lb, respectively) means it is going to release similar amounts of energy per pound of input when combusted in a coal-fired power plant (New Biomass Energy, 2011).

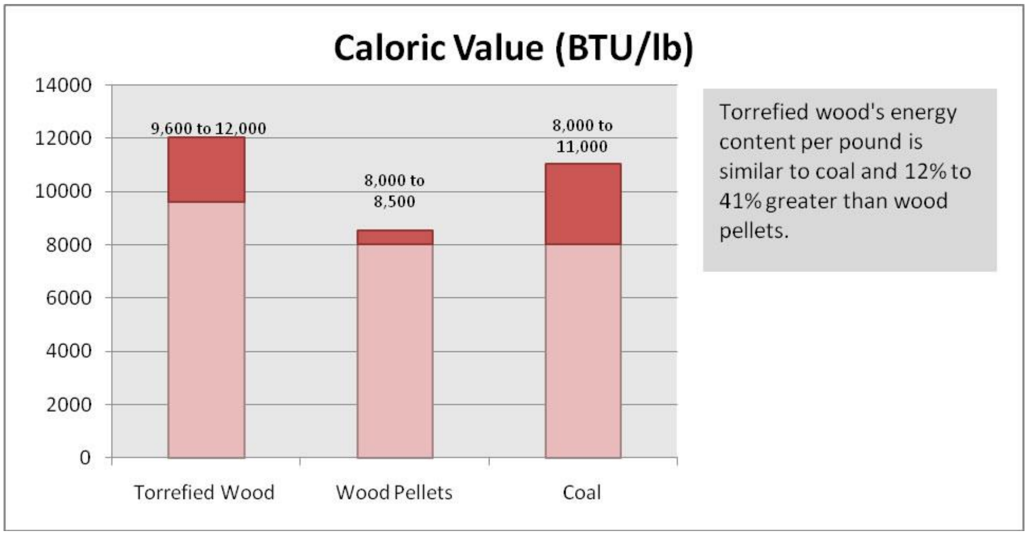


Figure 4 - Caloric Value of torrefied wood, wood pellets, and coal (New Biomass Energy, 2011)

The bulk density of torrefied wood isn't quite as high as coal (40 to 45 lbs/ft^3 versus 56 to 62 lbs/ft^3), as can be seen in Figure 7, but when introducing pelleting or briquetting to the torrefied wood, this value will increase. Bulk density is important in relation to transport costs. The higher the bulk density, the less costly the shipping will be because the caloric value will increase and more energy will be delivered (New Biomass Energy, 2011).

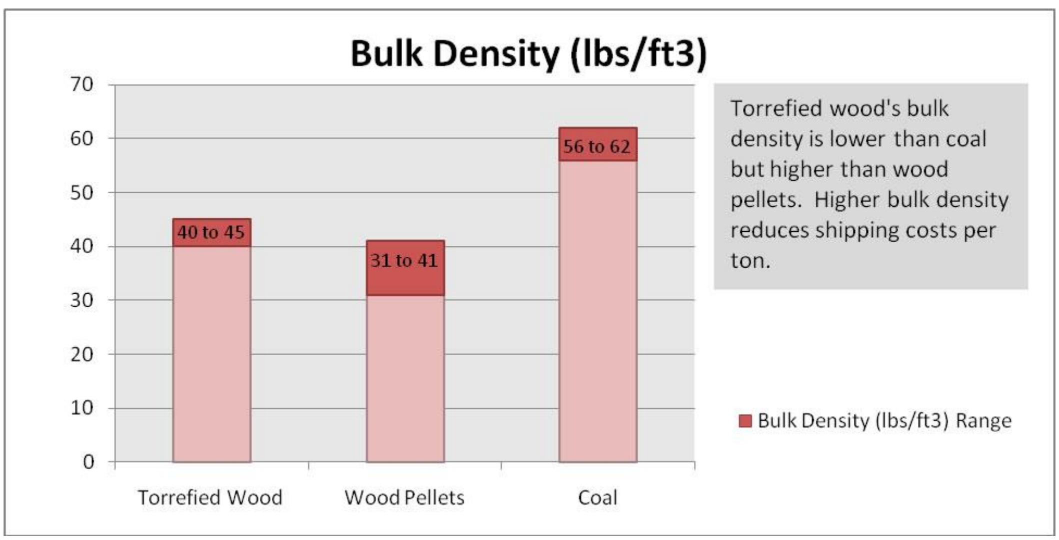


Figure 5 Bulk density of torrefied wood, pellets, and coal (New Biomass Energy, 2011)

The energy density in terms of MMBTU per cubic foot is similar to coal (.4 to .5 MMBTU/ft^3 versus .45 to .68 MMBTU/ft^3), which is important for shipping costs. It will require less energy to ship a given amount of energy as torrefied bio-char than untorrefied wood. In other words, in takes similar volumes of torrefied wood and coal to produce the same amount of energy. These values can be seen in the figure on the following page (New Biomass Energy, 2011).

Another important aspect to consider is the energy required to grind torrefied wood versus that of coal (1 kwe/MWth versus 3 kwe/MWth). Because the torrefied wood has increased grindability, it will require less energy to pulverize before being added to the coal fired power plant combustor, which can be seen in figure below (New Biomass Energy, 2011). This is important as the local power plants are pulverized coal based.

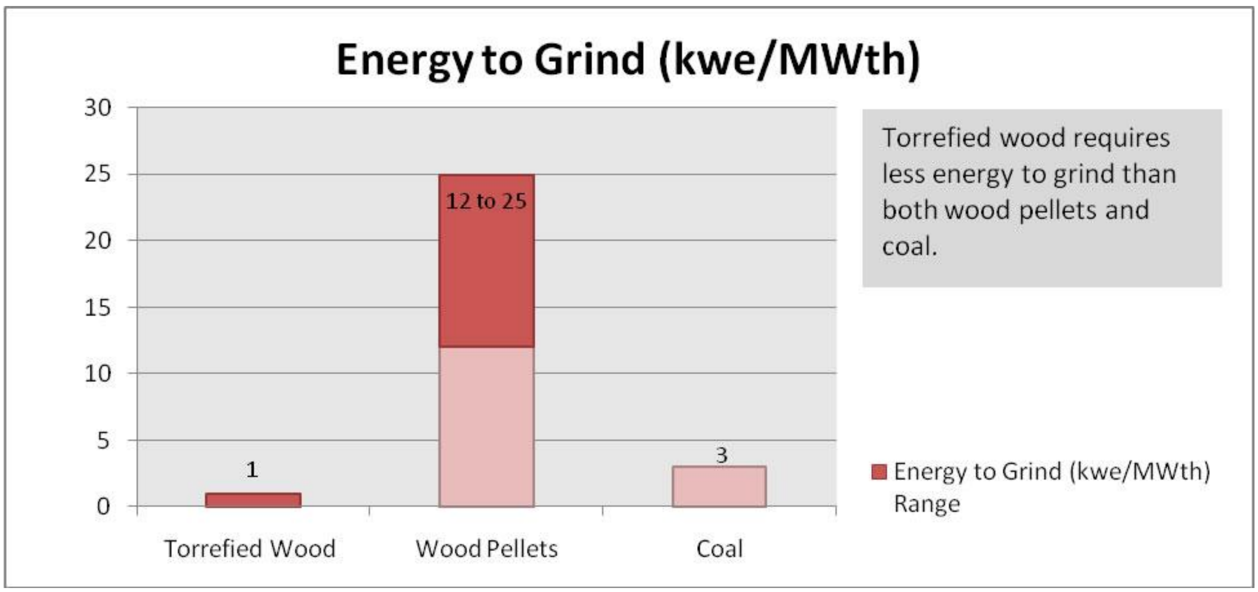


Figure 6 Energy require to grind torrefied wood, pellets, and coal (New Biomass Energy, 2011)

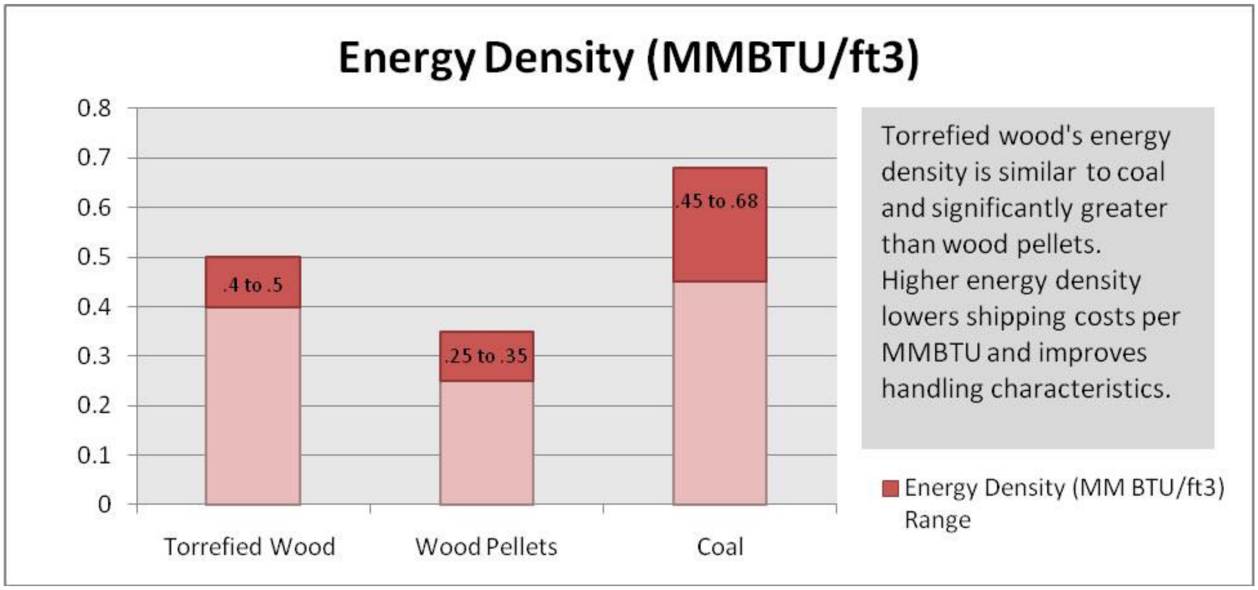


Figure 7 Energy density of torrefied wood, pellets, and coal (New Biomass Energy, 2011)

Torrefied wood has much lower ash content than coal (>1% versus 9% for coal). Ash is an unwanted byproduct of burning coal. The figure below shows ash content of torrefied wood in relation to wood pellets and coal (New Biomass Energy, 2011).

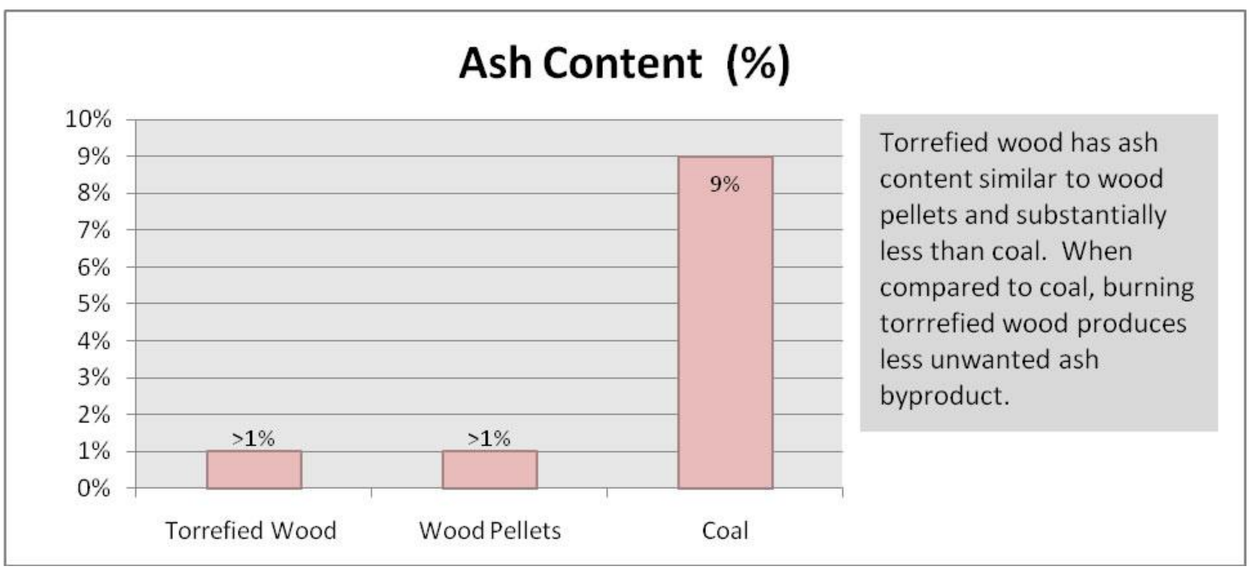


Figure 8 Ash content of torrefied wood, pellets, and coal (New Biomass Energy, 2011)

Another unwanted byproduct of firing coal in a power plant is the emission of SOx or sulfer oxides. The reduction of these pollutants is important in respect to lowering pollutant levels being emitted from power plants. The lower sulfur content of torrefied wood (0.1% versus 4 to 10% for coal) means less SOx and less pollutants being emitted. This could also mean fewer air pollution control devices, such as scrubbers, on the actual power plant. Sulfur content of torrefied wood, wood pellets, and coal are seen in the figure below (New Biomass Energy, 2011).

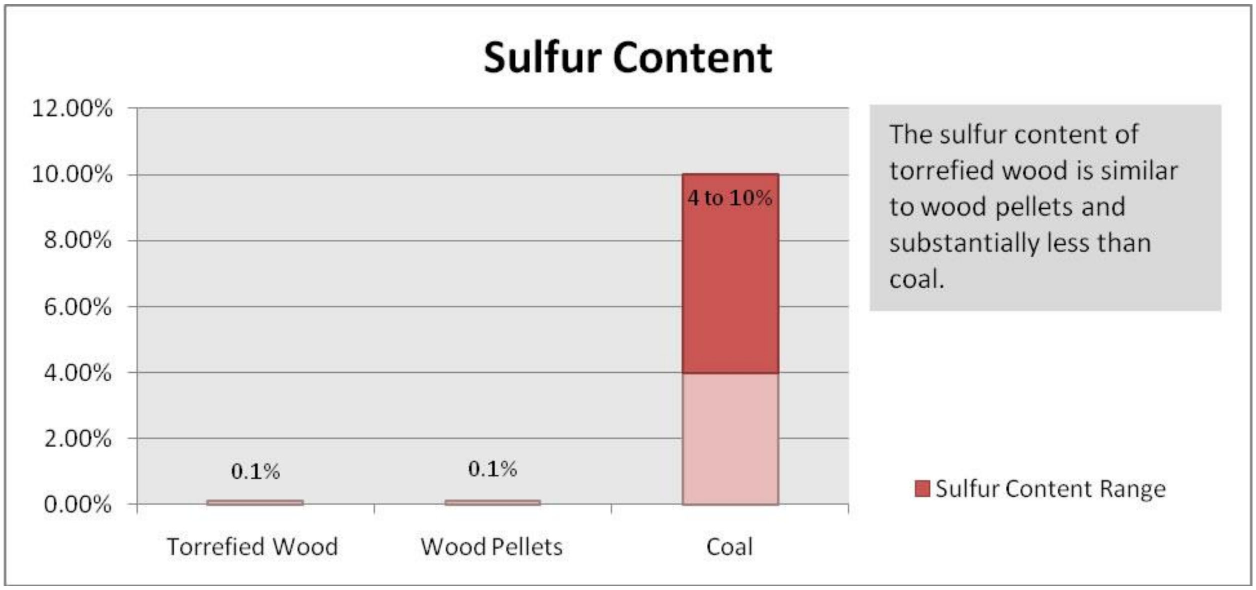


Figure 9 Sulfur content (New Biomass Energy, 2011)

Some of the most important aspects of torrefied wood are its hydrophobic and carbon neutral properties. Like coal, it is hydrophobic meaning that it is water repellent. This is very important when considering handling and storage as it does not have to be carefully kept from moisture and can be openly stored outside or transported in uncovered rail cars. Unlike coal, torrefied is carbon neutral. It is considered carbon neutral because the carbon in the biomass is being recycled through the carbon cycle. Coal, whose carbon has been stored underground for thousands of years, is considered not to be in the carbon cycle. When this coal is burned, it emits carbon into the atmosphere as CO2 which adds to the atmospheric loading. The burning of biomass is essentially just completing the cycle of carbon already present (what the plant takes up from the atmosphere is re-released). The figure on the following page shows these characteristics of torrefied wood versus wood pellets and coal (New Biomass Energy, 2011).

Other Characteristics			
	Torrefied Wood Pellets	Wood Pellets	Coal
Hydrophobic	✓	✗	✓
Carbon Neutral	✓	✓	✗

Figure 10 Hydrophobicity and carbon neutrality (New Biomass Energy, 2011)

Because of the similar properties of bio-char to those of coal, power plant owners and developers have incorporated the torrefied biomass in their combustion process. It is a cheaper and more environmentally friendly source of energy than its predecessor, coal. For instance, the 4,000-MW Drax Power Station in the United Kingdom has incorporated a retrofit allowing it to co-fire biomass with coal using its existing technology. The pellets are delivered to the plant by train, stored in four large silos, and finally reclaimed and conveyed to a fuel feed where they are fed into the combustor (Mahr, 2011). In 2007, the Ontario Power Generation (OPG) installed a direct injection system for torrefied biomass with a capacity of 50 MW at its Nanticoke Generating Station, which generates 3,640 MW. The system has proven successful as of now because of bio-char's ability to be easily co-fired with coal using the plants existing firing systems and control devices (Marshall, 2011).

The companies Integro Earth Fuels, Inc. located in North Carolina and Topell Energy in the Netherlands are beginning design and construction on their first commercial pellet torrefaction facilities. The Topell Energy facility will produce 60,000 tons per year of bio-char beginning 2011 by utilizing raw materials such as verge grass, rice hulls, nutshells, straw, wood cuttings and woodchips (Forest2Market, 2011). Integro Earth Fuels has sent their output to European power plants where test burns were considered successful (Forest2Market, 2011) and are now in the process of raising the capital necessary to begin construction and can potentially service United States sites.

Biomass Inputs and Torrefied Outputs

Following discussion with iCAST representatives and knowing the composition of Delta Timber's forestry residue, it was decided that this torrefaction process will be designed strictly for aspen wood inputs. Aspen is a hardwood and the torrefaction inputs will be "green" with an initial moisture content of 40%. After encountering torrefaction, the moisture content of the torrified wood will be less than 1%

(Thermya, 2009). Aspen wood is naturally hygroscopic and torrefaction works to exchange the hygroscopic property with hydrophobicity. Hydrophobicity of torrefied biomass is achieved by the destruction of hydroxide groups through dehydration reactions which limits the ability of forming hydrogen bonds with water (Bergman Patrick C.A., 2005). The unsaturated structures that are left are non-polar and result in the torrefied biomass becoming hydrophobic in nature (Bergman Patrick C.A., 2005). These properties, along with the prevention of biological activity, allow for the biochar to be stored outside like coal without absorbing water or decomposing. During torrefaction, the decomposition of three main polymers found in wood are critical for achieving the desired biochar product.

The three main polymer constituents in woods include cellulose, hemicellulose, and lignin. Cellulose is a polysaccharide of the form $(C_6H_{10}O_5)_n$, hemicellulose is very similar to cellulose, but differs chain length while lignin is of the form $C_9H_{10}O_2$. In aspen wood, there are 50, 25, and 18 wt% of these respective polymers found (Bjork, 1995). As lignin is heated it softens and promotes the binding and densification of the biomass (Miller B. K., 2011). When depolymerisation occurs, the shortened polymers condense within the solid structure and the hydrogen to carbon and oxygen to carbon ratios are lowered (Bergman Patrick C.A., 2005). The lowering of these elemental ratios provides a lower heating value (LHV) of the biochar that is more comparable to coal. While the calorific value and energy density of the biomass increase during the torrefaction process, so does transportation density. As described by Bergman, the solid product contains 90% of the initial energy content, but only 70% of the initial mass. The loss in mass is due not only to water loss, but also the loss of volatiles. These values exemplify the benefits of torrefaction on energy densification. Overall, the torrefied aspen wood will come out with improved hydrophobicity, homogeneity and grindability, little biological activity, low moisture content, higher energy density, and higher transportation density. The values of important properties are outlined in the table below.

Table 3 Properties of Aspen and Coal (Sources: (Thermya, 2009), (Mitchell, 2010)*, (Engineering Toolbox, 2010)")

Property	Crushed Aspen Wood (before torrefaction)	Biochar (after torrefaction)	Coal
LHV (MJ/kg)	7.4-11.4	20-21	25-30
Moisture Content	30-50 %	< 1 %	< 1 %
Transport Density (kg/m^3)	250-400	900	800-930"
Energetic Density (kWh/m^3)	815	5,085	7,268*

Regulations and Permits

State

All parts of this process will comply with Colorado's Air Quality Control Commission's air pollution guidelines. The pollutants to be concerned with during the torrefaction process are Carbon Dioxide, volatile organic compounds (VOCs) and particulate matter (PM). A "Stationary Source and Air Pollution Emission Notice" will need to be applied for. (Air Quality Control Comission, 2007).

The opacity of smoke that the plant will be allowed to emit depends on the number of days of operation. If running for less than 180 days it would be considered a "Pilot Plant or Experimental Operation" and be allowed 30% opacity in the flu gas. The gas itself must not emit for more than six minutes in any sixty consecutive minutes. In the unlikely event that our process runs over 180 days we have the option of applying for an extension to 365 days. Otherwise we would be considered a "Stationary Source" and have to reduce our emissions to 20% opacity. (Air Quality Control Comission, 2007).

The amount of particulate matter allowed to be released in the flue gas is dependent on the power of the fuel burning equipment. For equipment emitting less than $10^6\,\frac{BTU}{hr}$ the particulate matter released cannot exceed 0.5 lbs per $10^6\,\frac{BTU}{hr}$ input. For equipment between $10^6\,\frac{BTU}{hr}$ and $500 * 10^6\,\frac{BTU}{hr}$ the allowed output is determined by the equation:

$$PE=0.5(FE)^{-0.26}$$

Where
PE = Particulate Emissions in lbs per $10^6\,\frac{BTU}{hr}$
FE = Fuel Input in $10^6\,\frac{BTU}{hr}$.
If the equipment output is larger than $500 * 10^6\,\frac{BTU}{hr}$ then 0.1 lbs per $10^6\,\frac{BTU}{hr}$ is allowed. (Air Quality Control Comission, 2007).

In order to operate an incinerator a division incinerator permit will need to be obtained. If the sawmill is in a designated non-attainment area then the allowed emission for the incinerator will be 0.10 grain of particulate matter per standard cubic foot of biomass. Otherwise, if the area is designated as attainment for particulate matter, the limit is 0.15 grain per cubic foot of air released (Air Quality Control Comission, 2007).

During the time that the process is running an operator will submit a written report of all excess emissions within 30 days to each calendar quarter. This report will contain the magnitude of excess emissions as well as the date and time it occurred. The cause of the emission will also be noted as will the date and time of any equipment malfunctions and repairs. (Air Quality Control Comission, 2007).

Power companies may have to apply for a different emissions permit if they choose to include biofuel depending on the terms of their initial permit. The overall emissions release will change, as will the materials being burned. (Air Quality Control Comission, 2007).

Federal

The federal opacity allowement for a heat input capacity of 8.7 MW or greater should not exceed 20%, based on a six minute average. If the PM emissions for the source are less that 0.030 lbm/MMBtu then the source is exempt from the opacity standard. (Environmental Protection Agency, 2011, p. 60.43).

If the heating capacity exceeds 8.7 MW for a non-coal heat source then the allowable amount of PM in the flue gas is dependent on the annual capacity factor. If the factor is less than or equal to 10% then the allowable emission is 0.051 lb/MMBtu heat input. If the factor is greater than 10% then this amount becomes 0.30 lb/MMBtu heat input. (Environmental Protection Agency, 2011, p. 60.43)

In the event that the heating source is less than 8.7 MW then the amount of particulate matter allowed becomes 0.03 lb/MMBtu. (Environmental Protection Agency, 2011, p. 60.42Da)

Under Federal standards an incinerator shall not emit more than 0.18 grains per cubic foot of air released. (Environmental Protection Agency, 2011, p. 60.52)

Under the clean air act the mill would have to apply for a Title V permit for a stationary source if any of the criteria pollutants, (NO_x, CO, SO_2, Ozone, VOCs, PM10, and lead) exceeds 100 tons per year. There are no charges associated with applying for a permit but a stationary source will be required to pay emission fees. Fees are determined the amount of emissions of Particulate matter, sulfur dioxide, nitrogen oxides, organic compounds and lead and are based on a fee of $25/ton in 1989 dollars that will be increased annually as a result of inflation. (Control, 2008)

The permits will be issued for a fixed length of time that is not to exceed five years. The total emission of a pollutant may not be allowed under Title V if it exceeds 4,000 tons per year. (Programs, 1990)

Once again, depending on their initial Title V permit, power companies may be in a situation where they would have to alter their permit specifics before burning biofuel. However, as switching to biofuel reduces the emissions of criteria pollutants, the power companies will find themselves paying less in Clean Air Act Fees. (Programs, 1990)

Tax Incentives

State

While there are no direct Colorado State tax incentives for either a biomass producer or user, Delta Timber could be eligible to receive money from the “Colorado Carbon Fund.” The fund is run off of donations from individuals who are unable to reduce carbon emissions themselves. The money is then rewarded to new clean energy projects that reduce carbon. Preference is given to projects that have an emphasis on efficiency, renewable technology, and community based initiatives (Recharge Colorado, 2010). In order to qualify, a project must divert at least 40,000 metric tons of CO_2. In order to apply for these funds a project has to first submit a proposal and then go through a negotiation process with project developers. (Colorado Carbon Fund, 2011)

Federal

The amount of tax credit received under federal law depends on if the biomass is open or closed loop. Under the Federal Renewable Electricity Production Tax Credit (PTC), closed loop biomass producers receive 2.2 cents per kWh of energy produced while open loop receives 1.1 cents per kWh of energy produced. The amount of tax credit received under federal law depends on if the biomass is open or closed loop. Because Delta Timber would be producing biomass from a waste product, and not growing an Aspen trees for the specific purposed of turning it into biochar, it is considered open loop biomass. This credit applies to all production over 150 kW of electricity for the first ten years of operation. (Federal Government, 2010)

Municipal power plants purchasing the biofuel are also able to receive money under the Renewable Energy Production Incentive (REPI). They would, again, be eligible to receive 2.2 cents per kWh of closed loop biomass burned and 1.1 cents per kWh of open loop biomass burned. This also applies to the first ten years of use and is only applicable to production over 150 kW. (Federal Government, 2011)

Decision Matrix Flowchart

iCAST provided the Bio-Buff Consulting team with a general decision matrix to utilize when making decisions. This decision matrix included criteria such as costs, technical feasibility, environment, safety and social aspect. When comparing alternatives it was essential that the option must be economically feasible. This entire design is dependent on the fact that Delta Timber would have the potential to make money or at least break even with the profit that is currently being made on feedstock waste. For this reason, cost was the most heavily weighted option in our decision making process. Beyond cost considerations, technical feasibility and environment were the next heaviest options.

Technical feasibility included components such as mass balances, mobility, reliability, and ease of implementation. Because this unit is desired to be a mobile unit, it is imperative that the equipment and design be technically feasible for mobile set up and take down operations. Environment became a surprisingly important factor in our decision making process due to state and federal regulations and incentives, as well as the carbon neutral ideas and producing a “green fuel”. Environmental considerations also included water usage and emissions. Safety is always an important factor, but because this unit is relatively safe, for operators, bystanders, and the environment, the weights were not as heavy in this category.

The social aspect was the lowest weighted category. This unit will be mobile and when set-up will generally be in remote locations representing little interference with communities. The Delta community, however, is an intensely coal mining community and is also hesitant to accept coal alternatives. We did take the culture of Delta into consideration when designing this unit, but our individual decision matrices for each piece of equipment were not heavily dependent on public or political support.

The iCAST RFP outlined many specifics regarding the mobile torrefaction system.
These specifics included:

- Variable operation rates
- Flexible capacities
- Economic feasibility
- Product compatibility with coal co-firing
- Skid-mounted
- Mobile or semi-mobile
- Self-powered

Due to the specificity of this project and the constraints outlined above, the Bio-Buff Consulting team was not able to compare all of our design components within a single decision matrix. Utilizing the relative importance of each criteria and slightly modifying weights and requirements for each design step, our design components were independently examined in a step-wise fashion. Each step in our design process will have varying weights to a certain degree within each decision matrix category, but all design components were compared with the same relative importance. The table below shows the average weights, on a scale from 1-10, for each decision and each staple criteria, but the reasons for which will be described in the respective sections. A higher number represents greater importance in that design component comparison.

Table 4 Average Weight for Individual Design Matrices

Criteria	Reactor Process	Thermal Operation	Biomass Compaction	Air Pollution Control
Cost	8.3	8.3	8.3	9
Technical	4.5	5.25	4.5	4.3
Environmental	3.6	5	3.6	6.75
Safety	6.5	6.5	6.5	4
Social	0	4	0	1

To further illustrate our decision making process, the flowchart below outlines the decisions and steps taken to ensure the best alternative is found beginning with the mobile torrefaction unit.

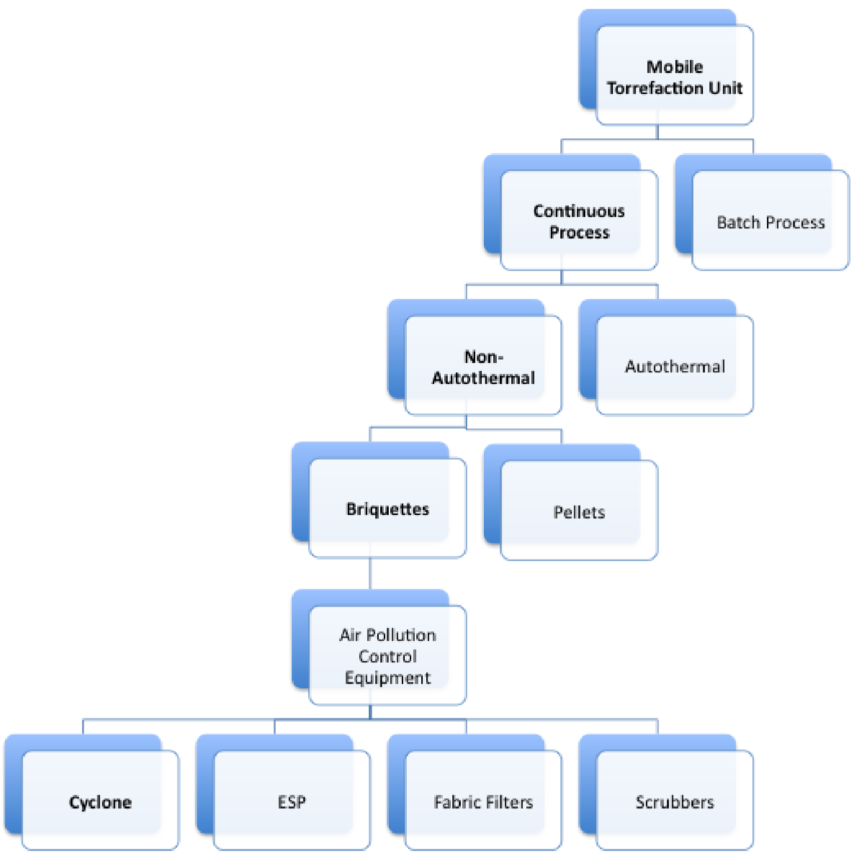


Figure 11 Decision Matrix Flowchart

The first major decision was determining whether or not this torrefaction process should be conducted continuously or as a batch process. After determining that a continuous process better suited the project goals, as discussed in the reactor processes section, the optimal process temperature was explored. This decision was dependent upon the choice for continuous operation and thus needed to occur following that discussion. Autothermal operation was compared to non-autothermal operation as discussed in the torrefaction and thermal operations section. Autothermal operation was found to be the most economically feasible and it was at this point that power generation was explored. Flue gas and some biomass will be used to power the process as discussed in the thermal operations section. After knowing optimal process temperature and power generation, the biomass compaction was researched. Briquettes were compared to pelletization and it was found that briquettes better suited our goals as discussed in the pelletization and briquetting section. While the design does not specifically target air pollution control, various air pollution equipment was compared to determine the most cost effective and efficient process for our design thus far. This analysis is discussed in the air pollution control section. Cyclones were found to be best suited for the operation.

The decision flowchart aided the design process by allowing different design configurations to be compared after knowing the final decision on dependent processes. A single, mass decision matrix could have been used, but the large number of alternative design paths to compare in this manner creates a confusing matrix. The flowchart method provides a more understandable and coherent comparison of design alternatives for this project. Each sub-decision matrix is discussed in each respective section.

Operating Systems

A schematic overview of the most general concepts and requirements within a torrefaction unit is shown in the figure below. The four main components include chopping, drying, torrefaction, and fuel combustion. Chopping, not shown in the schematic, will be implemented into the final Bio-Buff mobile torrefaction system design immediately before the drying stage.

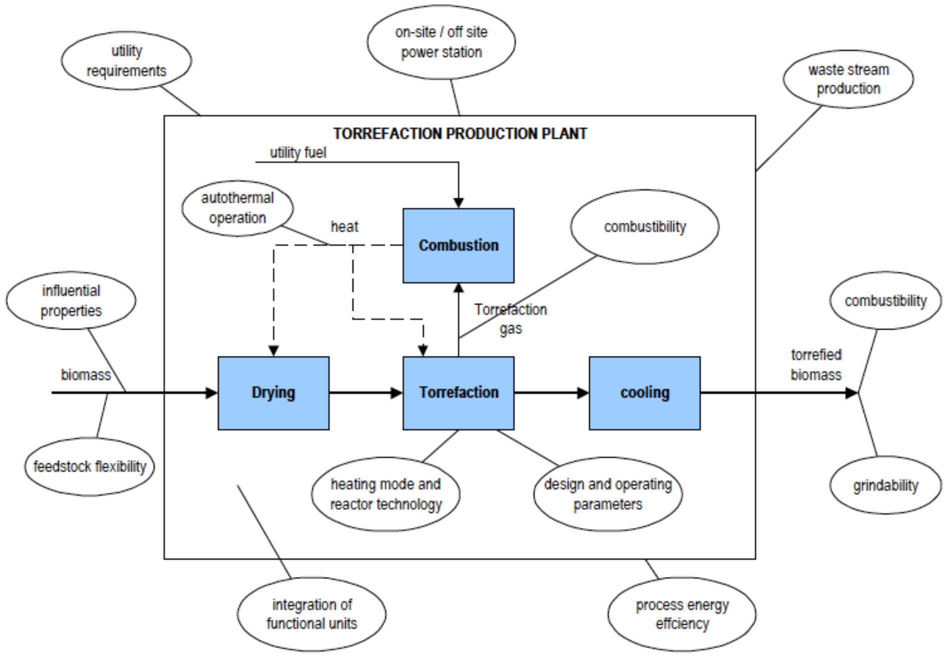
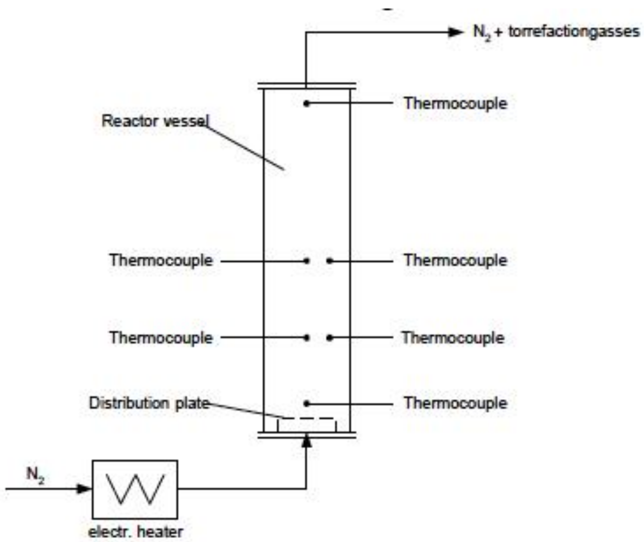


Figure 12 General Torrefaction Schematic (Bergman Patrick C.A., 2005)

As discussed in the *Biomass Inputs and Torrefied Outputs* section, the aspen biomass received will be green and have a moisture content of 40%. Before this biomass can enter a torrefaction reactor, the moisture content within the wood must be decreased in a dryer to 15% or lower. Hot air or torrefaction flue gases can be used within the dryer for this purpose (Bergman 2005). The next step in the process is the roaster or torrefaction reactor. Much of the overall cost and efficiency of torrefaction systems is dependent on the type of reactor unit chosen. There are multiple industrial options for this unit, but the first reactor decision to be made is whether or not to pursue a batch or a continuous torrefaction reactor.

Reactor Processes

A batch process involves sending "batches" of aspen biomass through the torrefaction unit versus a continuous flow of biomass. This is appealing because the aspen chips are not required to be a specific grain size, cleaning is easy, and operational conditions can be fine-tuned before each batch. The ECN experimental batch reactor is shown below.



Schematic of the batch reactor

Picture of the Batch reactor

Figure 13 ECN Batch Reactor (Bergman Patrick C.A., 2005)

Continuous processes allow for a steady feed of biomass to be entering and exiting the torrefaction reactor. This continuous operation allows for steady state operation to be reached relatively fast and therefore makes the reactor easier to understand and control. Continuous monitoring systems can detect when a trend is deviating from the optimal parameters or steady state values and can automatically adjust what is needed (GEA Pharma Systems, 2011). This minimizes waste biochar and prevents entire batches from encountering undesired reaction conditions. In continuous systems, grain size needs to be consistent, thus a grinder will need to be used in front of the dryer in order to ensure a consistent grain size input to the dryer and torrefaction reactor. While continuous processes are considerably more complex and require more advanced monitoring and control equipment, steady state operation greatly increases process efficiency. Because flue gas does not need to be heated and cooled at different times throughout the reaction, it eliminates a critical energy requirement of batch systems. The initial startup and technology costs of continuous systems generally outweigh those of batch units, but the cost is offset by the net energy balance and efficiency. These qualitative advantages and disadvantages are shown quantitatively in the decision matrix below.

Table 5 Batch versus Continuous Reactor Decision Matrix

	Raw Score (scale of 1 to 10)			Weighted Score (weight x raw score)	
	Batch	Continous	Weight	Batch	Continuous
Costs:					
Capital Required(Order of Magnitude Estimate)	4	7	7	28	49
Operating Expenses (Order of Magnitude Estimate)	5	5	8	40	40
Return on Investment (ROI)	4	7	10	40	70
Technical Feasibility					
Energy in V.S. Energy out (Energy Balance)	2	9	8	16	72
Mass Balance	2	2	4	8	8
Particle Sizes Accepted	6	6	3	18	18
BTU value of Biochar	9	9	4	36	36
Permit requirements and approval	1	1	0	-	-
Reliability of process/equipment	6	5	8	48	40
Complexity of process/equipment, O&M needs	6	2	7	42	14
Ease of Implementation	1	1	1	1	1
Environment					
Environmental Mitigation (Environ. Benefits Gained)	7	7	7	49	49
Life Cycle Analysis	1	4	4	4	16
Emissions	1	1	3	3	3
Noise, Odor, Traffic	1	1	3	3	3
Water Usage	1	1	1	1	1
Safety:					
Safety Hazard	1	1	8	8	8
Hazardous By-products	1	1	5	5	5
Social Aspect					
Public Support (not in my back yard attitude)	1	1	0	-	-
Political Support (is it mainstream, heavily talked about or not)	1	1	0	-	-
Total:				**350.00**	**433.00**

Higher values are more desirable in this matrix, thus the process with the higher value is by definition the more desirable process. The social aspect was taken out of this decision matrix comparison by assigning a weighted value of zero. Public support is important, but it is not a deciding factor when choosing a component of a process that is not likely going to be within town limits. Score values of one indicate that the criteria in question need to be considered, but either that criteria is not heavily influential or has the same impact regardless of process. With overall scores of 350 versus 433, the benefits of the continuous process clearly outweigh those of the batch process. Cost analysis for various industrially sized, continuous reactors is covered in the *Continuous Operation* section.

Even with the advantages of a batch process for the torrefaction unit, it was eliminated for multiple reasons. First, batch processes are "difficult to understand and control because they are in a continuous state of change" and if an "out-of-specification result is detected, it is often not possible to correct it by changing process parameters and an entire batch is wasted" (GEA Pharma Systems). Perhaps the most detrimental aspect of batch torrefaction is the requirement of heating and cooling the torrefaction vessel, before and after each batch respectively (BioBuff Proposal). The flue gases would need to be heated and then cooled for different times within the process. This is energy intensive and thus, increases operation costs and monitoring requirements. This repeated, intensive heating is also the cause for a lower score in the life cycle analysis criteria. A batch process would require storage of the gases and more biomass to start the processes initially. Running Delta Timber's forestry residue through a torrefaction process instead of selling the byproducts must prove to be economically profitable or the mobile system will gain no footing in Delta. This project is dependent on cost, thus because continuous systems prove to be more cost effective, they will be used.

Continuous Operation

The application of continuous reactor technology can be divided into two areas: indirectly-heated or directly-heated. Biomass being indirectly-heated is in direct contact with metal or some other surface separating it from the heat carrier (thermal oil). This process uses flue gas combusted in combination with utility fuel to provide heat to thermal oil and the drying process as seen in the general schematic below (Bergman Patrick C.A., 2005). For a schematic specific to our process, please see the material and energy balances section later in this report.

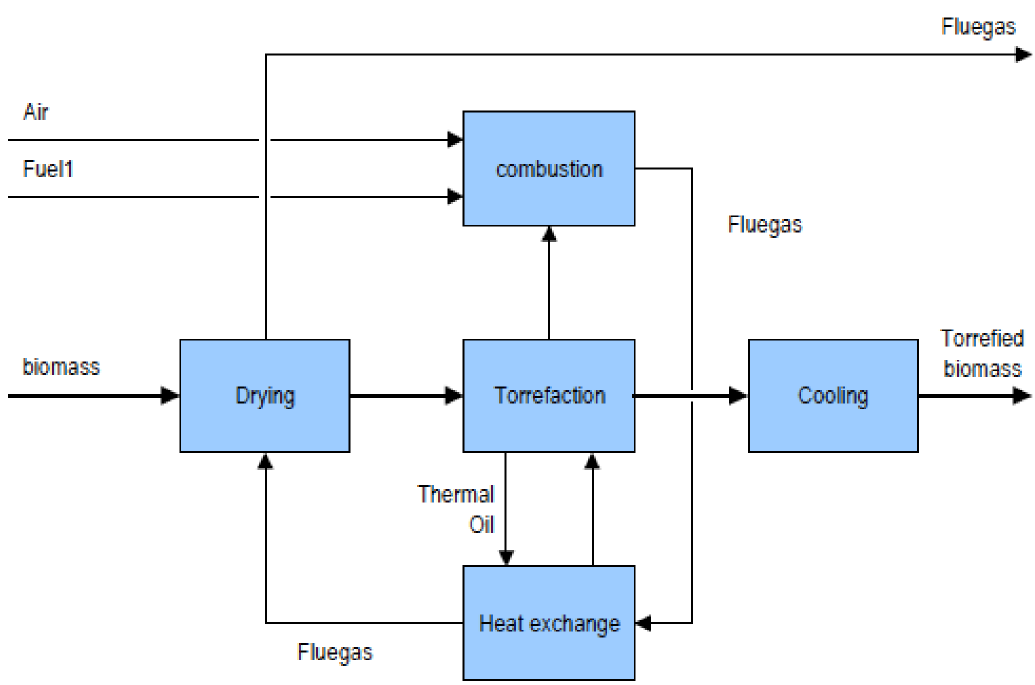


Figure 14 Indirect heating schematic (Bergman Patrick C.A., 2005)

The directly-heated process involves biomass being dried and torrefied while in direct contact with a gaseous heat carrier (Bergman Patrick C.A., 2005). It is relatively the same process as indirectly heated, utilizing the same utility fuel as fuel 1 in the previous figure, but involves a gas re-pressuring operation, labeled "DP", to enable gas recycling. The schematic is shown below.

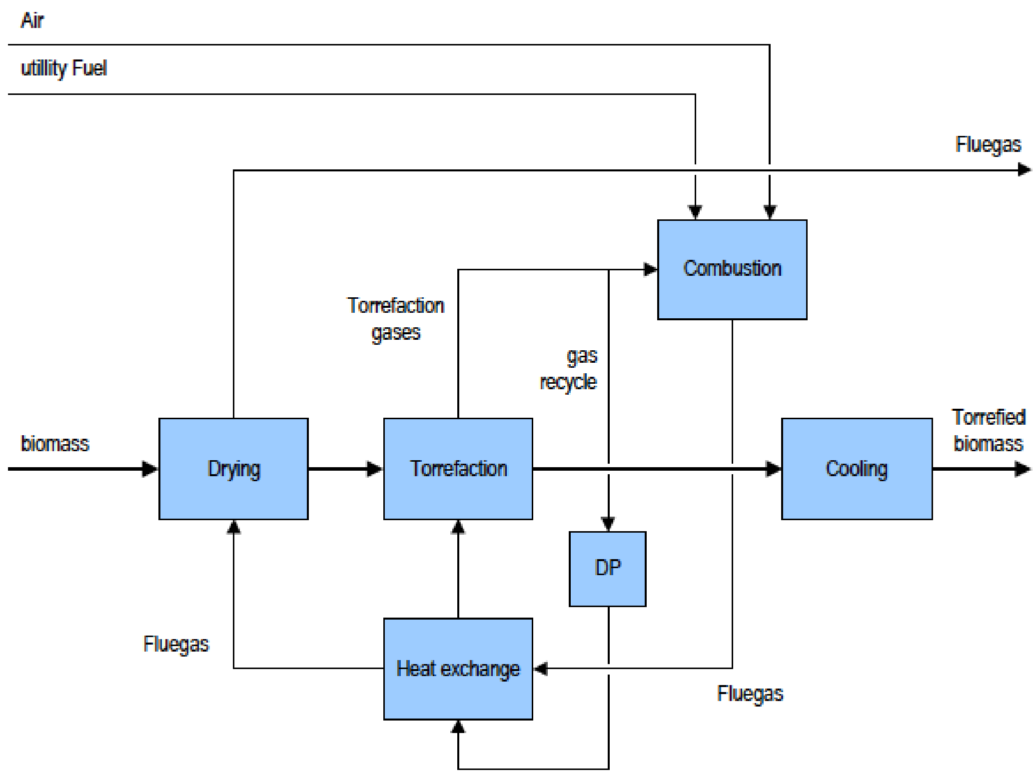


Figure 15 Direct heating schematic (Bergman Patrick C.A., 2005)

Some issues associated with directly-heated biomass include dust and heavy volatile condensation that can foul equipment like the dryer, but overall heat exchange between a gas and a solid is much quicker (Bergman Patrick C.A., 2005). The faster heat exchange with direct heating leads to a more efficient process and decreases process costs due to decreased residence times (Bergman Patrick C.A., 2005). Bio-Buff Consulting will be designing a process that utilizes direct heating in order to produce a more efficient and economically viable unit.

Continuous Torrefaction Reactors

There are many types of continuous torrefaction reactors including, but not limited to:

- Screw
- Rotating Circular Tray
- Column

Each type of continuous reactor listed above will be examined in this section, but the selection of a reactor will be delayed until the design phase of this project.

Screw reactors, such as the Swiss produced LIST seen in the figure below, use conductive heat transfer through the shell and screw to heat biomass. Thermal oil is run through the reactor and heat is conducted across the metal to the biomass.

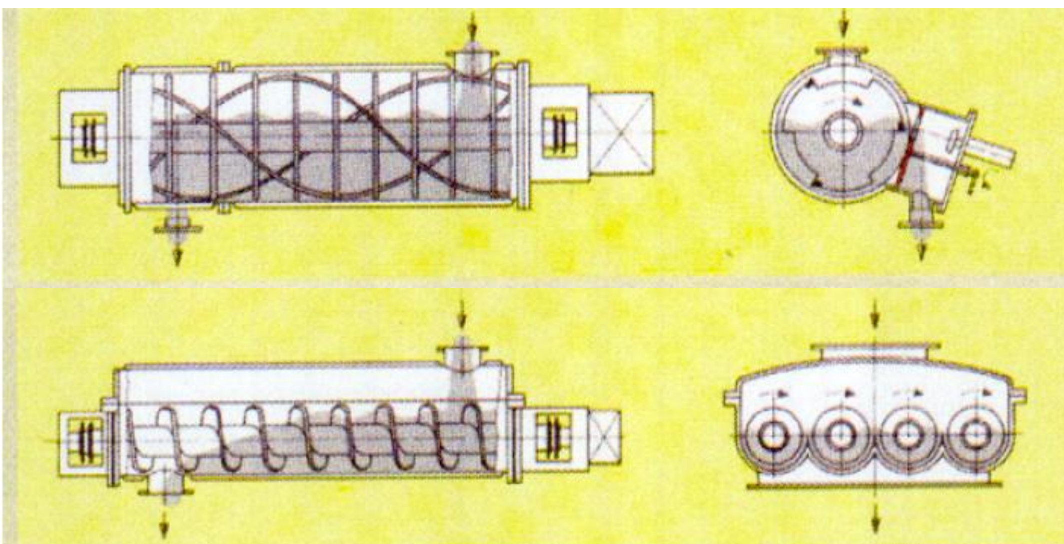


Figure 16 Swiss LIST screw reactor (Bergman Patrick C.A., 2005)

The LIST reactor works in plug-flow operation and has a net efficiency of 65-75%. The maximum biomass input for this reactor is 2 tons per hour, which does not meet our needed input rate of 2.7 tons per hour, and the efficiency is not suitable for our goals. This particular reactor was used in France from 1985 to 1990, but was shut down because it was not economical in operation. The price breakdown of a general screw reactor can be found in the cost comparisons table. (Bergman Patrick C.A., 2005)

Rotating circular tray reactors, such as Wyssmont's TURBO-DRYER, are generally plug-flow operations using heated air or gas circulated by internal fans to promote drying (Wyssmont Company Inc., 2011). Biomass is fed onto the top tray and is mixed, dried, and subsequently swept to the next, lower tray level until it reaches the bottom of the reactor as seen in the illustrations below.

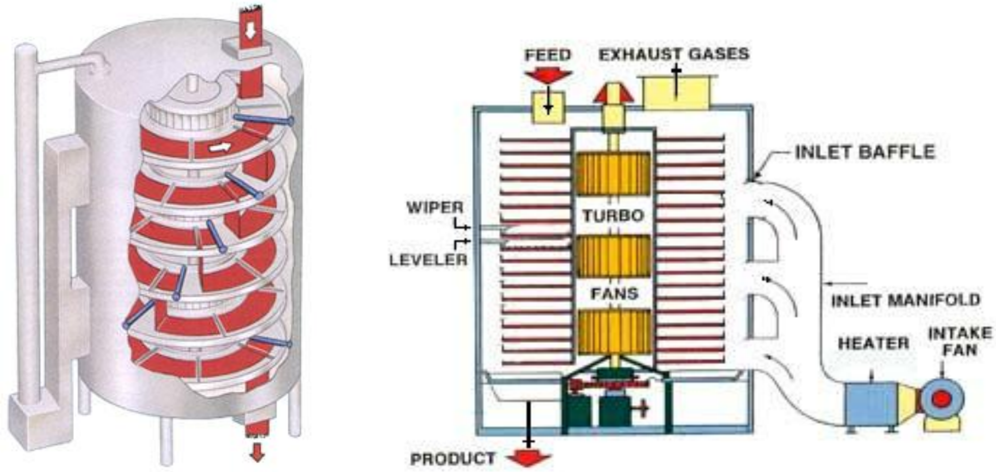


Figure 17 Wyssmont rotary tray dryer (Wyssmont Company Inc., 2011)

The Turbo-Dryer is commercially available to handle feed rates upwards of 22.7 tons per hour, which can easily handle our desired 2.7 tons per hour. The turbo dryer has many advantages including a self-cleaning action when the wipers sweep the biomass to the next level eliminating the need for manual cleaning at product changeovers, easily adjustable drying conditions and feed rates, and the ability to use any heating medium desired (Wyssmont Company Inc., 2011). These advantages coupled with low energy costs make this technology a promising option for the Delta Timber torrefaction unit. The estimated capital cost can be found in the cost comparisons table.

A column reactor consists of tall vertical vessels with baffles to cascade biomass down while heating occurs by contact with baffles or heated gas (GlobalSpec, 2011). The TORSPYD process, by Thermya, operates in a continuous column reactor fashion as seen in the diagram on the following page.

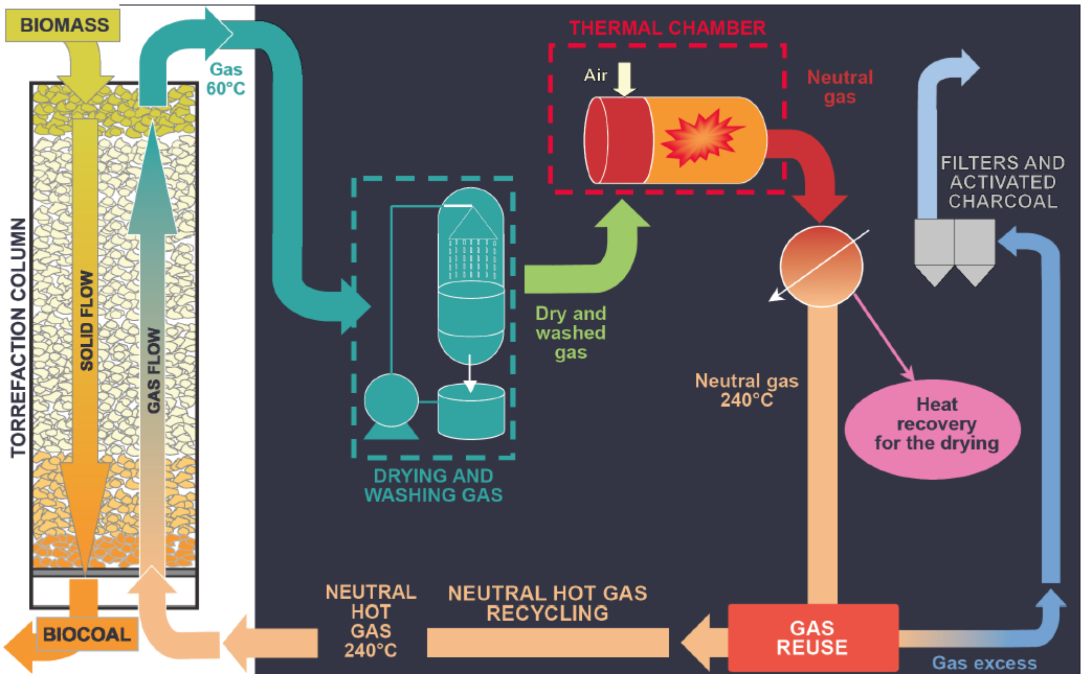


Figure 18 Thermya TORSPYD column schematic (Thermya, 2009)

As the gas flows up, the biomass compacts and moves downward progressively losing water and breaking polymers (Thermya, 2009). This system is ideal because it utilizes and recycles flue gas for heating purposes, but no known industrial applications have been found thus far.

Another known torrefaction reactor is the rotating drums. Rotating drums feed biomass into a tumbling unit (rotating drum) and pass heated air or gas through the unit while moving beds use belts to transfer biomass into the reactor and then flowing heated air or gas surrounds the belt within the reactor (GlobalSpec, 2011). No successful industrial or commercial torrefaction processes have implemented these techniques as of yet. The Energy Center of the Netherlands performed a capital cost comparison of these technologies for equivalent feed rates in 2005 and the current estimated cost of each reactor unit is listed in the cost comparison table below.

Table 6 Equipment 2011 Capital Cost Comparisons (Wyssmont Company Inc., 2011)', (Bergman Patrick C.A., 2005)

Cost Item	Screw	Rotating Tray	Rotating Drum	Moving Bed
Capital Investment (in Million $)	18.6	1.6 ’	7.8	3.1

Additional research will be performed to determine the optimal continuous reactor technology that will be selected. Inquires will be made to industrial companies in order to most accurately estimate the cost of the reactor that will be needed for the Delta Timber mobile torrefaction unit.

Torrefaction and Thermal Operation

Torrefaction is a mild pre-treatment of biomass at temperatures between 200-300 °C at or near atmospheric pressure in the absence of oxygen. Chipped biomass at less than 15% moisture content is the general input to a torrefaction reactor. Under these conditions decomposition reactions breakdown the fibrous biomass structure resulting in a loss of the hygroscopic properties of the biomass. Through the process of torrefaction, biomass is chemically altered to create a hydrophobic bio-coal which is colored brown to dark-brown. This bio-coal approaches the properties of coal in grindability, energy density, and hydrophobicity. During the torrefaction process biopolymers cellulose, hemicellulose and lignin partly decompose giving off water and various types of volatiles. The liberated volatiles can be recovered and combusted to provide energy for the process. (Bergman Patrick C.A., 2005).

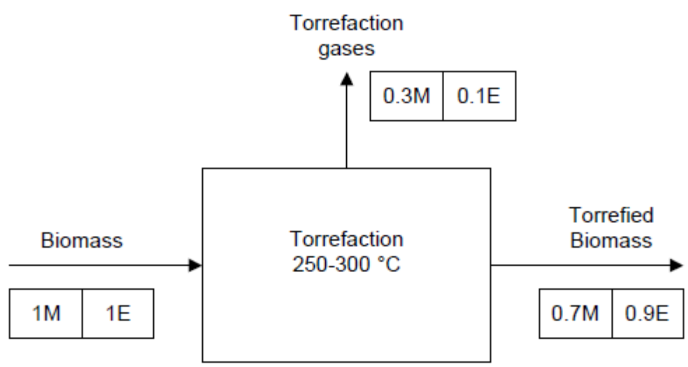


Figure 19 – Typical mass and energy balance of the torrefaction process. Symbols: E = energy unit, M = mass unit (Bergman Patrick C.A., 2005)

Typically, 70% of the mass is retained as a solid product which contains 90% of the initial energy content. Aproximately 30% of the initial mass of the biomass is converted to off gases containing 10% of the initial energy content (Bergman Patrick C.A., 2005). Because of this capture and combustion of the off gas stream is highly desirable and allows for the opportunity to operate the process autothermally (operation without additional heat input to the reactor).

The volatiles realeased during torrefaction consist of a condensable fraction (organics and lipids) and a non-condensable fraction (CO_2 , CO, and hydrocarbons). The majority of the energy content is contained within the lipids and organics (Bergman Patrick C.A., 2005). As the residence time and temperature are increased the quantity of volatiles released increases **Invalid source specified.**. Due to this there exists an operating line at which the process will operate autothermally. Above this operating line the energy content of the volatiles is greater than the energy required to sustain the process. Below this line the energy content of the volatiles is less than the energy required to sustain the process and additional energy must be supplied to the reactor. The required reactor size for a given throughput will be controlled by the residence time of the biomass in the reactor. As the residence time increases the size of the reactor must increase to accommodate a give throughput since the biomass must remain in the reactor for a longer period of time. Based on this and overall material and energy balances on the reactor it is most economical to operate below the autothermal line at high temperature and short residence time (Bergman Patrick C.A., 2005). Please view the figure below for a graphical representation of this.

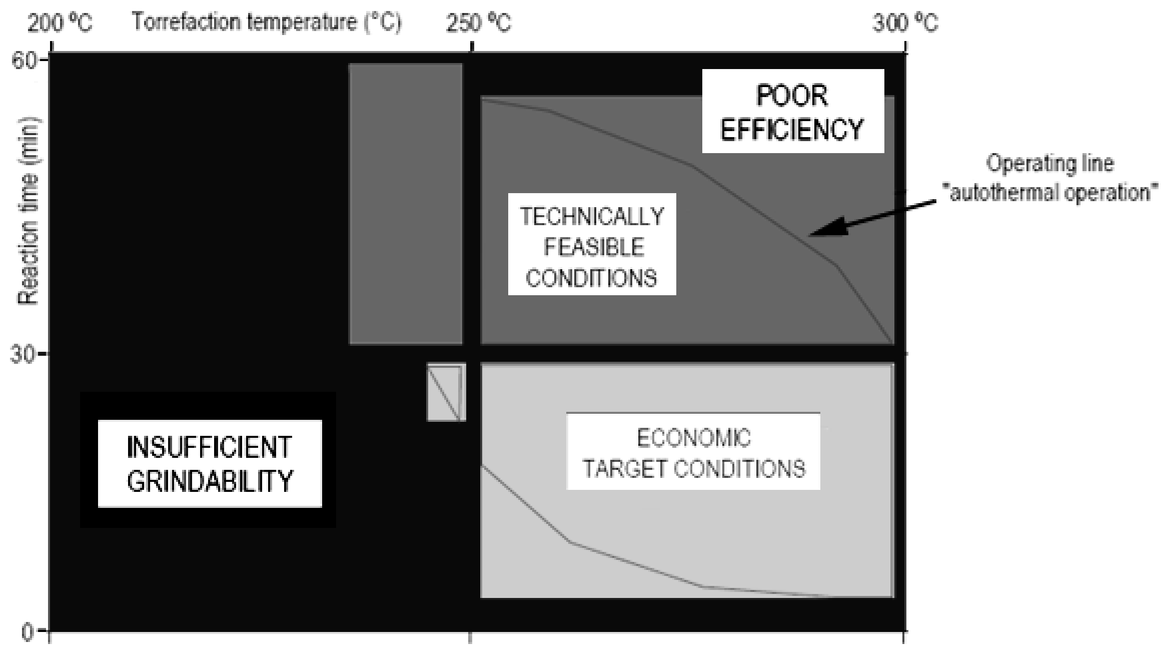


Figure 20 – Artist impression of the operating window of torrefaction. (Bergman Patrick C.A., 2005)

One of the most significant steps in designing this process was to determine the operating conditions of the torrefaction reactor. Since torrefaction can be performed over a range of temperatures, both a residence time and a temperature must be specified for the torrefaction reactor. Based on literature research the economically feasible operating conditions of the reactor range from temperatures of 260 to 300 °C and residence times of 7.5-30 minutes (Bergman Patrick C.A., 2005). In this range favorable combustibility properties of the torrefied biomass are observed and operating expenses due to energy consumption are optimized. The exact operating conditions are highly dependent on the composition of the biomass. Due to the varying composition of biomass the reactor will need to be tuned to the type of biomass on which it is operating and also the moisture content of the biomass.

To complete the alternative assessment of the operating conditions a decision matrix was constructed to compare the autothermal process versus the non-autothermal process. This decision matrix is shown on the next page.

Table 7 Thermal decision matrix

	Raw Score (scale of 1 to 10)		Weighted Score (weight x raw score)		
	Autothermal	Non-Autothermal	Weight	Autothermal	Non-Autothermal
Costs:					
Capital Required(Order of Magnitude Estimate)	6	10	7	42	70
Operating Expenses (Order of Magnitude Estimate)	6	10	8	48	80
Return on Investment (ROI)	6	10	10	60	100
Environment					
Environmental Mitigation (What environmental benefits are gained)	8	10	7	56	70
Emissions	10	8	8	80	64
Noise, odor, traffic, etc.	7	7	3	21	21
Public Approval for facility (NIMBY issues)	8	8	7	56	56
Permit requirements and approval	8	8	9	72	72
Life Cycle Analysis	10	10	4	40	40
Land requirements	9	10	2	18	20
Water usage	10	10	2	20	20
Technical Feasibility					
Energy in V.S. Energy out (Energy Balance)	6	10	4	24	40
Mass Balance	6	10	4	24	40
Complexity of process/equipment	10	10	5	50	50
Reliability of process/equipment	9	10	8	72	80
Ease of Implementation	10	10	4	40	40
Safety:					
Safety Hazard	9	10	8	72	80
Hazardous By-products	9	10	5	45	50
Social Aspect					
Public Support (not in my back yard attitude)	8	8	4	32	32
Political Support (is it mainstream, heavily talked about or not)	8	8	4	32	32
Total:				**904.00**	**1,057.00**

In comparing the two processes five main categories were analyzed. The categories were cost, environment, technical feasibility, safety, and social aspect with the highest influence being placed on cost.

To analyze the costs of the process the subcategories of capital required, operating expenses, and return on investment were evaluated. Capital costs for the non-autothermal reactor are much lower than the autothermal reactor due to the increased residence time for the autothermal reactor and thus reactor size for a given throughput. Operating expenses for the autothermal reactor are much greater than the non-autothermal reactor due to the increased energy consumption. Due to the previous two cost considerations the return on investment for the non-autothermal reactor will be greatest.

To analyze the environmental aspects of the process the subcategories of environmental mitigation, emissions, nuisances, public approval, permitting, life cycle analysis, land requirements, and water usage were evaluated. Due to the variable nature of the biomass entering the process it would be nearly impossible to operate exactly on the autothermal line. Thus to operate the reactor autothermally the reactor must be operated above the autothermal line meaning that excess energy will be generated and lead to inefficiencies and thus lower the environmental mitigation. Emissions for the non-autothermal process will be greater since additional biomass must be burned to generate the heat required to operate the reactor. Also the efficiency of the combustion of raw biomass is likely to be more inefficient than combusting the volatile off gases. Nuisances such as noise, order, etc. should be similar for both processes. Public approval should be similar for both processes. Permit requirements will likely not vary. The life cycle analysis for both processes should be very similar. The land requirements for the autothermal process will be greater due to increased reactor size for a given throughput. Both processes should require little to no water.

To analyze the technical feasibility of the process the subcategories of energy balance, mass balance, complexity of process/equipment, reliability of process/equipment, and ease of implementation were evaluated. Due to the energy inefficiencies of the autothermal process discussed earlier the mass and energy balances for the non-autothermal process will be more favorable. The complexity of the process equipment is nearly identical for both processes. The reliability of the process equipment for the non-autothermal process should be slightly improved due to more uniform operating conditions versus the autothermal process which will be more oscillatory in nature due to tighter constraints on the operating conditions set point. Both processes should be similar to implement since the difference between the auto-thermal and non-autothermal operating conditions will be small and thus not require significantly different reactor design. Due to the energy inefficiencies of the autothermal process discussed earlier the mass and energy balances for the non-autothermal process will be more favorable.

To analyze the safety aspects of the process the subcategories of safety hazards and hazardous by-products were evaluated. The hazards associated with the autothermal reactor will be slightly higher than the non-autothermal process mainly due to the increased reactor temperature and also the increased production of hazardous off gases.

To analyze the social aspects of the process the subcategories of public support and political support were evaluated. There should be virtually no difference between the two processes in the eye of the public or politics since the overall outcome of the process is essentially the same to the lay person. Overall both processes are self-sustaining and thus should be favorable to public and political opinion. In conclusion of the alternative assessment of the operating conditions it was determined that non-autothermal operation is most desirable with a score of 1,057 versus 924. It was also concluded that an operating reactor range from temperatures of 260 to 300 °C and residence times of 7.5-30 minutes should be employed. The temperature and time will be further narrowed down in the design phase.

Pellets vs. Briquettes

The coupling of torrefied biomass and pelleting/briquetting serves to be beneficial. Torrefaction of biomass solves two major problems encountered with untorrefied products: moisture resistance and biological degradation (Maciejewska et al 2006). Since the terrified biomass is hydrophobic and resistant to biological degradation, it will be easier to store and transport. Also, compressing the torrefied biomass into the smaller, more compact form of pellets or briquettes increases mass density, energy density, limits dust formation, and solves issues of handling problems as shown in **Error! Reference ource not found.**(Maciejewska et al. 2006). Pellets and briquettes will be alternatively assessed to conclude which will be most beneficial for implementation into the mobile torrefaction unit.

Table 8 Properties of wood, torrefied biomass, wood pellets, and torrefied wood pellets (Maciejewska et al. 2006).

Properties	Unit	Wood	Torrefied biomass	Wood pellets	TOP pellets
Moisture content	%wt	35	3	7-10	1-5%
LHV dry	MJ/kg	17,7	20,4	17,7	20,4-22,7
LHV as received	MJ/kg	10,5	19,9	15,6-16,2	19,9-21,6
Mass density (bulk)	Kg/m3	550	230	500-650	750-850
Energy density (bulk)	GJ/m3	5,8	4,6	7,8-10,5	14,9-18,4
Pellets strength		-	-	Good	Very good
Dust formation		Moderate	High	Limited	Limited
Hygroscopic nature		Water uptake	Hydrophobic	Swelling/water uptake	Poor swelling (hydrophobic)
Biological degradation		Possible	Impossible	Possible	Impossible
Handling properties		Normal	Normal	Good	Good

Torrefied pellets are much easier to handle and implement into automated feed systems found in coal-fired power plants, rather than the raw bio-char form. Pellets are most commonly cylindrical shaped with a diameter between 6 and 8 millimeters and a length under 38 millimeters (Ciolkosz, 2009). Because of their small size, they can theoretically be crushed into a fine powder easier than the larger torrefied briquettes. This is important when considering bio-char implementation into coal-fired power plants where coal is pulverized into a fine dust before it enters the kiln. This fine dust burns more efficiently as there is more surface area for the product to combust and acts more closely to a liquid fuel (IECG, 2002). Though the pellets and briquettes would have the same friability because of their identical composition, the pellets would require less grinding to reach the powder stage due to their smaller size. This proves important when considering the energy costs of grinding and other processes that may be necessary for pellet production. Typical pelleting processes incorporate a grinder/mill, drying oven with cyclone separator, infeed hopper, screw auger, die extruder, pellet dryer, and a bagging device (Ciolkosz, 2009).

The grinder/mill is where the raw torrefied bio-char is pulverized into smaller bits no larger than 3 millimeters in length. The drying oven with cyclone separator acts to reduce moisture and separate any larger particles that made it past the grinder. For the torrefaction unit under design, this initial drying oven in the pelleting step can be removed since the output bio-char will be at relatively high temperatures and the moisture will already be significantly reduced. The infeed hopper then takes the pulverized bio-char and feeds it into the die extruder where the actual pellets are produced. The material is rolled through a die or a hot metal plate with small holes where high temperature and pressure fuses the biomass together into the pellet. Lignin acts as a binder, which holds the bio-char together in pellet form (Ciolkosz, 2009). A study by Bergman et al estimates the cost of producing pellets to be around 100 to 120 euros per ton produced based on the feedstock input (Bergman Patrick C.A., 2005) whereas Maciejewska et al estimates the costs to be between 12 to 40 Euros per ton based on current Dutch facilities. The difference is likely due to the larger plant capacities and the recovery of heat from the dryers which can be sold to local heating networks (Maciejewska, 2006). It is also important to note that these estimates include cost of raw material, costs of drying wet material, and of being a large-scale producer. Because the operation has a mid-scale production capacity of 25,000 tons per year, feedstock available at no cost (valued by Bergman et al 2005 as being 25 Euros per ton), no required drying units, and local power plants, it is assumed that the cost will be around 25 Euros per ton. Taking the production capacity of 25,000 tons per year, an operating duration of 180 days per year and 24 hours a day, and a conversion factor of $1.39 US to 1 Euro, this gives a rough total cost of $868,750 per year or $4,826 per day of operation. The figure below shows regular wood pellets versus the torrefied biofuel and second figure shows a mid-scale pelleting mill.

Figure 21 Raw wood pellets vs torrefied wood pellets (CNFbiofuel, 2011.)

Figure 22 Mid-scale pelleting mill (Henan Kingman M&E)

The process of producing briquettes is similar to that of producing pellets, but the energy demands are lower. The briquetting material is fed into a hopper feed which pushes the biomass into a pre-compression chamber where the material pressed into the form of briquettes (a larger cylinder) by a hydraulic press and then cooled (Friz, 2011). Briquetting does not require the smaller sized particles that pelletization does because of the larger briquette size. The typical diameter of a briquette ranges from 30 to 100 millimeters. This results in less energy required for the pulverization of the torrefied output and essentially a lower cost of production (Maciejewska, 2006). Bergman et al estimates the cost for producing briquettes to be 18 to 59 dollars per ton which again includes cost of raw material, costs of drying wet material, and of being a larger-scale producer (Bergman Patrick C.A., 2005). For the alternative assessment, it is assumed that the cost of producing briquettes will be on the lower end as assumed with pellets. This gives an estimated cost of 22 dollars per ton and assuming the same operating conditions and conversion factors used for estimating cost of pelleting, gives a rough total cost of $521,250 per year or $2,896 per operating day. These values are significantly cheaper than producing pellets and are taken into account in the decision matrix. **Error! Reference source not ound.** figures below show torrefied briquettes and a mid-scale version of the process equipment.

Figure 23 Torrefied wood briquettes (ecoTECH Energy Group, 2010) (Bionomic Fuel, 2009)

Figure 24 - Mid-scale briquetting equipment (Hermance Machine Company)

The capital required for the two processes is relatively similar in that it will cost no more to purchase pre-manufactured pelleting equipment than briquetting equipment. However, because is a greater abundance of pelleting equipment on the market in the United States, the pellets rank slightly higher. The lower power consumption used in the production of briquettes is weighted within the operating expenses, as it can be seen that briquetting is more power efficient than pelleting. When considering the return on investment, both rank similarly since they have the same composition and will be assumed to sell at the similar prices.

The next major issue studied in the decision matrix was the technical feasibility of each biomass end product. As it was stated earlier, less energy is required to create briquettes than pellets. Therefore the briquettes received a higher score for the energy balance aspect. The mass balance will be the same for both briquettes and pellets because both processes exhibit low mass loss. For the particle sizes accepted, the briquetting received higher scores because the larger diameter briquettes do not require that the input material be crushed to the 3 millimeter size which pelleting requires. Since both processes use the same bio-char material, and no significant chemical reactions occur, the energy/mass for each process will be consistent. There are no special permitting requirements for each of the processes not required for the overall process. Also, both pelleting and briquetting processes are fairly reliable, have low complexity, and low operation/maintenance. Both processes are easily implemented with the purchase of pre-manufactured equipment, but pelletization will require less grinding if input to a pulverized-coal fired power plant. Due to this issue, pellets receive a slightly higher score for the ease of implementation. It is also important to note that there are manufacturing companies in the United States who specialize in the production of pelleting and briquetting units. It will prove more economically viable to investigate the possibility of purchasing one of these units rather than fabricating it, which adds ease to the implementable aspect of the matrix.

The environmental concerns associated with pellets and briquettes are the same. They both reduce greenhouse gas (GHG) emissions by burning carbon already in the carbon cycle. Also, the production lines of both have low emissions, low water usage, and similar noise levels. The safety and social aspects of briquetting versus pelleting are not going to vary significantly.

In constructing a decision matrix, weights were assigned to cost, technical feasibility, environment, safety, and social aspects by input from iCAST. Raw scores were assigned for each aspect of pellets and briquettes on a scale of 1 to 10 with higher scores meaning more desirable. These raw values were assigned to issues concerning costs, technical feasibility, the environment, safety, and social aspects based on the information discussed above. Multiplying the raw scores by the individual weights gives a weighted score for each criteria and summing them for each gives a total score for both pellets and briquettes. The scores are seen in the decision matrix below. When comparing the two alternatives in a decision matrix, it is found that briquettes are a better solution for the mobile torrefaction unit as they outweigh the pelleting option by 36 points.

Table 9 Decision matrix showing inputted values for pellets versus briquettes.

	Raw Score (scale of 1 to 10)			Weighted Score (weight x raw score)	
	Pellets	Briquettes	Weight	Pellets	Briquettes
Costs:					
Capital Required(Order of Magnitude Estimate)	6	5	7	42	35
Operating Expenses (Order of Magnitude Estimate)	1	3	8	8	24
Return on Investment (ROI)	6	6	10	60	60
Technical Feasibility					
Energy in V.S. Energy out (Energy Balance)	4	6	8	32	48
Mass Balance	9	9	4	36	36
Particle Sizes Accepted	4	7	3	12	21
BTU value of Biochar	8	8	4	32	32
Permit requirements and approval	1	1	-	-	-
Reliability of process/equipment	6	5	8	48	40
Complexity of process/equipment, O&M needs	4	4	7	28	28
Ease of Implementation	6	4	1	6	4
Environment					
Environmental Mitigation (Environ. Benefits Gained)	7	7	7	49	49
Life Cycle Analysis	1	4	4	4	16
Emissions	6	6	3	18	18
Noise, Odor, Traffic	2	2	3	6	6
Water Usage	1	1	1	1	1
Safety:					
Safety Hazard	1	1	8	8	8
Hazardous By-products	1	1	5	5	5
Social Aspect					
Public Support (not in my back yard attitude)	1	1	-	-	-
Political Support (is it mainstream, heavily talked about or not)	1	1	-	-	-
Total:				**395.00**	**431.00**

Air Pollution Control

Background

In terms of air pollution control the main concern for the combustion of biomass is emissions of particulate matter (PM). Adverse health effects occur from exposure to PM that is 10 microns and smaller (PM_{10}) and 2.5 microns and smaller ($PM_{2.5}$), and combustion results in PM of this size range. Please view the Regulations section of this report for a more detailed discussion of air pollution regulation. Because of these regulations, air pollution control devices were an important consideration for the assessment of the design of this mobile bio-char production unit. To control PM, numerous devices can be placed in the exhaust stream of the process to mechanically separate the particles from the air. Four different types of air pollution control devices were analyzed for regulating the exhaust from the mobile torrefaction unit: cyclones, electrostatic precipitators, fabric filters/ baghouses, and scrubbers. Background information on each of these devices is discussed below. (C. David Cooper, 2002)

Cyclones are essentially devices that force PM laden air into a vortex type of rotation, causing centrifugal force to separate the particles. Particles are pushed into the walls of the cyclone, causing them to drop out of the air, and fall out into a collection basin. The lack of moving parts significantly limits the amount of maintenance needed for these devices. This simplicity also allows for low capital costs for cyclones (roughly $11k for an industrial sized unit. Another key advantage of cyclones is the ability to operate at high temperatures. Collection efficiencies are a drawback of cyclones. Efficiency wanes as the size of the PM decreases. A “high efficiency” cyclone will operate with efficiency around 90% for PM_{10} and around 60% for $PM_{2.5}$. This lower collection efficiency is something that was considered for the use in a combustion process, where PM_{10} and $PM_{2.5}$ are major byproducts. Also, cyclones, by design, result in a large pressure drop, which can increase operational costs. (C. David Cooper, 2002)

Electrostatic precipitators (ESPs) use a process that involves three general steps. First, PM laden air is ionized as it flows between electrodes. Second, the charged particles migrate toward, and are eventually collected on oppositely charged plates. Finally, the particles are collected off the plates. The forces used in ESPs interact solely with the particles, as opposed to the entire air stream, which is unique only to this type of air pollution control device. Low-pressure drops and few moving parts make operating costs relatively low. ESPs are very efficient, even for small particles, and can handle high temperatures. However, ESPs come with very high capital costs (between $500k and $1.5 million). Maintenance can be an issue with ESPs, as well. Electric arcing can occur if PM builds up too thick on the plates, so the device requires frequent cleaning. ESPs also take up a lot of space, which is a concern for a mobile processing facility. Also, some particles resist being charged by the ESP, which would affect the device’s collection efficiency. (C. David Cooper, 2002)

Fabric filters are efficient PM control devices that can be used in a number of different ways. One method of fabric filter application is the use of a baghouse. Essentially, baghouses are structures filled with fabric filter bags that exhaust streams are pumped through. Baghouses have very high collections efficiencies for a wide range of PM sizes, including very small particles. However, baghouses require a lot of space, require frequent maintenance, cannot manage corrosive material, and cannot tolerate high temperature gas streams. Baghouses also come with a high capital cost (about that of an ESP). Another method of fabric filter collection is with individual filter cartages. These are cheaper alternatives to the baghouse, because filter cartridges take up less space, and fit right into the exhaust system infrastructure (cost estimate ongoing with manufactures). Filter cartridges are effective for large PM size ranges, like the baghouse, and have high collection efficiencies. However, like the baghouse, fabric filter cartridges cannot withstand high heat gas streams or corrosive materials. Also, these cartridges are meant for lower concentrations of PM than baghouses, and will clog much quicker than their larger counterparts, requiring more frequent cleaning and replacement. (C. David Cooper, 2002)

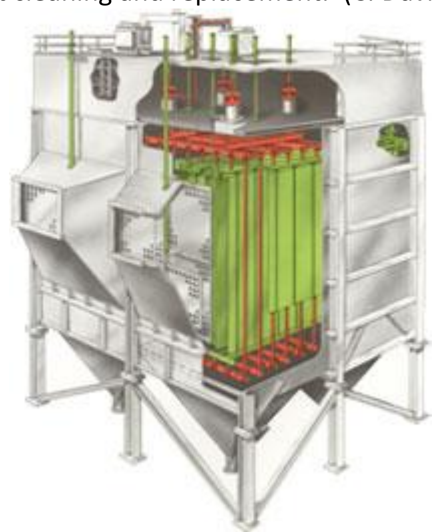


Figure 25- Electrostatic precipitator (ESP)

Particle scrubbers are high efficient PM control devices that use particle impaction with liquid droplets as their collection method. Essentially, a water-based liquid is sprayed in a fine mist into the exhaust stream where. Particles will collide with the liquid droplets and carried down to a collection basin. Scrubbers can handle high temperature gas streams, as well as corrosive PM. However, collection of corrosive PM will require expensive waste disposal procedures. A unique advantage of scrubbers is their ability to remove gas emissions as well as PM emissions. Scrubbers are also useful in their ability to cool gas streams. The operator can vary collection efficiencies, and different scrubber designs offer varied collection efficiencies. However, maintenance due to the wet collection is a large expense. Precautions for corrosion, cold outside temperatures, and water pollution from the scrubber effluent must be taken. (C. David Cooper, 2002)

Table 10 Air Pollution Control Decision Matrix

	Raw Score (scale of 1 to 10)					Weighted Score (weight x raw score)			
	Cyclone	Fab Filters	Scrubber	ESP	Weight	Cyclone	Fab Filters	Scrubber	ESP
Costs:									
Capital Required	10	10	4	1	10	100	100	40	10
Operating Expenses	8	6	2	6	9	72	54	18	54
Environment									
Permit requirements and approval	6	6	4	6	2	12	12	8	12
Land requirements	10	10	3	3	6	60	60	18	18
Water usage	10	9	1	9	5	50	45	5	45
Technical Feasibility									
Collection Efficiency	4	8	10	8	8	32	64	80	64
Ease of Implementation	10	8	1	5	5	50	40	5	25
Maintenance	10	4	4	5	7	70	28	28	35
Temperature Dependence	10	2	10	10	7	70	14	70	70
Safety:									
Safety Hazard	10	10	6	5	6	60	60	36	30
Hazardous By-products	7	7	4	7	2	14	14	8	14
Social Aspect									
Public Support	8	8	8	8	1	8	8	8	8
Political Support	8	8	8	8	1	8	8	8	8
Total:						**606**	**507**	**332**	**393**

Air Pollution Control Device Decision

In deciding which of the above devices should be used for controlling PM emissions for the mobile bio-char production unit, five categories were assessed at depth: costs, environment, technical feasibility, safety, and social aspect. Each of these categories was put in a design matrix along with each of the control devices, except for the baghouse. The baghouse was scrapped right away because of its high cost and low tolerance for high temperature streams, which will be present for this process. Specific subcategories for each category were listed and given a weight. These will be detailed below. Weights were assigned on a 1 to 10 basis, with 10 being the highest, most important weight. Then, each device was scored in each subcategory on a scale of 1 to 10, with being the highest score. These scores were then multiplied by the weights, and the device with the largest summed weighted score would be the best option for the bio-char process.

The subcategories for cost were: capital required for device purchase and device operating cost.

The capital requirement took into account the initial purchasing cost for each device, as well as the purchase of other essential parts, such as airtight valves for the cyclone. For each device, purchasing cost depends on the design parameters for the specific system requirements. For this assessment, a range of parameters was used when calculating the cost estimates, and the average cost was used for the decision matrix. Please see the air pollution cost estimate calculations in the Appendix for more detail on these estimates. The capital cost was assigned a weight of 10 out of 10 because of the importance of the client's return of investment for this bio-char production unit. (C. David Cooper, 2002)

The operating cost took into account energy consumption the device would use, or cause due to pressure drops, as well as maintenance costs. Because the exact design of the process has not commenced yet, these considerations were estimated with the knowledge of the tendencies of each device. For example, the scrubber was assigned a 2 on the decision matrix for operating cost because of the high amount of maintenance and potentially hazardous waste it yields. The cyclone was assigned an 8 because cyclones generally produce a large pressure drop, yet there are no moving parts or much cleaning to deal with. (C. David Cooper, 2002)

The subcategories for the environment aspects of the design were: permit requirements and approval, land requirements, and water usage.

Permit requirements and approval took into account any special permitting or approvals that would be needed for the use of any of the air pollution control devices. The only main concern for permitting would be with collected waste disposal. This subcategory was rated low, 2, because whether or not permitting is an issue, the use of air pollution devices is essential to avoiding fines for over emitting pollution. The wet scrubber was scored lower than the rest of the devices here because the waste fluid is more difficult to dispose of and may incur regulation if there is a potential for local water contamination. (C. David Cooper, 2002)

The land requirements subcategory took into account the size of the individual control devices and the amount of space they would take up. Delta Timber is limited in space for this production unit, so the materials used in the unit's design need to be conservative in the space they take up. This is also helpful for the mobilization aspect of the design. This subcategory was weighted around mid-level importance, 6, because of the space restrictions required in the design. The ESP and scrubber were scored very low in this subcategory because they each take up a lot of space. (C. David Cooper, 2002)

The water usage subcategory took into account the amount of water that each device would require for operation and cleaning. This was weighted mid-level, 5, because the water usage is inevitable for cleaning purposes, but extensive use of water for operation would be difficult to maintain in rural areas where the mobile torrefaction unit will be operating. Other than the scrubber, the other devices were scored very high in this field because they require water only for cleaning purposes. The cyclone, by design, is the easiest to clean with water because nothing has to be taken apart. The scrubber, however, uses water, or a water solution, for its collection mechanism, and would require large amounts of water for continual operation. Therefore, it was scored very low. (C. David Cooper, 2002)

The subcategories for the technical feasibility section were: collection efficiency, ease of implementation, maintenance, and temperature dependence.

The collection efficiency subcategory took into account how efficient each device is with collecting particles in the size range of PM_{10} and $PM_{2.5}$, which are the main source of PM emissions from the combustion of wood. This was highly weighted, 8, because the collection of the target PM is the main goal for using one of these control devices in the process. Other than the cyclone, each device scored high in this subcategory because they collect small particles very efficiently. Cyclones are typically better at collecting larger particles (PM_{10} and larger) though they can be designed to collect $PM_{2.5}$ but will not have efficiencies in the 99% range like the other devices. Therefore, cyclones were scored low in this subcategory. (C. David Cooper, 2002)

The ease of implementation subcategory took into account how easy it would be to incorporate the control device into the process. This was weighted mid-level, 5, because modifications can be made to the system for devices that are more difficult to incorporate if the device turns out to be the best choice. Scrubbers would be the most difficult to implement in the process because of the water usage and the waste disposal issues, as well as its size. The ESP would be easier to implement than the scrubber, though the electricity usage and large size of the device would add difficulty to its incorporation. The other two devices would easily fit right into the exhaust stream of the process. Each device was scored accordingly. (C. David Cooper, 2002)

The maintenance subcategory took into account the amount of maintenance each device would require throughout its lifetime. This subcategory was weighted moderately high, 7, because maintenance on these devices can be costly, as well as may require replacing parts, which could mean shutting down the entire process. Since the cyclone only needs occasional cleaning, and has no moving parts, it scored the highest. Fabric filter cartridges need constant cleaning and replacement. Scrubbers need frequent cleaning so as to avoid corrosion from the high moisture, and the spraying devices must be cleaned and replaced due to particle clogging. ESPs must be cleaned often to avoid arcing, and increased pressure drops. Each of these devices was score low in this subcategory. (C. David Cooper, 2002)

The temperature dependence subcategory took into account whether or not the device had any operating limits due to temperature. This subcategory was weighted moderately high, 7, because the torrefaction of biomass requires high temperatures, resulting in exhaust gasses in excess of 60 ^oC. The only device that has limitations with temperature is the fabric filter cartridge. Because the fabric will warp or burn at high temperatures, this device was scored low in this subcategory. (C. David Cooper, 2002)

The subcategories for the safety category were: safety hazards, and hazardous by-products.

The safety hazards subcategory took into account any dangers that may be inherent with the operation of the each control device, separate from the hazards of the collected PM. An example is the potential for explosions with baghouses, resulting from igniting the aerosolized PM with the structure. This subcategory was weighted mid-level, 6, in importance, because, if operated correctly, each of these control devices are safe. The ESP was scored lowest because of the potential for arcing between plates if they are packed with too much PM. This arcing could be dangerous for an operator to be around. The scrubber has some inherent risk due to high-pressured sprayers. The other two devices have few safety concerns. (C. David Cooper, 2002)

The hazardous by-products subcategory takes into account the collected PM waste resulting from each devices use in the process exhaust stream. This was weighted low, 2, because any PM that is collected is somewhat hazardous, and, therefore, is a necessary problem. The only control device with a particular concern with hazardous waste, and scored low in this subcategory, is the scrubber because the by-products can be corrosive, and can be a potential contaminant in the local water system. The other three devices were scored relatively high because their only concern is the inhalation of the collected PM, which is an unavoidable issue with any PM control device.

The subcategories in the social aspect category were: public support and political support. Both of these subcategories were weighted the exact same, 2, because the use of air pollution control devices is looked at as good protocol by private citizens and governing bodies. The use of these devices would not be considered as highly without the government regulations on PM emissions. With the torrefaction process happening close to moderately populated areas in Delta County, private citizens will want there to be methods to control pollution due to health concerns, so the use of PM control devices is agreeable with them. Each device was scored the same, because each device has the same common purpose.

The decision matrix's output supports the use of a **cyclone** over the other three devices. This device will be the control device used for collecting PM for the exhaust of the torrefaction process. Cost effectiveness is major appeal of the cyclone. Cyclones come with low capital, use no moving parts, and are easy to operate. The one drawback to using cyclones is the relatively low collection efficiency for small particles, especially those resulting from combustion. A solution is to couple a cyclone with fabric filter cartridges. Though the initial capital for this method is low, the constant replacement of the filters would added up to be a large expense. A better solution to this problem is to operate two or more cyclones in series, allowing more opportunities for PM to be collected. This exact setup will be explored during the design phase of this project.

Material and Energy Balances

Before any equipment cost estimates could be made for this process it was first necessary to perform overall material and energy balances on each piece of equipment in the system. To do this, values for the material and energy balances of a similar process were obtained through research (Bergman Patrick C.A., 2005). These values were then scaled to our process to give accurate estimates of the overall material and energy balances of all important pieces of equipment. The figure below summarizes these balances. A detailed analysis of the material and energy balances is located in the appendix.

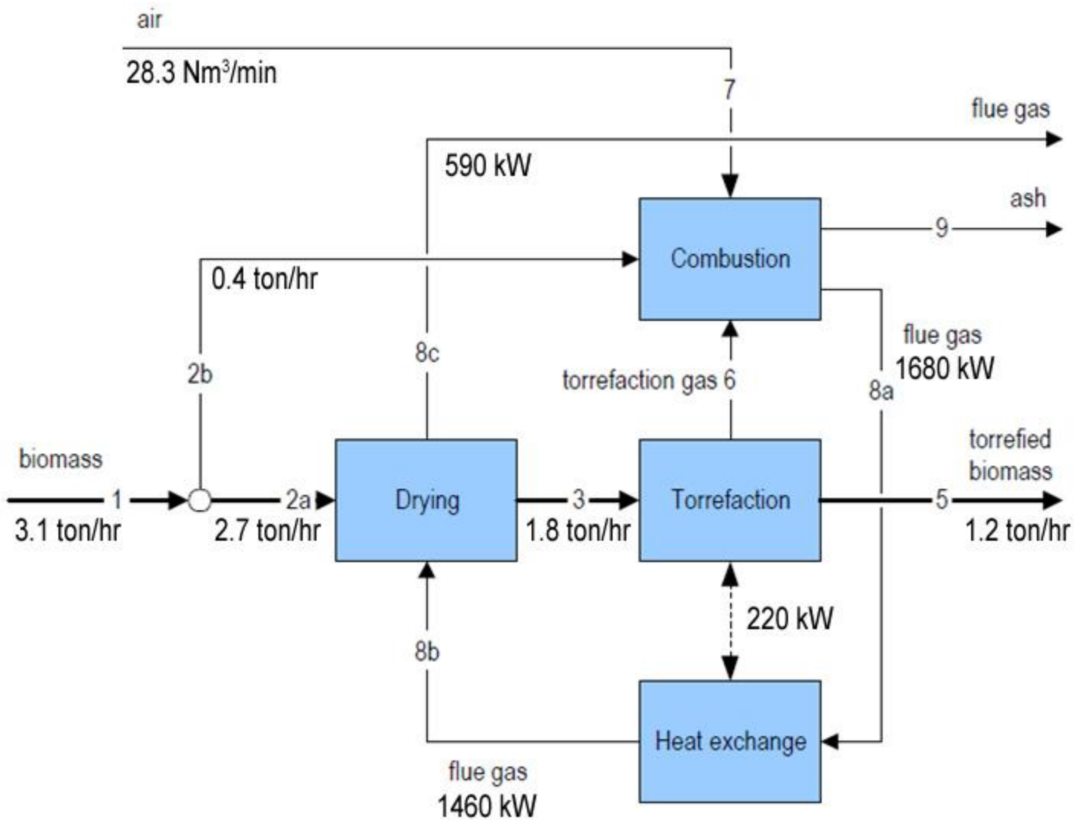


Figure 26 - Material and energy balances for the torrefaction of 25,000 tons/yr of biomass

Design Analysis

Size Reduction Equipment

Before drying takes place, the raw biomass needs to be reduced to a size feasible for the process. Since it is not important to reduce the material to a fine power or sawdust-like state, it would be more practical to purchase a wood chipper rather than a hammer mill or crusher seen in other biofuel systems. Designing the system with a chipper also allows sawmills and other forestry companies to use materials they most likely already have on site that is if they are not being employed by other processes. By using equipment already purchased by the plants, the capital cost of the system can be reduced. The smaller size materials expedited from a wood chipper, up to 2 inches in length, would be sufficient for the drying and torrefaction processes; once the biomass is torrefied, the product becomes friable meaning longer chips of 2 inches should not play a factor in hindering the production of briquettes. (Bandit Industries, Inc., 2010) (Miller B. A., 2011)

The chipper needs to handle an input rate of 6262 pounds per hour of biomass on average. This value was obtained assuming a feed rate of 0.681 kilograms per second derived from a comparison of a torrefaction system study (Bergman Patrick, 2005). To handle this required feed rate, a Bandit Model 1990XP wood chipper will be incorporated into the process train. This machine can take in larger pieces of biomass - up to 21 inches in diameter - making it perfect for use at the Delta Sawmill where unused biomass could include larger sized timber. As well as having a 21-inch diameter biomass limit, the machine is equipped with a 41 inch high by 64-inch wide in-feed hopper with a 30-inch fold down in-feed tray. This proves ideal for feeding the chipper with a front-end loader or similar device as the biomass can be deposited into the in-feed hopper quite easily. The 10,500 to 12,500 pound unit (depending on available option customization) is powered by a 63.9 cubic inch hydraulic drive motor, which handles a feed rate of 96 feet per minute or 260,000 pounds per hour when the density of aspen wood is assumed 18.7 pounds per cubic foot (Miller B. A., 2011). The wood chipper has a length of 20' 2", a width of 7' 7", and a height of 10' 2". This means that the equipment takes up roughly 153 square feet of the 10,000 square foot concrete pad - just over one and a half percent of the total available area. The chipper is also trailer mounted meaning greater mobility for process relocation (Bandit Industries, Inc., 2010).

Table 11 Technical specifications of the Bandit 1990XP (Bandit Industries, Inc., 2010).

Technical Specification	Value
Width	7’ 7’’
Height	10’2’’
Length	20’ 2”
Weight	10,500 to 12,500 lbs
Chipper Input Capacity	21” diameter
Drive Motor Size	63.9 in3

These wood chippers are easy to find both new and used. Prices of the Bandit Model 1990XP range from $52,900 for new to $47,000 (Apollo Equipment, 2009) (EBAY.com). Taking an average of these two values give a cost of roughly $49,950 for the capital cost of the equipment. Since the chipper is trailer mounted and pre-fabricated, it is assumed that there will be no installation fees to be considered in the equipment capital cost. Again, assuming a 20%

engineering fee of that initial capital cost, gives a final cost of $59,940.00 excluding contingency.

Figure 1. Trailer mounted Bandit 1990XP and feed inlet (Bandit Industries, Inc., 2010).

Dryer

Due to the high moisture content of the aspen biomass it needs to be treated prior to entering the torrefaction reactor. Because natural drying doesn't generally reduce moisture content below 20%, the aspen will be treated in a single-pass rotary dryer to decrease the water content to 15%. The single-pass rotary dryer is the most widely used rotary dryer, but it was chosen for this unit for many different reasons. Rotary dryers allow hot flue gas and biomass to flow concurrently through the reactor, biomass does not have to be a uniform size, it can accept the hottest flue gases, there are low maintenance and energy costs, and it has the greatest capacity of any type of dryer (NREL, 1998). A co-current rotary dryer will be implemented as seen in the schematic below:

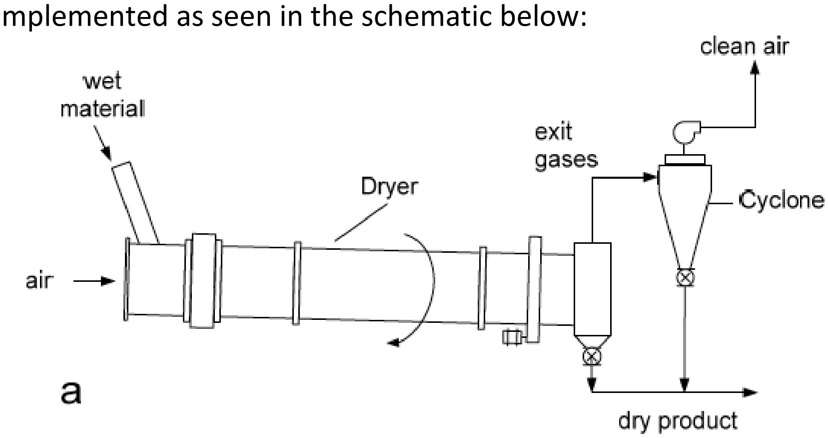


Figure 27 Co-current rotary dryer (J. Meza, 2008)

The co-current rotary dryer allows the wet, chipped biomass and the hot flue gas to flow in the same direction through the dryer to the exit. While this presents a thermal inefficiency due to the air increasing in humidity as it flows over the wet biomass, it also presents a lower ignition and firing risk (J. Meza, 2008). A truck-mounted rotary dryer by Buhler Aeroglide Corporation will be purchased to accomplish the task of drying the aspen wood to a maximum of 15% moisture content as seen below. If there is an unusually high moisture content in a certain batch of biomass, the feedstock can be fed through the dryer more than one time until the desired moisture content range is reached.

Figure 28 Aeroglide Rotary Dryer (Aeroglide, 2011)

Utilizing the material and energy balances for the overall process, it can be seen that the wet biomass feed rate into the dryer is going to be 2.7 ton/hr. Utilizing this number and published sizing charts from the Henan Zhongke Engineering Technology Co., Ltd, the equipment specifications for size, weight, power, moisture removal, cylinder speed, and thermal efficiency were estimated. Cost was calculated by utilizing a costing chart given in a biomass drying technology report written by NREL as seen below.

Table 12 Rotary Dryer Costing Chart (NREL, 1998)

Dryer Type	Capital cost per lb/h of water evaporated	Capital cost per kg/h of water evaporated	Source
Single-Pass	$12/lb/h	$26/kg/h	Fredrikson 1984
Triple-Pass	$10/lb/h	$22/kg/h	Fredrikson 1984
Stearns and Roger, Single-Pass	$18-$32/lb/h	$40-$71/kg/h	Intercontinental Engineering, Ltd. 1980
Aeroglide	$11-$21/lb/h	$24-$46/ kg/h	Intercontinental Engineering, Ltd. 1980
Heil	$17-$48/lb/h	$37-$106/kg/h	Intercontinental Engineering, Ltd. 1980
*Rotary	* $102/lb/h	* $224/kg/h	Frea 1984
*Rotary	* $80/lb/h	* $176/kg/h	Technology Application Laboratory 1984
*Flue Gas Dryer	* $346/lb/h	* $761/kg/h	Wardrop Engineering, Inc. 1990
*Rotary Dryer	* $136-362/lb/h	* $300-796/kg/h	MacCallum et al. 1981

Utilizing the Aeroglide row and calculating the capital cost off of the kg/hr of water evaporated a cost of $69, 065 was found. This has been adjusted to include installation costs with an installation factor and the money has been adjusted to represent 2011 present value. Costing equations and calculations can be found in the appendix. A contingency fund of 10% and an engineering and administrative fund of 20% has been included in these costing analyses. The specification of the dryer and the costing is summarized in the table below:

Table 13 Aeroglide Rotary Dryer Specifications and Cost (Henan Zhongke Engineering Technology Co. Ltd., 2011), (Bio-Gas Technology , 2011)*

Cost ($2011 Installation + Capital Cost)	$69,065
Size (Diameter x Length) (m)	1.2 x 12
Equipment Weight (ton)	16.5
Processing Capacity (ton/hr)	2.5 - 5
Moisture Content Removal (%)*	30 – 45
Power (kW)	15
Cylinder Speed (4.8 r/min)	4.8
Thermal Efficiency (%)	60

Torrefaction Reactor

To meet the goal of processing 25,000 tons of biomass per year, one of the most significant pieces of equipment is the torrefaction reactor. In selecting this equipment it was necessary to first find manufactures of equipment capable of handling this process. Upon research it was found that the only commercially viable manufacturer of torrefaction equipment was Wyssmont (Wyssmont). Upon search, a previous quote for a Wyssmont TURBO-Dryer which was specified to process biomass to torrefied wood was found. This quote was for a unit a little bit larger than twice the size of the unit required for our process. To account for this discrepancy the sixth-tens rule for economy of scale was used scale the reactor to cost to the size of our process and then the purchase cost was multiplied by a bare module factor to calculate the estimated install cost (Seider, 2009). Using this method an installed cost of $1,948,000 is estimated. The calculations for this process are shown in the appendix. The figure below illustrates the design of the reactor.

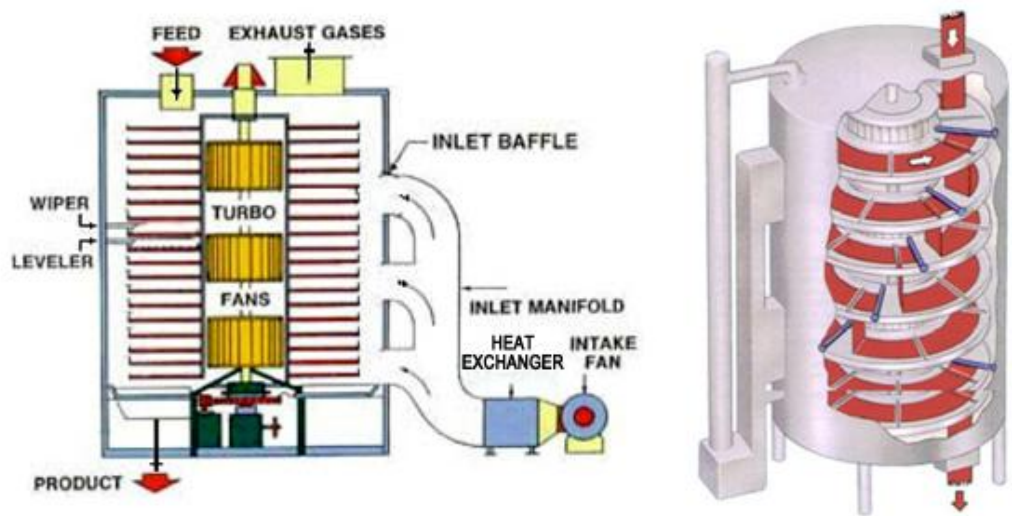


Figure 29 - Wyssmont TURBO-Dryer

The Wyssmont TURBO-Dryer is equipped with dual airlocks meaning the off-gases can be captured in the exhaust and diverted to the combustor to supply heat to the process. Also, the large surface area of the reactor allows for the biomass to be evenly heated and thus torrefy in a consistent manner. To supply heat to the reactor, hot flue gases are passed through a heat exchanger which is equipped with a fan to circulate heated air throughout the reactor. Dry biomass, less than 15% moisture, enters the top of the reactor at 240-250C and is then heated to 280C to being the torrefaction process. The biomass spends a total of 18.5 minutes in the reactor and is then ejected from the bottom of the reactor.

Table 14 – Reactor specifications

Height (m):	8.4m
Diameter (m):	6.5
Volume (m3):	275.8
Temperature (°C):	280
Residence Time (min):	18.5

From the above table it can be seen that the reactor is quite large and will not fit on a flatbed trailer while fully assembled. However, this reactor is constructed in a manner such that it can be dissembled for transport, thus lending to the semi-mobile design requirement.

Heat Exchanger and Combustor

The purchase price of the Wyssmont TURBO-Dry does not include the heat exchanger or combustor necessary to supply heat to this process. Therefore, it was necessary to develop an estimate for a combustor and heat exchanger capable of meeting the heating needs of the torrefaction reactor and the dryer. Quotes for biomass combustors similar to that of the combustor required for our process were obtained from Biomass Combustion Systems, Inc. (Biomass Combustion Systems, Inc.). These quotes were then linearly extrapolated to the size requirement of our system. The table below lists the design specs of this furnace.

Table 15 – Combustor specifications

Heat, KBtu/hr	1600
Installed Cost	$ 25,000
Weight (Lbs)	10500
Height (in)	164
Width (in)	69
Length (in)	104

To obtain a cost estimate for the heat exchanger required for this process it was first necessary to determine the interfacial surface area required between the flue gas stream and the TURBO-Dryer. To achieve this goal, software from Aspen Tech Inc. was used. The heat exchanger was simulated using Aspen Plus and then exported to Aspen Energy Analyzer to determine the interfacial surface area of the heat exchanger.

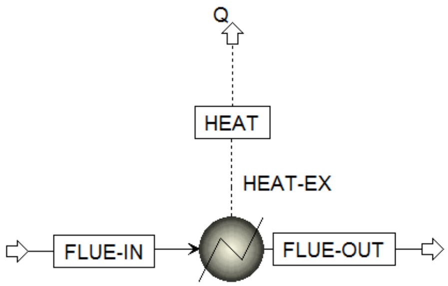


Figure 30 - Aspen Plus diagram

Upon calculating the interfacial surface area the cost of the heat exchanger was estimated using general cost equations provided by Professor Alan Wiemer (Weimer, Fall 2010). The material of construction for the heat exchanger is specified as stainless steel for durability.

Table 16 - Heat exchanger specifications

Surface Area (m^2):	22.74
Installed Cost:	$ 196,000

The total combined installation cost of the heating system is approximately $221,000.

Briquetter

In order to improve transportation feasibility, a briquetter system is implemented into the design. A briquetter puts the biochar into a compressed disk or block that is much easier to handle than untouched biochar. It also increases the biochar's mass density, making it better for packing and increases energy density meaning Delta Sawmill can ship more energy in each shipment to the power plant (Miller B. A., 2011).

The feed rate out of the torrefaction column was determined to be 2460 pounds per hour from 0.310 kilograms per second. This value was derived in the mass balance calculation from the same case study aforementioned, using conversion factors (Bergman Patrick, 2005). To find the specifications necessary to handle this feed rate, five separate briquetters were analyzed: Topline Recycling Equipment LTD's B60 (Topline Recycling Equipment, LTD., 2011), BHS Energy's Slugger Model 1520 (BHS Energy LLC, 2010), Komar's Briquetting System (Komar Industries Inc.), Wiema Maschinenbau GmbH's TH 820 (Weima, 2007), and Alvan Blanch's BP 5000 (Alcan Blanch). Data was collected on these briquetters including dimensions, max feed rate, briquette length and width, and cost. These specifications can be see in Table 2 with the exclusion of unobtainable information.

Table 17 Briquetter specifications used for sizing of Delta Sawmill's briquetter.

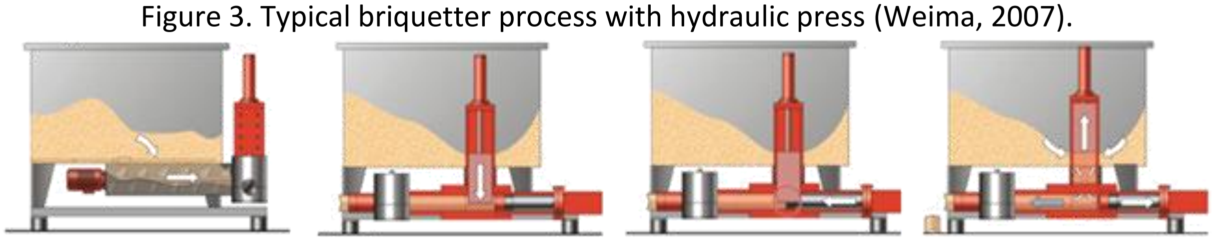
Make	Model	Weight (lbs)	Length (in)	Height (in)	Width (in)	Max Feed Rate (lbs/hr)	Cost
Topline Recycling Equipment LTD	B60	1500	70	50	32	500	---
BHS Energy	Slugger Model 1520	5000	108	---	72	1200	$48,000.00
Komar	Briquetting System	---	---	---	---	300,000	$89,500.00
*WEIMA Maschinenbau GmbH	TH 820	3306.9	78.7	78.7	37.8	396.8	---
*Alvan Blanch	BP 5000	---	---	---	---	2646	---

Topline Recycling Equipment LTD's B60 is a smaller scale briquetter equipped to handle a feed rate of 500 pounds per hour - much less than the 2460 pounds per hour required by Delta Sawmill. Dimensions of the unit are 70 inches in length, 32 inches in width, and 50 inches in height. These dimensions prove valuable for scaling the required size briquetter. BHS Energy's Slugger Model 1520 can handle a slightly larger feed rate at 1200 pounds per hour but still falls short of the required 2460 pounds per hour. It has dimensions of 108 inches in length and 72 inches in width. Again these dimensions can be used to help size the briquetter for the required feed rate of the Delta Sawmill system. Komar's Briquetting System is found to be much too large for the requirements of Delta Sawmill with a maximum feed rate of 300,000 pounds per hour. The increase in feed rate can be seen as it is taken into account in its cost - $89,500 for a used unit. Wiema's TH 820 also has a max feed rate which falls short of the requirement. The unit handles just under 400 pounds per hour and has dimensions of 79 inches in length, 38 inches of width, and 79 inches in height. Alvan Blanch's BP 5000 can handle a feed rate closest to the required. The unit with a feed rate of 2645.5 pounds per hour is manufactured in the United Kingdom, so shipping costs of transporting a manufactured unit would outweigh the benefits of ordering this unit. Another specification of the system is the shape and size of the briquettes. The size of the briquettes can be determined by the point at which a "breaker" forces sections of briquettes to break off the end of the outlet. The length is important to consider because cooling rods are usually implemented into the design. These rods allow the briquettes to cool while under pressure to ensure the compaction of the biochar. The cooling rods can be seen on a briquetter in Figure 2.

Figure 2. Briquetter system with cooling rods (Biomass Briquetting Systems LLC, 2007).

Using this data, correlations were made while assuming linear relationships between briqutter feed rate and dimensions. Change in dimensions (length/width/height) per change in max feed rate were determined and then applied to find the dimensions for a briquetter able to handle 3000 pounds per hour; a max feed rate of 3000 pounds per hour was chosen to account for excess inputs not necessarily accounted for in the feed rate requirement such as increased biomass inputs encountered during days of high sawmill production. These correlations gave measurements of 17 feet 2 inches for the length, 25 feet for the height, and 12 feet 5 inches for the width. Because the Alvan Blanch BP 500 has a similar maximum feed rate of what Delta Sawmill is looking for, it is assumed that briquette sizes will be similar. Since the BP 500 creates block shaped briquettes, these will be the assumed output shape of the BioBuff Consulting's briquettes with dimensions of 10 inches in length and 4 inches in width. Figure 3 below shows a hydraulic briquetter where biomass is fed from a hopper into a screw-drive which forces the material into a tube where a hydraulic press exerts great force onto the biomass. The biochar will be of high temperature as it exits the torrefaction unit and enters the briquetter which proves important for the binding process. The torrefaction process itself is also important for the release of binding agents from the denaturing of the lignin components within the wood (Miller B. A., 2011). Because of this, no binding agents will need to be used to ensure briquette homogeneity.

Figure 3. Typical briquetter process with hydraulic press (Weima, 2007).



Taking a cost estimation from Peters and Timmerhaus, and the two quotes given from BHS Energy and Komar, the initial equipment cost of the briquetter comes out to be $49,000 (Peters and Timmerhaus, 2001) (Reggie, 2011). To find the cost after installation, the initial capital cost is multiplied by a factor of 3.0 and comes out to be $147,000 (Woods D. R., 2007). Again, assuming a 20% engineering fee, the total capital cost of the briquetter with installation comes to $176,400.

Conveyors

There will be two conveyor systems implemented into the overall process. The first is a vertical screw conveyor that will take biomass from the dryer to the torrefaction in-feed. A screw conveyor was chosen over a typical belt conveyor for this process because of the large height the conveyor needs to reach. Having a belt conveyor reach a height of 28 ½ feet would mean a belt conveyor would take up an area of roughly 50 feet by 2 feet, assuming a conveyor angle of 30 degrees. This area can be greatly reduced using a screw conveyor where the material can be transported at a 90-degree angle to the ground. This process acts similar to an Archimedes screw, spinning the dried biomass upward to where it can be deposited into the torrefaction hopper. This conveyor can be purchased from Flexicon, an equipment manufacturer out of which specializes in processing equipment. Since the conveyor will take dry biomass, clogging issues should not be a concern (Flexicon, 2008). A case study of the in-feed material should be done to ensure proper the proper screw equipment is chosen; factors that determine which kind of internal screw to be used include density of the material, particle size, fluidity of the material, and moisture content. By weighing these factors, Flexicon can recommend a product that will perform to meet the unit's exact needs. The screw conveyor will need to reach a height of roughly 28 ½ feet to where it can be deposited into the torrefaction in-feed. Using this information and the factors previously mentioned, Flexicon can scale the pump properly to handle the required feed rate. The feed rate through the conveyor will be 0.433 kilograms per second or roughly 9500 cubic feet per hour. This value was obtained from the mass balance on the overall reactor process. Taking this height requirement and the costing spreadsheet from Peters and Timmerhaus, the overall cost including installation fees comes out to be $15,913.02 (Peters and Timmerhaus, 2001). This value accounts for a capital cost conversion from 2001 dollars to 2011 dollars by multiplying the 2001 cost by an inflation factor of 1.224 and by applying an installation multiple of 1.6 (Sahr, 2009) (Woods D. R., 2007). A common Flexicon screw conveyor can be seen in Figure 5.

The next conveyor will be placed at the briquetter outlet and deposits the briquettes directly into the semi-truck trailer where they can be picked up and transported to the buyer. A cleated incline conveyor will work best in this situation to prevent briquettes from rolling off of the belt. Assuming conveyor will have to reach a height of 12 feet to deposit the briquettes into the semi-truck trailer and a maximum angle of 30 degrees for viable conveying slope, the conveyor length will need to be 24 feet. Taking the 24 foot length and applying that to a costing equation for a typical belt conveyor, the initial capital cost comes out to be $34,071.46 (Peters and Timmerhaus, 2001). This cost includes using the same inflation factor of 1.224 to convert into

2011 dollars and the installation multiple of 1.6 (Sahr, 2009) (Woods D. R., 2007). Belt conveyors can be easily purchased used as they are quite common in industrial applications – this means capital cost could be lower than the actual costing estimate. Figure 5 shows a typical belt conveyor with cleats to prevent briquettes from rolling off.

Figure 31 Flexicon screw conveyor and typical belt conveyor (Flexicon, 2008) (Zimbio, 2010).

Cyclone

Based on the decision matrix performed for air pollution control devices, it was decided to use at least one cyclone. Using a costing equation from the text book *Air Pollution Control* by C. Cooper and F.C. Alley, it was found that the average cost of a cyclone with inlet diameters between 1 and 2 feet was roughly $50K including installation and engineering fees. Compared to an ESP, which averages just under $1 million without any installation fees, and wet scrubbers whose operation and maintenance costs are huge, the cyclone is the best option (C. David Cooper, 2002).

The state of Colorado mandates that particulate matter be controlled to an emission rate of 0.45 kg/hr or less (State). In the material and energy balance, it was estimated that the torrefaction process would result in a PM release of roughly 17 kg/hr, meaning that a collection efficiency of around 99% would be needed. Without knowing the specific ash content of aspen wood, and the fact that off gasses are also being combusted, this is likely an over estimate. Because of

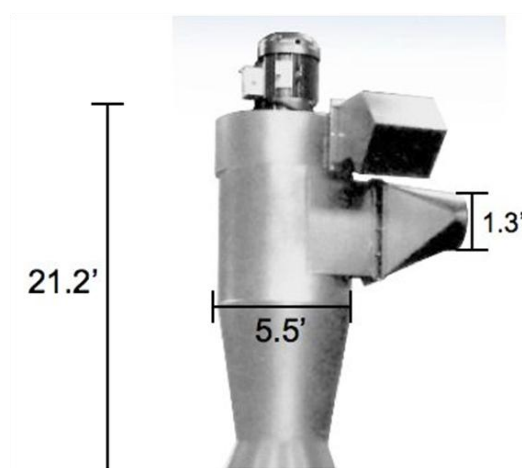


Figure 32: American Air Filter International model AAF-CY36-20 with critical dimensions in feet

the strict regulation, cyclones with a high efficiency for PM_{10} to $PM_{2.5}$ were investigated. The cyclones would need to be able to handle the calculated 4500 cfm (cubic feet per minute) flow rate that the process would be producing.

American Air Filter International (AAF) is a company that specializes in high efficiency cyclones, among other air pollution control devices. It manufactures cyclones that can handle flow rates up to 12,000 cfm. Most of their cyclones come with the air lock valve that was accounted for in the cost estimates for the Cooper, Alley costing equation (see appendix). AAF's cyclone model AAF-CY30-15 can handle a flow rate between 3500 and 4500 cfm with an inlet diameter of 1.2 ft. AAF's model AAF-CY36-20 can handle a flow 5000 and 7000 cfm with an inlet diameter of 1.3 ft (AAF). Table 18 shows the height, width, weight, cost, and other pertinent information about these two cyclone models (AAF).

Model AAF-CY36-20 handles a minimum flow rate greater than that calculated for the torrefaction process. On the other hand, model AAF-CY30-15 cannot handle a flow rate over the calculated flow rate. The best option would most likely to go with the larger flow rate model because it is more efficient, since it has a similar size inlet diameter, but a much higher flow rate. It also leaves room for a larger flow rate to be used if the process is expanded (C. David Cooper, 2002).

A ten percent contingency was assumed for the cyclone (ten percent of the cost disregarding fees and installation). This figure includes all operation and maintenance costs for the unit annually. However, this figure is a very conservative estimate for contingency because cyclones inherently do not require much maintenance due to the lack of moving parts.

Table 18- Cost estimations for AAF cyclones. Flow rate in cfm.

AAF Cyclone									
Model	Flow Rate (C	H (ft)	W (ft)	D (ft)	Weight (lb)	Inlet D (in)	Inlet D (ft)	Capital	Contingency
AAF-CY36-20	5K-7K	21.17	5.5	5.5	2600	16	1.3	$45,449	$1,623
AAF-CY30-15	3.5K-4.5K	17.92	3.5	3.5	980	14	1.2	$42,372	$1,513
							Avg:	$43,910	$1,568

Mobile Process

One of the main requirements of this project was to design the torrefaction process for Delta Timber to be mobile. The original plan was to mount all of the process equipment onto trailers, or "skid mount." After seeing just how large some of the equipment was going to be, it was decided that "skid mounting" is not feasible. Essentially, equipment like the reaction column would not fit on a semi-trailer. A separate problem dealing with the delivery of the final product to the customer was also being investigated at the same time. Coal is normally shipped to power plants via rail car, but the torrefaction unit would not always be able to have access to a rail line.

The team came up with a dual solution for the above problems. The solution to the problems is to have Delta Timber purchase their own semi-truck and task specific trailers for themselves. When the process site is moved, a partially permanent concrete foundation will be poured to provide stability and level ground for the process equipment. A crane service will be hired during the moving process for the lifting of the equipment, and Delta Timber will move the equipment themselves, in many trips. The materials needed for making the torrefaction process mobile, and for the delivery of the product to the customer, are:

- 1 conventional day cab 3 axel semi-truck
- 1 flatbed trailer
- 2+ dump trailers
- Concrete for each new site
- Hired crane service

Semi-Truck and Trailer

A semi-truck is needed to transport the torrefied biomass product to the local power plants as well as transport the process equipment between different job sites to fulfill the mobility context of this project. It is assumed that Delta Timber will be responsible for this 40 to 75 mile one way product delivery trip to the Nucla and Grand Junction power plants. Delta Timber could purchase a new truck and trailers, but it is far cheaper to purchase a used truck. Semi-trucks can tack on much higher mileage than the overage domestic car because of their diesel engines. The lifespan of these trucks can range anywhere from 800K to 1.5 million miles before an engine overhaul has to be performed (yahoo answers). Used trucks ranging from 100K to 600K miles were looked at.

It was found that used semi-trucks with 100k to 600K miles had an average cost of about $43,000 for a three-axel conventional day cab truck. Table 19 shows a list of various makes, models and prices found during our research (Trucker to Trucker listings , 2011).

Table 19- Cost estimations for various used 3 axel day cab semi-trucks

Year	Make	Model	Mileage	Price
2001	FREIGHTLINE	FLD120	340,000	$ 32,000
1999	MACK	CH613	370,000	$ 26,000
2007	KENWORTH	T800	500,000	$ 58,000
2006	INTERNATIOI	9200i EAGLE	200,000	$ 55,000
2006	VOLVO	VNL64T	520,000	$ 42,000
			AVG $	$ 42,600

Each of the quotes in Table ### were found in either Delta or Grand Junction, Colorado. The average price for a used semi-truck was found to be about $43K.

A flatbed trailer is needed for the transport of the process equipment between job sites. Originally, a trucking service was going to be used for this task, but it was decided that Delta Timber would be responsible for the delivery of its product, and, therefore, needed a truck. Since Delta Timber will own a semi-truck, it will ultimately save money by performing its own bio-char processing site relocations. Used flatbed trailers were looked at in both Delta and Grand Junction, Colorado. Two different materials, aluminum and steel, were examined. Table 20 shows a list of flatbed trailers with their prices.

Table 20-Cost estimations for various used 2 axel flatbed trailers

Year	Make	Material	Length (ft)	Width (in)	Price
1999	GREAT DANE	STEEL	48	102	$ 12,000
1998	FONTAINE	STEEL	48	96	$ 9,850
2006	MANAC	ALUMINIUM	48	102	$ 27,000
2008	EAST	ALUMINIUM	48	102	$ 29,000
				AVERAGE $	$ 19,463

The average price for a used flatbed trailer that was found near Delta Timber was just under $20K. The aluminum trailers were far more expensive than the steel trucks, but they are also much lighter than the steel trailers (Trucker to Trucker listings , 2011).

For transporting the torrefied product to the power plant customers, Delta Timber would need to purchase at least two dump trailers. Having more than one trailer would allow them to fill one trailer while another is being delivered. This will be an efficient method for delivery, and it saves money in capital cost since only one truck is being purchased. Dump trailers come in various different configurations that have different capacities. Table 21 shows a list of dump trailers with their prices and capacities.

Table 21-Cost estimations for various 2 axel dumping trailers

Year	Make	Dump Type	Capacity CF	Length (ft)	Width (in)	Price
1999	TRAIL KING	BELLY	1400	40	102	$ 15,000
2006	VANTAGE	END	1660	39	102	$ 34,000
2004	RANCO	END (HALF CYL)	2160	38	102	$ 24,000
					AVERAGE $	$ 24,333

Belly dump trailers had the smallest capacity, but would be the most convenient for unloading since no extra space is needed. However, it was decided to go the half cylinder end dump trailer because it has a superior capacity. This trailer is also designed to transporting material like biochar. The average price for a dump trailer was found to be a little over $24K (Trucker to Trucker listings , 2011).

Concrete

A concrete foundation would need to be poured at each processing site. A conservative estimate of around a quarter acre, or roughly a 100' X 100' area would need to be covered in concrete to create a stable foundation for the processing equipment. It was assumed that the thickness of this concrete would be 6 inches. The total amount of concrete needed would be roughly 5000 cubic feet (cft) or about 186 cubic yards (cyd). The cost of concrete was found to be around $70/ cyd and the cost of labor was found to be roughly $1 per square foot (Concrete Prices).Table 22 shows the costing of concrete for one processing site.

Table 22-Cost estimates for concrete and concrete labor

Concrete Costing for Processing Site	
Length	100 ft
Width	100 ft
Area	1111 sqyd
Depth	0.5 ft
Volume	185.2 cyd
Cost/cyd	$ 70
Concrete Cost	$ 12,963
Labor	$ 1.00 /sqft
Labor	$ 9.00 /sqyd
Cost Labor	$ 10,000 /site
Total Cost	**$ 22,963 /site**

The total estimated cost for a single site's foundation is about $23K with labor. Compared to the cost of a light-weight aluminum trailer, $27K each, that would be used for equipment mounting, this is not very expensive thus confirming the decision not to "skid mount."

Crane

A crane will be needed to lift the process equipment during the move between job sites. Because moving is going to be infrequent, there is no point in purchasing a crane. Instead, local crane services were investigated for contract work. Some local companies would simply rent a crane to Delta Timber for the required time, but this would require an employee at Delta Timber to be a skilled crane operator (steringcrane). This may not be the case. A few local companies were contacted for pricing on their services. The only company that responded was Jake's Crane Service in Olathe, Colorado. Jake's performs lifts for up to 17 tons and averages 12 tons. None of the equipment in the torrefaction process is over 17 tons. The cost for Jake's Crane Service is $75/hr with a minimum of 2 hours. They also charge a $40 transportation fee for the fuel used to get from Olathe to Delta (Service, 2011). Jake's Crane service: (970) 874-2866

Cost of Transporting Product

The cost of transporting the final product to the customer was found using a few assumptions. The first assumption used was that the density of the torrefied briquettes would be similar to that of charcoal. The density used in calculating the cost of transporting the product was roughly 13 lb/ft^3 (Density of Materials). The other assumption used was that the gas mileage for a semi-truck is 10 mpg. A reliable source could not be found for this figure, so an assumption had to be made using the information that could be found.

Using the mass flow rate of product from the mass balance and the density of torrefied biomass, the volumetric flow rate of product was found. The capacity of the various trailers was divided by volumetric flow rate of the product to find how many daily loads of product would need to be transported to the power plants. This number was rounded up to give a maximum number of trips needed per day. For example, if the trip count came out as 2.1, the trip number was taken as 3. The number of trips, fuel price, gas mileage, and round trip distance to the power plants were used to calculate the estimated annual cost of the transport of product to the customers. Table 23 shows these figures.

Table 23-Cost estimation for annual delivery to customers by semi-truck

Trip Estimation for Product Delivery						
	Trailer Cap.(CF)	Loads/day	Trips/day	Rnd Trip (mi)	$ fuel/day	Annual Cost
Trip to Nucla	1,400	3.25	4	80	$ 134.40	$ 49,056
Power Plant	1,660	2.74	3	80	$ 100.80	$ 36,792
	2,160	2.11	3	80	$ 100.80	$ 36,792
Trip to Grand Jct	1,400	3.25	4	150	$ 252.00	$ 91,980
Power Plant	1,660	2.74	3	150	$ 189.00	$ 68,985
	2,160	**2.11**	**3**	**150**	**$ 189.00**	**$ 68,985**
	Density of Product lb/cf		12.99			
	Product Mass Flow Rate (kg/s)		0.31			
	Product Mass Flow Rate (lb/day)		59049			
	Product Volume Flow Rate (CF/day)		4547			
	Disiel Fuel Price per gallon:		$ 4.20			
		Truck mpg	10			

The bold faced values in Table 23 represent the overall cheapest option. This option is using the half cylinder trailer with the largest capacity and cheapest cost for an end dump trailer found. Though this trailer will take roughly the same number of trips that the regular end dump trailer will, it has the cheaper cost up front.

Labor

For all of the torrefaction operating calculations it was assumed that the process would be running for 8000 hours. To make the process work, employees are needed . Other than a truck driver, people must be operating the process at all times during the 8000 hours. It was assumed that the process would require three full time operators, including a skilled process engineer who would also act as the site foreman. Because of the specialized work of the process engineer/ foreman, a conservatively estimated wage of $30 per hour was assigned to the job. The two other operators would perform tasks like loading feedstock into the system and operating the various equipment like the chipper. These jobs were assigned a wage of $20 per hour. A truck driver is needed to transport the product to the customer. It was assumed that this driver would work the equivalent of 50 weeks a year at 40 hours a week, yielding a total time of 2000 hours. The driving job was assigned a conservative wage of $20 per hour. Table 16 shows each position with their respective hours and wages, and a total annual payroll estimate. The total estimated annual payroll is $600K.

Table 24- Annual labor expenses estimation

Process Jobs	Pay Rate/hr	total hrs	Total cost
Process Eng	$ 30	8,000	$ 240,000
Equip Op	$ 20	8,000	$ 160,000
Equip Op	$ 20	8,000	$ 160,000
Truck Driver	$ 20	2,000	$ 40,000
		Total:	$ 600,000

Pilot Testing

Pilot testing is an invaluable resource when designing a novel process. It can help expose design flaws and prevent financial loss in the event of a product or equipment failure. Torrefaction itself is a relatively new procedure, but there is no solid literature or research on the torrefaction of aspen biomass, our target feedstock. This design has been created using literature and research on other hardwoods such as birch and also pine wood, so it is essential that tests be conducted on aspen . It is this reason that makes pilot testing of our mobile torrefaction unit crucial to becoming a success. The pre-torrefaction stage dryer, screw conveyor, torrefaction reactor, and briquetter will all need to have pilot tests run to ensure that the equipment can be accurately designed to produce the desired biochar product. The table below outlines the companies that Bio-Buff consulting recommends purchasing prospective equipment from and utilizing the pilot testing operations they provide.

Table 25 Table of companies and desired pilot tests

Company	Pilot Test	Goal
Aeroglide	Drying chipped Aspen	Ensure moisture content < 15%
Flexicon	Screw conveyor into reactor	Size internal screw
Wyssmont	Torrefying chipped, dried aspen at <15% moisture content	Ensure target biochar properties achieved

A briquetting company has not yet been chosen, but when that desired piece of equipment has been found, it is recommended that a pilot test also be run to ensure that the briquetter can compact the torrefied aspen appropriately.

Perhaps the most important pilot test that needs to be conducted is for the torrefaction reactor. If the biochar being produced does not have the energetic or bulk density that will make it comparable to coal and financially feasible to transport, the entire operation will be running in vein. In order for this to happen, 4-5 gallons of potential aspen biomass should be chipped and then sent to Aeroglide, the rotary dryer company, to have a test-dry conducted on that chipped aspen. This will ensure the dryer is appropriately sized and that the output dried biomass has the correct moisture content. Once that biomass has been dried to within 10-15% moisture content, 1-2 gallons of the dried, chipped aspen should be sent to Wyssmont for a pilot torrefaction test. Wyssmont provides pilot testing of material beginning at $800 per day and up to $1600 of the pilot test cost is creditable towards the purchase of their equipment. This pilot test will ensure that the chipped, dried aspen can be appropriately torrefied using the Wyssmont TURBO-Dryer system.

The remaining aspen biomass that went through the dryer pilot testing should be sent to Flexicon to undergo a pilot test with the screw conveyor. This test will ensure that the internal screw is sized appropriately and the biomass can be efficiently sent to the torrefaction reactor. Once all of the recommended pilot tests have been successfully conducted, decisions can be made on equipment purchases. If the resulting biochar produced has comparable properties to that of coal, it provides the necessary evidence that the chosen equipment, temperature specifications, residence times, and sizing are appropriate to achieving the desired product. If the resulting biochar is not ideal, then changes should be made or more research should be conducted on alternative design components or companies before purchasing full-size equipment.

Feasibility Analysis

In order for this to be a worthwhile venture for Delta Timber there are three criteria that need to be met.

1. The air pollution regulations need to be met at the State and Federal level.
2. The Power Producers need to be satisfied with the cost of the final product. It needs to be sold at a cost that is relatively equivalent to what is being charged for coal currently.
3. Delta Timber must obtain a larger profit for the sale of the biochar during the lifetime of the plant than they would most likely be getting from the current sale of the secondary products.

Air Regulations Compliance

In order to determine whether or not our project will be able to comply with the state and federal air regulations, we will have to take into consideration the heating element within the process. The total heating element that our process is designed for is approximately $3.6 * 10^6 \frac{BTU}{hr}$. This means that the equation:

$$PE=0.5(FE)^{-0.26}$$ (Air Quality Control Comission, 2007)

Will determine the particulate emission allowed at the state level. This translates to 0.358 lbs per $10^6 \frac{BTU}{hr}$ or $0.0451 \frac{Kg}{hr}$. At the Federal level for this specific heating element, being less than 8.7 MW, 0.03 lb/MMBtu total emission is allowed (Environmental Protection Agency, 2011). This translates into 0.0491 kg/hr making the state regulations slightly stricter and the one that we will have to adhere to.

From our Materials and energy balance we are assuming that 1% of the mass of the original wood is turned into ash, meaning 0.005 kg/s of aspen ash is created during the torrefaction process (Weirathmueller). This translates to 17.005 kg/hr of ash being created during operation. Our air pollution control device will need to have a 99% efficiency.

The model AAF-CY36-20 cyclone is estimated to have a 90% efficiency, meaning that one cyclone is not enough to reach federal regulations. Because of this we will have to use a series of two cyclones in order to meet federal regulations. This would, theoretically, create exactly a 99% percent efficiency overall. This is cutting the regulation standards very close but because of the extreme prices of the other options, we do not feel that the project could afford to use another option besides the cyclone. Careful precautions should be taken during installation and operation to ensure that the cyclones are functioning at their highest capacity.

The state regulations for opacity are 20% for long term operations, but 30% for pilot plant operations lasting less than 180 days (Air Quality Control Comission, 2007). Because our heating element is smaller than 8.7MW, there will be no federal regulations on opacity (Environmental Protection Agency, 2011). We are planning to run for around 334 days each year so we will have to adhere to the 20% opacity standard

Likely Sale Price

In order to calculate the likely market price of we need to make the assumption that both Xcel energy and Tri-State Generation and Transmission will not be inclined to make a financial decision that is not in the interest of their customers. In other words, we are assuming that in the end both the Cameo and Nuclea stations will not want to pay more for the amount of energy that they would be receiving with the biochar than they would be spending on the amount of coal that it would divert.

Currently, the going rate for coal in the Delta County area from the West Elk Mine is around $35 per ton (Browning, 2010). Over the last few years this amount has varied about $2.20 during the course of a given year depending on the change of operating and shipping costs in different seasons. This makes this cost estimate accurate to around seven percent. This cost is bound to fluctuate during the estimated twenty year lifetime of the plant depending on inflation and the economics of the region. Because the West Elk mine has recently gone through a round of layoffs of around 25% of their workforce, and experienced 29% decline in revenue, there is definite reason to believe that the demand for coal has declined in the region (Browning, 2010). This may be because of the decline of energy usage and industry in the local communities (Browning, 2010). Because a decrease in demand also means a decrease in price, it is likely to assume that if this decline continues during the torrefaction plant's life time that the price of coal would become even cheaper, lessening the amount that Delta Timber can expect to sell the biochar for. For the purpose of this analysis we are assuming a constant $35 per ton price of coal but it should be noted that this amount is bound to fluctuate.

Now, we wish to determine the price that the final product can be expected to sell for including differences in energy densities, as well as money received from the government in the form of tax incentives. In order to be properly utilized in a coal fired power plant, biochar must be burned at around a 10/90 ratio compared to the coal present. From our materials and energy balances we estimate 9,800 tons of biochar to be manufactured annually. We are assuming that this amount remains constant through the factory's life, but in reality, it will more likely change over time depending on the available biomass. The table below represents the amounts of coal and bio char needed for our two potential customers as well as the expected running time for one years' worth of biochar.

Table 26 Amounts of materials needed for each power producer

	Cameo	Nuclea
Power Ourput (kW)	66000	114,000
Coal currently used (tons/year)	300000	650,000
Coal currently used (tons/s)	0.009513	0.020611
Coal currently used (tons/day)	684.9239	1,484.002
Coal used (90% total energy) (J/d)	1.24E+13	3.04E+13
Amt of torrified wood used (10%total energy) (J/d)	1.37E+12	3.38E+12
Amount of coal(90% total energy) (tons/d)	616.4315	1,518.368
Amount of torrified wood used (10% total energy) (tons/d)	60.24794	148.4002
days biochar lasts	163.3472	66.31619
Total Amount of coal diverted (tons)	11188.15	11,188.15

It can be shown that both stations have enough energy needs to use the entire years' worth of biochar, proving that Delta Timber only needs to sell to one of the two potential customers. Another important aspect of the price is the money that the power plants will be getting back for every kWh of electricity that open loop biomass produces. This amount can be added to the total cost of the biomass, allowing the power producers to come out even in cost. The government is currently paying $0.011 for every kWh generated (Federal Government, 2010). This incentive is only good for the first ten years of operation, meaning that delta timber must offer a different price to a specific power producer after the incentive runs out. The following table shows the total assumed money awarded per year assuming a 30% efficient coal power plant (NPC Global, 18 July 2007).

Table 27 Total cash back annually with government tax incentive

total kWh present in biochar for year	62,3000,000
total kWh present in biochar with 30% efficiency	18,700,0000
total $ back annually	**$205,000**

Another source of cash back for the power companies occurs with the money saved for emitting less Title V criteria pollutants. Biochar produces virtually no SO_2 while regular coal produces about 13 $\frac{lbs\ SO2}{MWh}$. For every ton of pollutant that is diverted, the power plant will find itself paying $25 less in 1989 dollars to the U.S. government. The total amount of money saved annually is shown below.

Table 28 Money saved annually though Title V permit

Totals tons of SO2 diverted	405
Total 1989 dollars saved	$10,100
total 2011 dollars saved	**$18,000**

Taking into account the difference in energy density of biochar as well as the money being received from the federal government, we are able to calculate the equivalent cost of the final product for the power producers.

Table 29 Selling Cost Estimates

Total cost of diverted coal annually	$392,000
total tax incentive money back annually	$205,000
Total Title V Money saved annually	$18,000
Cost per ton first ten years	$62.51
Cost per ton after ten years	$41.62
Annual Revenue First ten years	$615,000
Annual Revenue After ten years	$409,000

Both prices per ton values are larger than the assumed $35 price for coal. The price is significantly different depending on whether or not the tax incentive is in effect. Assuming a twenty year plant lifetime, the total money that can be expected to be paid for the entire amount of produced biomass is a little over ten million dollars.

Return on Investment

From the design portions of the report we have an overall estimate of the capital and Operations and Maintenance cost. All values are given including Engineering and Installation fees.

Table 30 Capital and Operations & Maintenance Cost Summary

Capital	
Cyclone	$49,200
1 Flatbed trailer 2 Dump Trailers and Truck	$133,000
Crusher	$71,900
Concrete	$27,600
Dryer	$250,000
Briquetter	$211,000

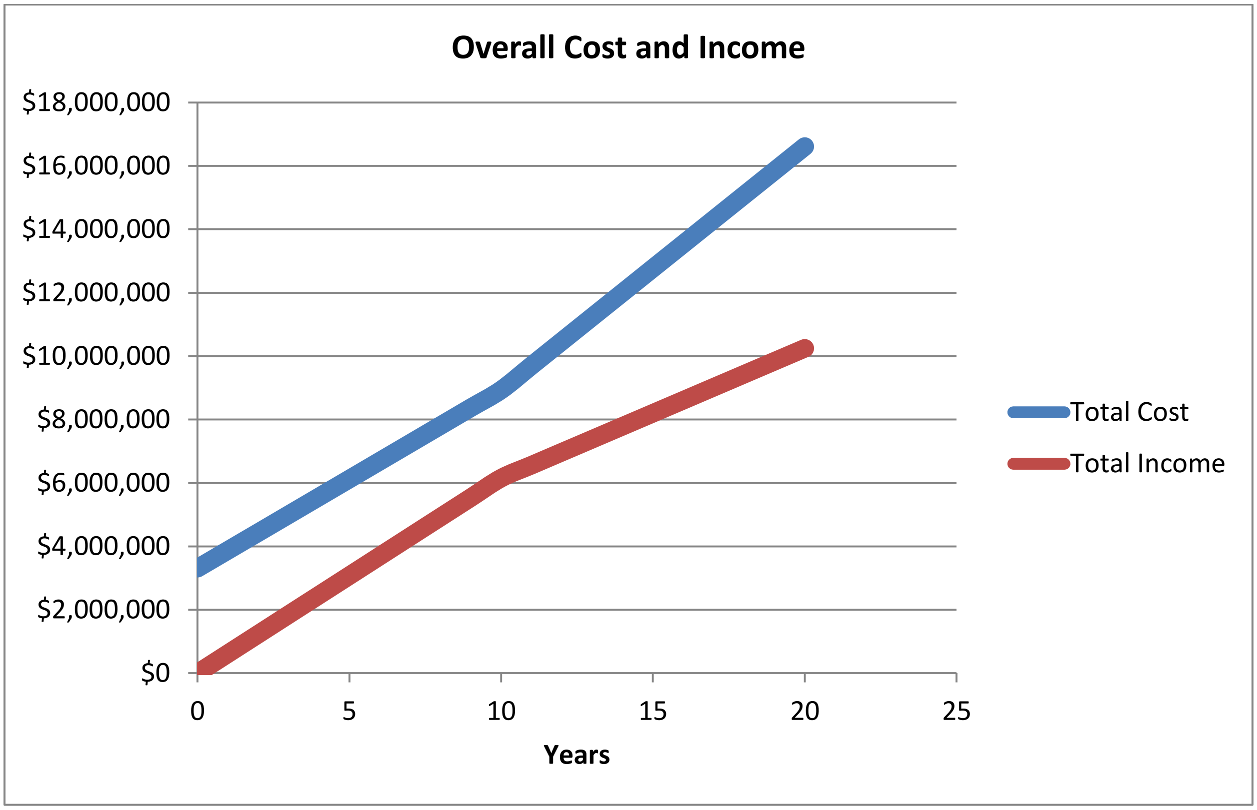
Torrefaction Turbo-Dryer	$2,340,000
Heating System	$265,000
Screw Conveyor	$15,000
Belt Conveyor	$33,000
Total:	**$3,390,000**

Operations and Maintenance	
Annual Transportation Minimum (Grand Junction)	$36,800
Annual Transportation Maximum (Nuclea)	$69,000
Labor	$600,000
Contingency	$283,000
Total: (assuming min. transportation)	$920,000

The above chart shows that the expected capital investment for Delta Timber is around $3.4 million dollars. Under operations and maintenance the Transportation estimations are given for both power stations but the total is given assuming that the Grand Junction site becomes the customer. The estimation of contingency is given assuming 10% of the capital cost. In this case $768,000 will be spent annually. It should be noted that Delta Timber will also receive $0.011 per kWh of biofuel produced under federal tax incentives for the first ten years of operation. This amount will also equal $205,000.

It is now a matter of determining if this cost is low enough to allow Delta Timber to generate a larger profit than it would be receiving if it continued to sell the raw secondary products. Delta produces approximately 800 cubic yards of secondary product on a given working day. Assuming that the company makes five dollars per cubic yard off of the sale of these products, Delta Timber is already receiving a little over a million dollars annually from this biomass.
The chart below displays continuous expected cost and profit over the lifespan of the plant.

Table 31 Comparison of Cost and Income over Plant's Lifetime



At no point in the plant's lifetime is the total income expected to be larger than the total cost making this venture non profitable. Overall, the venture will end up putting Delta Timber almost ten million dollars in debt.

Conclusions and Recommendations

Overall, we determine the designed torrefaction process to be technically feasible but not economical. The overall process will not result in a profit and the company is already receiving a substantial profit from selling the unprocessed biomass.

We strongly recommend that the client wait for either improvements in technology or better government incentives, such as carbon credits. The technology of the process is just not advanced enough at the current time to offer the efficiency and reliability that the client would need to properly utilize this process. Extra government money would also help this process turn a profit. For example, if Open loop biomass received the same $0.022 kWh incentive that Closed Loop received then this process would become profitable between years 8 and 13. The presence of any kind of carbon credit system could also potentially raise the value of the biochar, allowing for higher yearly income.

The best thing that could be done to make this process profitable is to move it to an area with an abnormally high cost of coal. Currently in the U.S. the average sale price of coal to electric utility plants is $41 per ton, putting Delta County well below the national average. We have calculated that, assuming everything else remains constant, this process becomes profitable when coal is over $80 a ton which is not the case anywhere in the United States. It, however, will not generate an income higher than the income from the secondary products already unless the price of coal is over $200 dollars per ton, which is also not the case anywhere in the United States. (U.S. Energy Information Administration, 2011)

In conclusion, while this new technology has huge potential, the technology and government incentives are not currently at a place where torrefaction is able to compete commercially with the already cheap cost of coal.

Acronym List

AAF: American Air Filter International
CFM: Cubic feet per minute
iCAST: International Center for Appropriate and Sustainable Technology
PTC: Production Tax Credit
PM: Particulate matter
RFP: Request for Proposal
REPI: Renewable Energy Production Incentive
SQFT: Square foot
SQYD: Square yard
TOP: Torrefaction and Pelletization Process

Works Cited

ecoTECH Energy Group. (2010). Torrefaction Technology:Torrefied Wood Briquettes. ecotechenergygroup.com/index.php/alternative-energy.

CAA Permit Programs. (1990). Retrieved March 2011, from Cornelll University Law School Online: http://www.law.cornell.edu/uscode/html/uscode42/usc_sec_42_00007661---a000-.html

Getting Roses Ready. (2002, September 15). Retrieved 2011, from Yard & Garden Line News: http://www.extension.umn.edu/yardandgarden/YGLNews/YGLN-Sept1502.html

Historic Power Plant. (2007). Retrieved January 27, 2011, from City of Delta: http://www.delta-co.gov/cityDepts_utilities_history.htm

(2008, October 8). Retrieved March 2011, from Division of Air Pollution Control: http://www.epa.state.oh.us/dapc/title_v/titlev.aspx

Russian Olive. (2008, March 14). Retrieved 2011, from Department of Natural Resources: http://dnr.wi.gov/invasives/photos/index.asp?mode=detail&spec=7

Delta city, Colorado. (2009). Retrieved January 27, 2011, from U.S. Census Bureau: http://factfinder.census.gov/servlet/SAFFPopulation?_event=ChangeGeoContext&geo_id=16000US0819850&_geoContext=01000US&_street=&_county=delta&_cityTown=delta&_state=04000US08&_zip=&_lang=en&_sse=on&ActiveGeoDiv=geoSelect&_useEV=&pctxt=fph&pgsl=010&_submenu

Delta County Agriculture. (2009). Retrieved January 27, 2011, from Delta Area Development: http://webcache.googleusercontent.com/search?q=cache:_eSr9Jir_qIJ:www.deltaareadevelopment.org/agriculture.html+delta+county+farming&hl=en&client=firefox-a&hs=ZZf&gl=us&strip=1

Species found in Delta County, Colorado. (2010, September 20). Retrieved January 27, 2011, from Center for Invasive Species and Ecosystem Health: http://www.eddmaps.org/tools/countyplants.cfm?id=us_co_08029

Study of Residual Agricultural Materials in Ontario for Use as Biomass in Power Plants. (2010, June 11). Retrieved January 27, 2011, from Ministry of Agriculture Food & Rural Affairs: http://www.omafra.gov.on.ca/english/engineer/biomass/study_residual.htm

Aeroglide. (2011). *Rotary Dryer.* Aeroglide.com/rotary-dryers.

Air Quality Control Comission. (2007, June 21). *Emission Control for Particulate Matter, Smoke, Carbon Monoxide, and Sulfur Oxides*. Retrieved Febuary 2011, from Department of Public Health and Environment: http://www.cdphe.state.co.us/regulations/airregs/5CCR1001-3.pdf

Alcan Blanch. (n.d.). *Briquetting of Wood Waste Material.* Retrieved April 24, 2011, from alvanblanch.com: http://www.alvanblanch.co.uk/briquetting%20machine.pdf

Apollo Equipment. (2009). *2007 Brush Bandit 1990XP*. Retrieved 2011 йил 18-April from ApolloEquipment.net: http://www.apolloequipment.net/equipment/C003034p_brush_bandit_chipper.html

Bandit Industries, Inc. (2010 йил 1-January). *Model 1990XP*. Retrieved 2011 йил 18-April from Bandit Industries, Inc.:

http://www.banditchippers.com/index.php?option=com_models&task=view&itemId=15&lineId=2&modelId=53
Bergman Patrick C.A., J. H. (2005). *Torrefaction for biomass upgrading.* Paris, France: 14th European Biomass Conference & Exhibition.
Bergman Patrick, C. J. (2005). Torrefaction for biomass upgrading. Paris, France: 14th European Biomass Conference & Exhibition.
BHS Energy LLC. (2010 йил 21-December). *Slugger Biomass Briquetting System*. Retrieved 2011 йил 19-April from bhsenergy.com: http://www.bhsenergy.com/slugger
Bio-Gas Technology . (2011). *Rotary Dryer System.* bio-gastech.com/Dryer_System_Pictures.html.
Biomass Briquetting Systems LLC. (2007). *Briquetting Machines - BP 1500*. Retrieved April 25, 2011, from Biomass Briquetting: http://www.hermance.com/StaticPages/Biomass/BP-1500.asp
Biomass Combustion Systems, Inc. (n.d.). *Hot-air Shop Heaters*. Retrieved April 22, 2011, from Biomass Combustion Systems, Inc.: http://www.biomasscombustion.com
Bionomic Fuel. (2009). Biomass Briquettes for Green Electricity Production. bionomicfuel.com/biomass-briquettes-for-green-electricity-production/.
Bjork, H. a. (1995). Moisture equilibrium of wood and bark chips in superheated steam. Elsevier Science Ltd. Great Britain. sciencedirect.com/science?_ob=ArticleURL&_udi=B6V3B - 46HFYG3V&_user=1. *Fuel Vol. 74 No 12* , 1887-1890.
Browning, K. (2010, May 12). *West Elk Mine GM: "We plan to be around"*. Retrieved February 2011, from Delta County Independant: http://www.deltacountyindependent.com/news/north-fork/15110-west-elk-mine-gm-we-plan-to-be-around.html
C. David Cooper, F. A. (2002). *Air Pollution Control, A design Approach Third Edition.* Long Grove, IL: Waveland Press, Inc.
Christoph Steiner, P. H. (2010). *U.S.-Focused Biochar Report: Assessment of Biochar's Benefits for the United States of America.* Colorado.
Ciolkosz, D. (2009). Renewable and Alternative Energy Fact Sheet. Manufacturing Fuel Pellets From Biomass.pubs.cas.psu.edu/FreePubs/pdfs/uc203.pdf.
City of Delta. (2007). *Historic Power Plant*. Retrieved January 27, 2011, from City of Delta: http://www.delta-co.gov/cityDepts_utilities_history.htm
CNFbiofuel. (2011.). CNF Biofuel Pellets. biocoal.net.
CO, Power Plants. (CO Power Plants). Retrieved Febuary 28, 2011, from Power Plant: http://www.powerplantjobs.com/ppj.nsf/powerplants1?openform&cat=co&Count=500
Colorado Carbon Fund. (2011). *The Quick Start Guide to Submitting Offset Project Proposals to the Colorado Carbon Fund*. Retrieved March 2011, from Colorado Carbon Fund: http://www.coloradocarbonfund.org/images/uploads/CCFProjectGuidelines_001.pdf
Control, D. o. (2008, October 8). Retrieved March 2011, from http://www.epa.state.oh.us/dapc/title_v/titlev.aspx

Dudgeon, R. (2009). *An Aspen Plus Model of Biomass Torrefaction.* University of Iowa. Charlotte, NC: Electric Power Research Institute.
EBAY.com. (n.d.). *2007 Bandit Chipper 1990 XP*. Retrieved 2011 йил 18-April from Ebay.com: http://cgi.ebay.com/2007-Bandit-Chipper-1990-XP-/290553740128
Energy, B. (2010, August 6). *Army National Guard Installs Solar Array in Grand Junction*. Retrieved Febuary 2011, from Bella Energy: http://www.bellaenergy.com/2010/08/army-national-guard-installs-solar-array-in-grand-junction/#more-1983
Engineering Toolbox. (2010). Classification of Coal. engineeringtoolbox.com/classification-coal-d_164.html.
Environmental Protection Agency. (2011, March 8). *Standards of Preformance for New Stationary Sources*. Retrieved March 2011, from Electronis Dode of Federal Regulations: http://ecfr.gpoaccess.gov/cgi/t/text/text-idx?c=ecfr&sid=84c2680363d69f6107f1d88d1a9b333c&tpl=/ecfrbrowse/Title40/40cfr60_main_02.tpl
Federal Government. (2010, May 4). *Renewable Electricity Production Tax Credit*. Retrieved March 2011, from Incentives/Policies for Renewables and Effeciency: http://www.dsireusa.org/incentives/incentive.cfm?Incentive_Code=US13F&re=1&ee=1
Federal Government. (2011, January 18). *Renewable Energy Production Incentive*. Retrieved March 2011, from Incentives/Policies for Renewables and Efficiency: http://www.dsireusa.org/incentives/incentive.cfm?Incentive_Code=US33F&re=1&ee=1
Flexicon. (2008). Bulk Handling Equipment and Engineered Systems. United States. Retrieved April 24, 2011, from flexicon.com: https://dl-web.dropbox.com/get/Bio-power%20Design%20Project/Final%20Report/Conveyors/ScrewConveyor.pdf?w=e668798a
Forest2Market. (2011). Progress for Torrefied Biomass Projects forest2market.com/f2m/us/f2m1/free/forest2fuel-archive/story/2011-Feb-Torrefied.
Friz, M. (2011). The Briquetting Process. weimaamerica.com/pages/shredding-briquetting/briquetting.htm. *WEIMA America*.
GEA Pharma Systems. (2011). Drying: moving from batch to continuous processes. gea-ps.com/npsportal/cmsdoc.nsf/WebDoc/webb86Qg2c.
GlobalSpec. (2011). Process Dryers Specifications. globalspec.com/Specifications/Processing_Equipment/Heat_Transfer_Equipment/Process_Dryers.
Google. (2011, March). *Google Maps*. Retrieved March 2011, from Google Maps: http://maps.google/
Hee, V. (2010, July 29). *Properties of Aspen Wood*. Retrieved January 27, 2011, from Ehow: http://www.ehow.com/list_6789112_properties-aspen-wood.html
Henan Kingman M&E. (n.d.). Pellet Mill - Ring Die. woodpelletline.com/pellet-mill.htm.
Henan Zhongke Engineering Technology Co. Ltd. (2011). *Rotary Sawdust Dryer.* mill-grinder.com/Dryer/Sawdust%20Dryer/.

Hermance Machine Company. (n.d.). Biomass Briquette Systems, LLC. Product Line. hermance.com/StaticPages/Biomass/index.asp.

iCAST. (2011, February 20). Email from Chris Jed.

IECG. (2002). International Electric Coal Generation. Coal Fired Power Generation .rst2.edu/ties/acidrain/iecoal/how.htm.

J. Meza, A. G. (2008). *Drying costs of woody biomass in a semi-industrial experimental rotary dryer.* Zaragoza.

Kluepfel, M. (2010). *All About Mulch*. Retrieved Febuary 2011, from Savy Gardener: http://www.savvygardener.com/Features/mulch.html

Komar Industries Inc. (n.d.). *Komar Briquetting System.* Retrieved April 25, 2011, from komarindustries.com: http://www.komarindustries.com/files/briquetter.pdf

Lohmeyer, H. (2010, September 1). County, coal mines see threat to local jobs. *Delta County Independent*.

Maciejewska, A. H. (2006). Co-firing of Biomass with Coal: Constraints and Role of Biomass Pre-Treatment techtp.com/cofiring/cofiring%20biomass%20with%20Coal.pdf. *European Commission Directorate-General Joint Research Centre0 Institute for Energy.*

Mahr, D. (2011). Designing fuel systems for large biomass plants. powermag.com/coal/Designing-Fuel-Systems-for-Large-Biomass-Plants 3394.html. *PowerMag*.

Manta. (2008). *Delta Timber Co*. Retrieved March 2011, from Manta: http://www.manta.com/c/mmydx6h/delta-timber-co

Marshall, G. a. (2011). OPG Charts Move from Coal to Biomass. powermag.com/issues/features/OPG-Charts-Move-from-Coal-to-Biomass_2570.html. *PowerMag*.

Miller, B. A. (2011). *Bio-Buff Consulting Alternatives Assessment.*

Miller, B. K. (2011). *Bio-Buff Proposal.* Boulder, CO: CEAE University of Colorado at Boulder.

Mitchell, D. a. (2010). Torrefaction? What's That? *Fueling the Future: 2010 Council on Forest Engineering Annual Meeting.* Auburn, Alabama.

New Biomass Energy. (2011). *Torrefied Wood vs. Wood Pellets vs. Coal*. Retrieved March 9, 2011, from newbiomass.com/torrefied-wood/torrefied-wood-pellets-vs-coal

NPC Global. (18 July 2007). *Electrical Generation Effeciency_Working Document of the NPC Glopal Oil & Gas Study.*

NREL. (1998). *Report on Biomass Technology.*

Patrick C.A. Bergman, J. H. (2005). *Torrefaction for biomass upgrading.* Paris, France: 14th European Biomass Conference & Exhibition.

Programs, C. P. (1990). Retrieved March 2011, from Cornelll University Law School Online: http://www.law.cornell.edu/uscode/html/uscode42/usc_sec_42_00007661---a000-.html

Recharge Colorado. (2010). *Advancing the New Energy Economy*. Retrieved March 2011, from Recharge Colorado:

http://www.rechargecolorado.com/index.php/programs_overview/colorado_carbon_fund/
Reggie, B. (2011, April 21). BHS Energy - Managing Member.
Sahr, R. C. (2009). *Consumer Price Index (CPI) Conversion Factors 1774 to estimated 2019 to Convert to Dollars of 2001.* Retrieved April 22, 2011, from oregonstate.edu: http://oregonstate.edu/cla/polisci/faculty-research/sahr/cv2001.pdf
Scott, C. (2010, July 12). World's First Hybrid Coal-Solar Power Plant Goes Online in Colorado. *Inhabitat.com*.
Seider, W. (2009). *Product and Process Design Principles.* John Wiley and Sons.
Sonrisa Publications. (2006). *Colorado-Wyoming Railroad Maps*. Retrieved March 2011, from Sonrisa Publications Online: http://www.djcooley.com/store/maps/cowy/cowy.htm
Thermya. (2009, May). *TORSPYD.* Retrieved January 30, 2011, from Thermya: http://www.thermya.com/pdf/90519_SD_JS_THERMYA_presentation_Torrefaction_mai_2009_UK-1.pdf
Topline Recycling Equipment, LTD. (2011). *Briquetting Systems*. Retrieved 2011 йил 19-April from toplinerecycling.com: http://www.toplinerecycling.com/product_details.php?p_id=55
U.S. Census Bureau. (2009). *Delta city, Colorado*. Retrieved January 27, 2011, from U.S. Census Bureau: http://factfinder.census.gov/servlet/SAFFPopulation?_event=ChangeGeoContext&geo_id=16000US0819850&_geoContext=01000US&_street=&_county=delta&_cityTown=delta&_state=04000US08&_zip=&_lang=en&_sse=on&ActiveGeoDiv=geoSelect&_useEV=&pctxt=fph&pgsl=010&_submenu
U.S. Department of Energy. (2007). *Coal Power Plant Data Base*. Retrieved from National Energy Technology Lab: http://www.netl.doe.gov/energy-analyses/pubs/database/XLS%20CPPDB%202007%20-%20Public.zip
U.S. Energy Information Administration. (2011, February 3). *Average Price of Coal Delivered to End Use Sector by Census Division and State*. Retrieved March 20, 2011, from http://www.eia.doe.gov/cneaf/coal/page/acr/table34.html
Umbanhowar, C. E. (2008). *Effect of freesing on Young's modulus for twigs of coniferous and deciduous trees and shrubs.* Minnesota: NRC Canada.
Weima. (2007, May). *Briquetting systems for volume reduction.* Retrieved April 24, 2011, from weima.com: http://www.olusummakine.com/pdfs/weima/th_serisi.pdf
Weimer, A. (Fall 2010). Personal Communication, Economics Spreadsheet.
Weirathmueller, F. (n.d.). *Torrefaction and Thermal Transition of Solid Bio Fuels.* Retrieved April 17, 2011, from F.W. : http://www.unb.ca/fredericton/forestry/wstc/cbec/_resources/pdf/11.pdf
Woods, D. R. (2007). *Rules of Thumb in Engineering Practice.* Wiley- VCH Verlag GmbH & Co.
Woods, P. D. (2007). *Rules of Thumb in Engineering Practice.* Wiley.
Wyssmont Company Inc. (2011). TURBO-DRYER. *Dryers. wyssmont.com/product_detail.php?section=Dryers&id=1.*

Wyssmont. (n.d.). *Wyssmont TURBO-Dryer*. Retrieved March 3, 2011, from http://wyssmont.com/home.php
Zimbio. (2010, June 30). *Belt Conveyor*. Retrieved April 26, 2011, from zimbio.com: http://www.zimbio.com/Manufacturing+Weekly/articles/HP_OqmfPKey/Belt+Conveyor

Appendix

Sixth-tens Rule

The following equation expresses the sixth-tenths rule:

$$C_B = C_A \left(\frac{S_B}{S_A}\right)^{0.6}$$

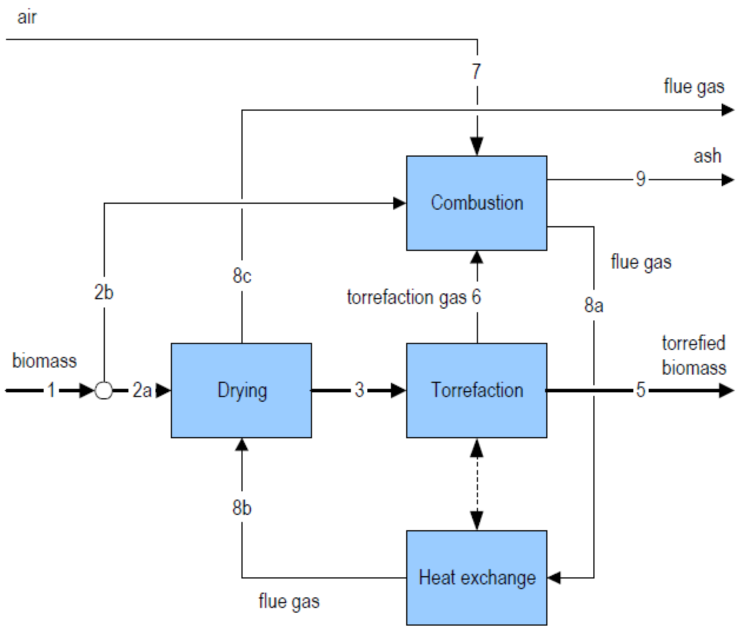
This rule is commonly used in engineering to estimate the cost of equipment when a previous quote for a piece of equipment is known, but that the quote desired is for a different size.

Bare Module Factors

Converting the FOB Cost into a Bare Module Cost
Although the FOB cost of equipment is of interest, usually we want to know the cost of a fully installed and functioning unit. The "bare module", BM, method is method for this. In the BM method, the FOB cost is multiplied by factors that account for all the concrete, piping, electrical, insulation, painting, supports needed in a space about 1 m out from the sides of the equipment. This whole space is called a module. The module is sized so that by putting together a series of cost modules for the equipment in the process we will account for all the costs required to make the process work. For each module we define a factor, L+M*, that represents the labor and material costs for all the ancillary materials. Some of these may be shown as a range, for example, 2.3–3. This means that for the installation of a single piece of equipment (say, one pump), the higher value should be used; the lower value is used when there are many pumps installed in the particular process. The L+M* factor includes the free-on-board the supplier, FOB, cost for carbon steel and excludes taxes, freight, delivery, duties and instruments unless instruments are part of the package. The * is added to remind us that the instrumentation material and labor costs have been excluded, (whereas most L+M values published in the 60s, 70s and 80s included the instrumentation material and labor costs). (Woods, 2007)

Material and Energy Balances

By Herron Kennedy Checked By: Ben Miller, Will Nabours, Deena Garland, and Kelly Albano



	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1							Off-gas			Raw Biomass %water	Dried Biomass %water			
2	LHV	19.02	MJ/kg			Calorific Value	11.4	MJ/Nm^3		50	15			
3														
4				Delta Saw Mill										
5	Feed Energy	152.1	MW	25000	ton/yr	Scale Factor	Operating hours							
6	Feed Rate	7.996845426	kg/s	0.789141414	kg/s	0.039287119	8000							
7														
8														
9	Reported:	Biomass in	Biomass to dry	Biomass to combustion	Dryer to torrefaction	HX Heat	Torrefied Biomass	Torrefaction off-gas	Air in	Flue gas to HX	Flue gas to dryer	Flue gas exhaust	Ash	Cooling
10	Stream	1	2a	2b	3	4	5	6	7	8a	8b	8c	9	
11	Energy Flow (MW_{th})	156.100	134.700	21.400	152.800	5.500	150.000	8.000		42.600	37.100	15.000		4.100
12	Flow rate (kg/s)	20.087	17.333	2.754	11.266		7.886	3.380					0.842	
13	Flow rate (Nm^3/s)							0.702	12.019	14.450	14.450	14.450		
14	Density (kg/Nm^3)							4.816						
15														
16	Scaled:	Biomass in	Biomass to dry	Biomass to combustion	Dryer to torrefaction	HX Heat	Torrefied Biomass	Torrefaction off-gas	Air in	Flue gas to HX	Flue gas to dryer	Flue gas exhaust	Ash	Cooling
17	Stream	1	2a	2b	3	4	5	6	7	8a	8b	8c	9	
18	Energy Flow (MW_{th})	6.133	5.292	0.841	6.003	0.216	5.893	0.314		1.674	1.458	0.589		0.161
19	Flow rate (kg/s)	0.789	0.681	0.108	0.443		0.310	0.133					0.033	
20	Flow rate (Nm^3/s)							0.028	0.472	0.568	0.568	0.568		
21	Density (kg/Nm^3)							4.816						

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1							Off-gas			Raw Biomass %water	Dried Biomass %water			
2	LHV	19.02	MJ/kg			Calorific Value	11.4	MJ/Nm^3		50	15			
3														
4				Delta Saw Mill										
5	Feed Energy	152.1	MW	25000	ton/yr	Scale Factor	Operating hours							
6	Feed Rate	=B5/B2	kg/s	=D5*2000/2.2/G6/3600	kg/s	=D6/B12	8000							
7														
8														
9	Reported:	Biomass in	Biomass to dry	Biomass to combustion	Dryer to torrefaction	HX Heat	Torrefied Biomass	Torrefaction off-gas	Air in	Flue gas to HX	Flue gas to dryer	Flue gas exhaust	Ash	Cooling
10	Stream	1	2a	2b	3	4	5	6	7	8a	8b	8c	9	
11	Energy Flow (MW_{th})	156.1	134.7	21.4	152.8	5.5	150	8		42.6	37.1	15		4.1
12	Flow rate (kg/s)	=C12+D12	=E12/(1-(J2-K2)/100)	=C12/C11*D11	=G12/0.7		=G11/B2	=E12*0.3					=B12*U2/100	
13	Flow rate (Nm^3/s)							=H11/G2	=X6	=Y6+Q6+R6+S6+H13	=J13	=K13		
14	Density (kg/Nm^3)							=H12/H13						
15														
16	Scaled:	Biomass in	Biomass to dry	Biomass to combustion	Dryer to torrefaction	HX Heat	Torrefied Biomass	Torrefaction off-gas	Air in	Flue gas to HX	Flue gas to dryer	Flue gas exhaust	Ash	Cooling
17	Stream	1	2a	2b	3	4	5	6	7	8a	8b	8c	9	
18	Energy Flow (MW_{th})	=B11*F6	=C11*F6	=D11*F6	=E11*F6	=F11*F6	=G11*F6	=H11*F6		=J11*F6	=K11*F6	=L11*F6		=N11*F6
19	Flow rate (kg/s)	=D6	=C12*F6	=D12*F6	=E12*F6		=G12*F6	=H12*F6					=M12*F6	
20	Flow rate (Nm^3/s)							=H13*F6	=I13*F6	=J13*F6		=K13*F6	=L13*F6	
21	Density (kg/Nm^3)							=H14						

Briquetter

By Will Nabours Checked By: Deena Garland

Number	Make	Model	Weight (lbs)
1	Topline Recycling Equipment LTD	B60	1500
2	BHS Energy	Slugger Model 1520	5000
3	Komar	Briquetting System	
4	*WEIMA Maschinenbau GmbH	TH 820	3306.9
5	*Alvan Blanch	BP 5000	
	BioMass Briquetter Systems	BP 1500	
*Denotes foreign manufacturer			

Length (in)	Height (in)	Width (in)	Max Feed (lbs/hr)
70	50	32	500
108		72	1200
			300,000
78.7	78.7	37.8	396.8
			2646
			1500

Briquette Le	Briquette Width (in)	Cost
6.0	2.5	
2.0	2.0	$48,000.00
		$89,500.00
	3.1	
9.1	3.0	

2460.4 lbs/hr
1.2 tons/hr
1116.0 kg/hr

Correlation Equation
Weight_a=((FlowRate_a*Weight_b)/FlowRate_b)

Roughly $50,000 but then need to consider cooling columns, etc.

AVG COST	Cost w/ Installation	20% Engineering	Contigency
$49,000.00	$147,000.00	$176,400.00	$17,640.00

*assuming 3.0 installation factor

Length (in)	Height (in)	Width (in)	Max Feed (lbs/hr)
70	50	32	500
108		72	1200
205.71	**300**	**149.14**	3000
Converting into feet, inches by dividing by 12...			
17 '2"	**25'**	**12' 5"**	3000

*These calculations were done assuming linear relationship between the max feed rate and dimensions.

Chipper

By Will Nabours Checked By: Deena Garland

Size Reduction Equipment			
Type	**Cost (1999 Dollars)**	**Cost (2011 Dollars)**	
Ball Mill	$65,881.66	$87,161.44	
Jet Mill	$37,147.13	$49,145.65	
	*costs estimated using Herron's spreadsheet		
	**using conversion factor of 1.323 to convert		
	http://oregonstate.edu/cla/polisci/faculty-research/sahr/cv1999.pdf		
Biomass Inlet Flow Rate			
0.789	kg/s		
1.739447247	lbs/s		
6262.01009	lbs/hr *converting to pounds per hour.		
		Max Area of Bandit Infeed	
		779.3113	in^2
		5.411884028	ft^2
96	ft/min		
5760	ft/hr		**Conversions**
31172.452	ft^3/hr	3.15	4.92125985
882.7055414	m^3/hr		26.2467192
264811.6624	kg/hr		
4413.527707	kg/s		
			2.9604
Bandit Model 1990 XP	**Dimensions**		11.055108
Global Machinery	Width	7' 7"	
(303)430-7130	Height	10' 2"	
Jeff Brown	Length	20' 2"	
	Weight	10,500 to 12,500 lbs	
http://www.banditchippers.com/index.php?option=			
com_models&task=view&itemId=15&lineId=2&modelId=53			
Price Quotes			
$52,900			
http://www.apolloequipment.net/equipment/C003034p_brush_bandit_chipper.html			
$47,000			
http://cgi.ebay.com/2007-Bandit-Chipper-1990-XP-/290553740128			
AVG 1990 XP	**20% for Engineering**	**Contigency 10%**	
$49,950	$59,940.0	$5,994.0	
	http://onlinelibrary.wiley.com/doi/10.1002/9783527611119.app4/pdf		
	using a value of 1.7		

Conveyors

By Will Nabours Checked By: Deena Garland

Dryer to Torrefaction		
Feed Rate	0.443	kg/s
2200 Series Conveyors		
Loads up to	80	lbs
Speeds up to	4800	in/min
Belt Width	24	in
Cleat Height	2.36	in
Rate	271872	in^3/min
	4531.2	in^3/sec
	157.3333333	ft^3/min
	9440	ft^3/hr

Required Feed Rate		
Density of Dry Aspen	25.03	lbs/ft^3
Feed into dryer	0.681	kg/s
	1.501348004	lbs/s
V Rate into Dryer	0.059981942	ft^3/s
	3.59891651	ft^3/min
	215.9349906	ft^3/hr
V Rate out of Dryer	215.9349906	ft^3/hr

If using belt conveyor for Conveyor #1:	
49.39372235	ft long

Belt Conveyor					
Conveying length	23.99999998	ft	*Calculated assuming height of 12 feet to trailer opening and 30 degree angle		
	7.315199995	m *converted to m			
	Initial Capital Cost (2001)	**ICC (2011)**	**Cost w/ Installation**	**Cost w/ 20% Engineering**	**Contigency**
Conveyor Cost	$17,117.90	$21,294.66	$34,071.46	$40,885.76	$4,088.58
		*1.61 Conversion factor for installation			
		*2011 adjustment			
		http://oregonstate.edu/cla/polisci/faculty-research/sahr/cv2001.pdf			

Screw					
Conveying length	22	ft			
	6.7056	m			
	Initial Capital	**ICC (2011)**	**Cost w/ Installation**	**Cost w/ 20%**	**Contigency**
Conveyor Cost	$7,994.89	$9,945.64	$15,913.02	$19,095.63	$1,909.56

Wyssmont Quote

Wyssmont has successfully demonstrated the ability to dry and torrefy cellulosic materials in a single operating system. The Wyssmont Torrefaction system can produce end products having different BTU values by simple adjustments of operating parameters.

Wyssmont is the front runner in this rapidly emerging business. We have the only large scale, **commercially viable,** process for producing torrified wood (or other cellulosic materials).

The Wyssmont laboratory is being used daily to continuously improve processing conditions and to increase the capacity of Wyssmont system.

Please visit our Web site at www.wyssmont.com frequently to keep up to date with our progress.

If you need additional information, or if you wish to test your cellulosic material in our laboratory, please contact me directly.

Torrefying in the Wyssmont TURBO-Dryer
Full Size Production Unit
Generic Budget Estimate

Issue date: October 25, 2010

Dear Customer,

We are pleased to provide a budget estimate to dry and torrefy cellulose based materials in the Wyssmont TURBO-DRYER®. This budgetary estimate is based upon our experience drying many different types of cellulosic materials.

This estimate is based upon the torrefaction of Southern Pine.

SPECIFICATIONS: Torrefaction

Feed Rate: lbs/hr	Species	Density; lbs/ft3	Feed Moisture; percent	Product Rate: lbs/hr
16,600	Southern Pine	15	10	10,450
49,500	Southern Pine	45 (pelletized)	10	31,200

Operating Hours: 24 hours/day, 360 days per year

Caloric value: 10,500 BTU's/lb. (23.1 MJ/kg)
The above capacities will vary depending upon;
1. The final BTU value desired

10,500 Btu/lb results listed above. Other values are possible.
2. The nature of the feed stock being used
3. The inlet moisture content
4. The bulk density of the wet feed

TURBO-DRYER Size Model: V-37

Quantity	**1 unit**
Diameter, ft.	30 feet = 9.2-meters
Height, ft.	39 feet =11.9-meters

Materials of Construction

Carbon steel construction

Includes sealed recirculation fan and all compact, interconnecting ductwork necessary to create the superheated steam loop for drying and torrefaction, and to connect to the external heating system (outlined below) and any additional piping or ductwork required to complete the system venting loop.

Horsepower Requirements;

Includes variable frequency drives for the TURBO-Fans and Tray Drive Motors.

TURBO-Fans	(1)	25 HP
Tray System	(1)	7½ HP
Rotary Valves	(3)	5 HP
Feeder	(1)	2 HP each

Ancillaries

A limited control system including temperature pressure and oxygen control instrumentation, all installed in a local control panel is included. The customer would need to provide a PLC controller to operate the torrefier.

A Multiple Screw Feeder and Airlock to continuously feed the TURBO-DRYER® and seal the feed opening are included.

At the discharge of the TURBO-DRYER® a double airlock system with a small transition between the two (2) airlocks is provided. The transition must be purged with steam or inert gas to keep oxygen out of the system. These airlocks are long rectangular units designed to minimize headroom requirements.

The system outlined above is very flexible. It can also be used to dry only or torrify only.

The unit listed above is shipped in sub-assemblies for erection in the field by bolting. Wyssmont provides erection drawings and instructions.

Approximate Price **each @$1,600,000**

The external heating system to recirculate the superheated steam which includes the following is **not included.**

1) A Biomass or a natural gas fired heater & heat exchanger to reheat the superheated steam
2) Interconnecting ductwork as required to tie into the TURBO-DRYER® superheated steam loop
3) A fully automated control panel utilizing a programmable logic controller (PLC). Air flow and fuel feed rates are constantly adjusted by way of variable frequency drives to insure a consistent heating air temperature. Temperature, and pressure receiver instrumentation necessary to control process conditions in the TURBO-DRYER® by way of the PLC would be mounted in this local control panel.

Prices listed in this letter are ex-works, export packed in US funds. Shipping time is approximately 7-9 months from the date of order.

We are appending our Laboratory Testing Bulletin in the event that you wish to proceed with specific laboratory testing of your materials.

Very truly yours,

WYSSMONT COMPANY, INC.

Bob Hang

Bob Hang Sales Engineer

f/sales/memo/v-37 generic
revised 10/25/10

1470 Bergen Boulevard
Fort Lee, NJ 07024
Phone: (201)947-4600
Fax: (201)947-0324
e-mail: sales@wyssmont.com
Website: www.wyssmont.com

TESTING BULLETIN
GUIDELINES & PROCEDURES

DRYING TEST

1. **Wet Material Required**: 1 – 2 gallons (usually 10 – 15 lbs)

2. **Dry Material Required for Comparison Purposes:** Few ounces (if available).

3. **Test Charges**: $800 for the initial eight-hour day or any part thereof plus the expense of any required special materials (i.e., inert gas). Up to $1600 is creditable towards purchase if an order for a new TURBO-Dryer results within one year of testing. Usually 1 – 2 days are required to complete the testing and analyses. For additional days of testing the same charge per day applies.

This $800 per day rate is partially subsidized by Wyssmont. It is the rate applicable where the information developed is to be used by the customer **only to assist Wyssmont in designing its equipment and for customer evaluation of proposed Wyssmont equipment. Where the information is to be used for other purposes,** Wyssmont charge of $5,000 per day for developmental testing will apply.

4. **Test Report**: Normally a test report will be submitted after the conclusion of these tests and their associated analyses.

FEEDING AND LUMPBREAKING TESTS

1. Material Required: 1 - 2 cubic feet

GENERAL GUIDELINES FOR TESTING

1. Lead-time for all tests generally will be 1 – 2 weeks. Unless brought by the client, materials should be shipped prepaid and scheduled to arrive at Wyssmont's facilities 3 – 5 working days prior to the test date. The client is encouraged to witness most tests.

2. Customer shall, before testing, provide all appropriate information as to the potential hazards and precautions to be taken during handling, storage, testing and cleaning.

3. **Material Safety Data Sheets (MSDS) are required prior to testing**. An MSDS should be included for the feed material, any end product should they differ from the feed material, and for any solvents present in the sample. All samples will be returned after completion of the testing, freight collect. Any special labels required for the return shipment should be included with the sample.

4. Unless indicated otherwise, all charges include normal test setup and simple water wash cleanup. Additional costs, if incurred, will be for customer's account.

5. Customer shall provide UPS or Federal Express account numbers for return of samples.

Torrefaction Reactor Cost Estimate

By Herron Kennedy Checked By Kelly Albano and Deena Garland

	A	B	C
1	Wyssmont TURBO-DRYER®	Quote	Needed
2			
3	Cost:	$ 1,600,000.00	$ 850,215.24
4	Flow rate (tons/yr):	71712	25000
5	Height (m):	11.9	8.37
6	Diameter (m):	9.2	6.48
7	Volume (m^3):	791.07	275.78
8	Height/Diameter:	1.29	1.29
9		Factor	2.06
10		Actual Cost	$1,947,605.06
11			
12		CE	
13		2006	500
14		2010	556

	A	B	C
1	Wyssmont TURBO-DRYER®	Quote	Needed
2			
3	Cost:	1600000	=(C4/B4)^0.6*B3
4	Flow rate (tons/yr):	71712	25000
5	Height (m):	11.9	=C7/(PI()*C6^2/4)
6	Diameter (m):	9.2	6.47576239663161
7	Volume (m^3):	=PI()*B6^2/4*B5	=C4/B4*B7
8	Height/Diameter:	=B5/B6	=C5/C6
9		Factor	2.06
10		Actual Cost	=C9*C3*C14/C13
11			
12		CE	
13		2006	500
14		2010	556

Biomass Combustor Cost Estimate

By Herron Kennedy Checked By: Ben Miller

	A	B	C	D
1		Quote1	Quote2	Actual
2	KBTU/HR	500	800	1600
3	Lbs	4300	6000	10533
4	Height (in)	87	108	164
5	Width (in)	40	48	69
6	Length (in)	82	88	104

	A	B	C	D
1		Quote1	Quote2	Actual
2	KBTU/HR	500	800	1600
3	Lbs	4300	6000	=B3+(D2-B2)/(C2-B2)*(C3-B3)
4	Height (in)	87	108	=B4+(D2-B2)/(C2-B2)*(C4-B4)
5	Width (in)	40	48	=B5+(D2-B2)/(C2-B2)*(C5-B5)
6	Length (in)	82	88	=B6+(D2-B2)/(C2-B2)*(C6-B6)

Heat Exchanger Cost Estimate

By Herron Kennedy Checked By: Ben Miller

	A	B
1	Surface Area (m^2)	22.74
2	Cost FOB	$ 53,338.30
3	Factor	3.3
4	Intalled Cost (2006)	$ 176,016.39
5	CE	
6	2006	500
7	2010	556
8	Acutal Cost:	$ 195,730.23

	A	B
1	Surface Area (m^2)	22.74
2	Cost FOB	=5.37035924692622*(LN(x))^6-118.375227971311*(LN(x))^5+1102.11224385246*(LN(x))^4-4724.23770491802*(LN(x))^3+13038.7219518442*(LN(x))^2-7876.63171106556*LN(x)+19985.2396260245
3	Factor	3.3
4	Intalled Cost (2006)	=B2*B3
5	CE	
6	2006	500
7	2010	556
8	Acutal Cost:	=B4*B7/B6

By Kelly Albano
Checked by Herron Kennedy

				total product to sell:	
Tollefied wood:	10800	BTU/lb		**8928000**	kg Torrefied wood/year
	25120791.9	J/kg		9841.334	tons
Coal:	9500	BTU/lb			
	22096992.88	J/kg	5.566418209	MW/ton	
			1669925.463		

Coal Plants

	Cameo	**Nucla**
Power Ourput (kW)	66000	114000
Coal used (tons/year)	300000	650000
Coal used (kg/s)	8.629984779	18.69830036
Coal used (kg/day)	621358.9041	1346277.626
*torrefied biomass must be used in a 10/90 energy ratio		
Coal used (J/day)	1.37302E+13	3.38196E+13
Coal used 90% (J/d)	1.23571E+13	3.04376E+13
Amt of torrified wood used (J/d)	1.37302E+1	3.38196E+1

Amount of coal (kg/d)	2559223.0137	1377454.581	
Amount of torrified wood used (kg/d)	54656.57027	134627.7626	
*calculate the run time of each of the plants with the correct ration of bio char			
days biochar lasts	163.3472418	66.31618791	(less than time spent making than using)
Federal tax credit ($0.022 per kWh w/ biomass)			
total Joules	2.24278E+14	2.24278E+14	
total kWh	62299563.92	62299563.92	*efficiency for a coal-power plant
Total w/ 40% efficiency	24919825.57	24919825.57	
total $ back	**$548,236.16**	**$548,236.16**	** only applies for first ten years
*Money saved though Title V for emitting less of criteria pollutants *save $25/ton in 1989 dollars for pollutant saved			coal emits:
Coal Produced SO2 (lbs)	809894.331	809894.331	13lbs so2/MWh
Coal Produced Nox (lbs)	373797.3835	373797.3835	6lbs nox/MWH
Coal Produced CO2 (lbs)	139737921.9	139737921.9	2243lbs co2/MWH

FIND AMTS	TM Produced SO2 (lbs)	0	0	
	TM Produced Nox (lbs)	37379 7.383 5	37379 7.383 5	Aproximatly the same
	TM Produced CO2 (lbs)	13973 7921. 9	13973 7921. 9	Aproximatly the same
	S02	80989 4.331	80989 4.331	
	Nox	0	0	
	CO2	0	0	
	Totals tons diverted	404.9 47165 5	404.9 47165 5	
	Total 1989 dollars saved	10123 .6791 4	10123 .6791 4	
	total 2011 dollars saved	**$17,9 78.26**	**$17,9 78.26**	
	*Find total amount being paid for coal that is to be diverted			
	amount of diverted coal (ton)	11188 .1549 6	11188 .1549 6	
	money paid ($35 per ton)	**$391, 585.4 2**	**$391, 585.4 2**	
	total amount willing to pay for entire quantity of biochar first 10 years			
	Price total annually	**$957, 799.8 4**	**$957, 799.8 4**	Price that we should be able to charge per year
	Price Per kg	$0.11	$0.11	
	price per ton	**$97.3 2**	**$97.3 2**	

total amount willing to pay for entire quantity of biochar after 10 year tax credit expires		
Price total annually	**$409,563.68**	**$409,563.68**
Price Per kg	$0.05	$0.05
price per ton	**$41.62**	**$41.62**
revenue over a 20 year lifetime	**$13,673,635.26**	**$13,673,635.26**
*10 years w/ tax incentive, 10 w/o		

By Kelly Albano
Checked by Ben Miller

Air Regulations Compliance Calculations

Total energy:

(0.841+0.216)MW *3412141 BTU/hr/MW=3606633 BTU/hr

PE=0.5(3.606)^-0.26=0.358 lbs per $10^6 \frac{BTU}{hr}$

PE = Particulate Emissions in lbs per $10^6 \frac{BTU}{hr}$

FE = Fuel Input in $10^6 \frac{BTU}{hr}$.

((0.358 lbs per $10^6 \frac{BTU}{hr}$) / 3.606 $10^6 \frac{BTU}{hr}$) * 0.45359 kg/lb = 0.0450589 kg/hr

3606633 BTU/hr /1000000= 3.606633MMbtu/hr

0.03 lb/MMBtu*3.606633MMbtu/hr *0.45359 kg/lb = 0.04907753 kg/hr

Total created:

0.005kg/s *3600= 17.005 kg/hr

Eff 1-(0.045/17.005)= 99.7% efficiency

2 Cyclones

1-(0.9*0.9)=99%

Air Pollution Control Costing

By Ben Miller

Checked by Herron Kennedy

Cost Cyclone:		Pc=6520A^0.903				
Cost rotary air lock valve (RALV)			Pv=273A^0.0965			
A is Cyclone inlet area			*note:equations based on 1988 US dolar			
			conversion: $1.90 (2011) / $1 (1988)			
			*note: does not account for operating costs			

A (ft^2)	Pc	Pv	Pc (current)	Pv (current)
0.25	$1,865	$239	**$3,543**	**$454**
0.5	$3,487	$255	**$6,625**	**$485**
0.75	$5,028	$266	**$9,554**	**$504**
1	$6,520	$273	**$12,388**	**$519**
1.5	$9,403	$284	**$17,865**	**$539**
2	$12,192	$292	**$23,165**	**$555**
2.5	$14,914	$298	**$28,336**	**$567**

ESP

Assume plate area is between 10k and 50k square ft

Unit cost:	P=962A^.628		*note:equations based on 1988 US dolar
A is plate area			conversion: $1.9 (2011) / $1 (1988)
			*note: does not account for energy costs

A (ft^2)	P	P (current)
10,000	$312,734	$594,195
15,000	$403,423	$766,503
20,000	$483,306	$918,281
25,000	$556,008	$1,056,416
30,000	$623,458	$1,184,570
35,000	**$686,831**	$1,304,979
40,000	$746,911	$1,419,131
45,000	$804,253	$1,528,080
50,000	$859,267	$1,632,608

Scrubber

Use of figure 7.12			*note:equations based on 1998 US dolar	
Assume 10,000 ft^3 /min			conversion: $1.9 (2011) / $1 (1988)	
Adjusted for 316 stainless steal (x2.7)			*note: does not account for energy costs	
Assume 2 hrs of labor daily				
Annual labor:	360 hrs	Wage $10/hr		Annual labor cost :$3600

Type	P	P (adjust)	P (current)
GSS	$7,000	$18,900.0	$35,910
WDS	$10,000	$27,000.0	$51,300
IS	$10,250	$27,675.0	$52,583
CS	$10,000	$27,000.0	$51,300
VLES	$10,500	$28,350.0	$53,865
VHES	$20,000	$54,000.0	$102,600

Cyclone Costing

Ben Miller check by Herron Kennedy

CYCLONE CC		Pc=6520A^0.903	
		Pv=273A^0.0965	
Cost Cyclone:		*note:equations based on 1988 US dolar	
Cost rotary air l		conversion: $1.90 (2011) / $1 (1988)	
A is Cyclone inle		*note: does not account for operating costs due to pressure drop	
		Instalation Cost Factor Assumed 1.6	
		contingency: assume 10% of capital due to maintence free nature of cyclones	
		Engineering and admin: Assume 20% of gross capital	

A (ft^2	Pc	Pv	Pc (curren	Pv (current	Gross Capita	Eng/admi	Inst Cos	Bare Modua	Net Capital	Contengency
0.25	$1,865	$239	$3,543	$454	$3,997	$799	$6,394	$10,391	**$11,190**	$400
0.5	$3,487	$255	$6,625	$485	$7,110	$1,422	$11,376	$18,486	**$19,908**	$711
0.75	$5,028	$266	$9,554	$504	$10,058	$2,012	$16,093	$26,152	**$28,164**	$1,006
1.3	$8,263	$280	$15,700	$532	$16,232	$3,246	$25,971	$42,202	**$45,449**	$1,623
1.2	$7,687	$278	$14,605	$528	$15,133	$3,027	$24,213	$39,346	**$42,372**	$1,513
2	$12,192	$292	$23,165	$555	$23,720	$4,744	$37,951	$61,671	**$66,415**	$2,372
2.5	$14,914	$298	$28,336	$567	$28,903	$5,781	$46,245	$75,147	**$80,928**	$2,890

AAF Cyclone									
Model	Flow Rate (C	H (ft)	W (ft)	D (ft)	Weight (lb	Inlet D (in)	Inlet D (ft)	Capital	Contingency
AAF-CY36-2(	5K-7K	21.17	5.5	5.5	2600	16	1.3	$45,449	$1,623
AAF-CY30-1!	3.5K-4.5K	17.92	3.5	3.5	980	14	1.2	$42,372	$1,513
							Avg:	$43,910	$1,568
Process flowrate about 4500 cfm									

Air flow rate	0.568	Nm^3/s	
Temp N	273	K	0 C
Pres N	1	atm	
Temp A	1033	K	760 C
Pres A	1	atm	
Air flow rate	2.14924542	m^3/s	
Air flow rate	4,554	ft^3/min	
pv=nrt			
p1v1/t1=p2v2/t2			
v2=p1v1t2/t1p2			
v2=v1t2/t1			

Demo Project (One 2.5 tph Reactor)

Key Financial Inputs	
Quantity sold (in tons/year)	17,850
Production rate (tons/hour)	2.5
Price of finished product (at gate) ($/ton)	$155.00
Process mass reduction	61.9%
Raw material consumed (in tons/day)	180.0
Raw material consumed (in tons/year)	53,550.0
Cost of Fiber landed at yard ($/ton)	$25.75
Operating Days per Year	297.5
Operating Hours per Year	7,140
Operating Hours per Day	24
Shipping Costs ($/ton)	$4.94
O&M ($/ton)	$10.30
Labor & benefits	$696,249
Elec, gas, diesel ($/ton)	$12.44
Other site expenses ($/ton)	$1.03
Steam/binder for pellets ($/ton)	$3.00
SG&A	1.00%
Offsite management fees	1.00%
Insurance, permits, etc.	1.00%
Depreciation rate	10.0%
Annual escalation	3.0%
Capital Investment	$6,019,384
Debt %	90%
Annual Interest rate	8%
Loan Term	15
%Finance fee (% of amount financed)	2%
Effective tax rate	35%

YEAR 2 (Expressed in dollars)	Projected
Net sales per year	$2,766,750
RECs	$547,834
Carbon credits, other incentives	$0
Annual Revenues	**$3,314,584**
Direct Costs	
Cost of raw material	$1,378,913
Shipping Costs	$88,250
O&M	$183,855
Labor & benefits	$696,249
Elec, gas, diesel	$222,125
Other site expenses	$18,386
Steam/binder for	$53,550
Total cost of product	**$2,641,327**
Annual Gross profit	**$673,257**
Indirect Costs	
SG&A	$27,668
fees	$27,668
Insurance, permits, etc.	$27,668
Total indirect expenses	**$83,003**
EBITDA	**$590,254**
Amortization	$621,263
Total Expenses	$3,345,593
Depreciation	$601,938
EBIT	**($632,947)**
Interest earned	$0
Profit before tax	**($632,947)**
Income taxes	$0
Net income	**($632,947)**

Amount Financed $5,417,445.60

Financing Fee $108,349

Product Shipping Costs Input	
$/mi for Semi Load	$2.060
Tons/Semi	25.0
Miles per Load	60
Shipping cost per mile per ton	$0.082

Cash Flow (Year 2)	**($31,009)**
Equity Investment	$601,938
IRR	6.7%

15.02 simple payback (years)

Calculation of IRR -rough	
Year 0	($601,938)
Year 1	-$48,201
Year 2	-$31,009
Year 3	-$13,301
Year 4	$4,938
Year 5	$23,724
Year 6	$43,073
Year 7	$63,003
Year 8	$83,531
Year 9	$104,675
Year 10	$126,453
Year 11	$148,885
Year 12	$171,989
Year 13	$195,787
Year 14	$220,298
Year 15	$245,545
Year 16	$892,813
IRR	6.66%

Margins	
Gross margin (excluding D&A)	24.3%
Selling expenses as % of net sales	1.0%
G&A expenses as % of net sales	6.6%
Other expense as % of net sales	37.4%
EBITDA margin	21.3%
EBIT margin	-22.9%
Net income margin	-22.9%

Elec, nat gas, diesel costs per ton of product				
Electricity	fuel cost	$0.1122	/kWh net	
	base consumption	225	kW	80% motor efficiency
	production cost	$8.08	/ton	
	hourly cost	$20.20	/hr	
	annual cost	**$144,255**	**/year**	
Natural gas	fuel cost	$12.50	/mmBtu	$1.25 /therm
	base consumption	0.200	mmBtu/hr	
	production cost	$1.00	/ton	
	hourly cost	$2.50	/hr	
	annual cost	**$17,850**	**/year**	
Diesel	fuel cost	$3.75	/gal	
	base consumption	2.00	gal/hr	
	production cost	$3.00	/ton	
	hourly cost	$7.50	/hr	
	annual cost	**$53,550**	**/year**	

RECs			
Heat rate (nominal)	11,179	Btu/kWh	(Cherokee Power Plant, Denver;
Energy density of TW pellets	9,028	Btu/lb	
Energy content of annual production	322,316	mmBtu/yr	
Net energy production	28,833,375	kWh	
REC value	$0.019	/kWh	
RECs	**$547,834**	**/yr**	
Coal heating value (wet):	11,723	Btu/lb	(PRB bituminous, as received)
Coal displaced	13,747	tpy	

PRB Bituminous, as received)

Assumptions:		dry basis
Mass reduction from torrefaction (dry basis)	30%	
Energy reduction from torrefaction	9%	
Initial M.C. (wb)	45.6%	83.7%
Air Dried (wb)	15.0%	17.6%
Furnace Dried M.C. (wb)	10.0%	11.1%
Torrefied chips M.C. (wb)	0.0%	0.0%
Torrefied pellets M.C. (wb)	0.0%	0.0%
Combustion efficiency	95%	
Furnace efficiency	75%	
Heat exchanger (torr gas) efficiency	55%	
Heat exchanger (condenser) efficiency	65%	
Electric consumption (kWh/ton)	90.0	
Natural gas consumption (mBtu/hr)	200	
Diesel consumption (gal/hr)	2.00	

Other assumptions:

- Majority of the water removal takes place during drying phase
- No volitalization takes place during drying phase
- Heat capacities constant over temperature
- No process water will be condensed in the process
- Mass ratio of raw material to finished product = 3:1

Definitions

Mtpy(d)(h)	= metric tons per year (day) (hour)	
sh. tpd	= short tons per day	
M.C. (wet)	= moisture content, wet basis, wt%	= 100 x (green wt - dry wt) / green wt
M.C. (dry)	= moisture content, dry basis	= 100 x (green wt - dry wt) / dry wt
M.C. (wet)	= M.C. (dry) x (dry wt / green wt)	= M.C. (dry) / (1 + M.C. (dry))
wb	= wet basis	

No input cells below this line.

Daily Material Requirements

Pine (green)	Mtpd	sh. tpd	sh. tpy	Mass ratio of raw material to pellets
Torrefaction Process	142.9	157.5	46,851	
Furnace (w/ En Recovery II)	20.43	22.5	6,699	
Furnace (w/ No Recovery)	31.94	35.2	10,473	
Total (w/ En Recovery II)	**163.29**	180.00	53,550	3.00
Total (w/ No Recovery)	**174.80**	**192.7**	**57,324**	**3.21**

Calorific Value - Net (LHV) and Gross (HHV)

LHV	kJ/kg	Btu/lb	@ %M.C.	HHV	kJ/kg	Btu/lb
Chips, pine - green	9,302	3,999	45.6%		11,055	4,753
Chips, pine - air dried	15,794	6,790	15.0%		17,265	7,423
Chips, pine -furnace dried	16,856	7,247	10.0%		18,280	7,859
Chips, pine - moisture free	18,980	8,160	0%		20,312	8,733
Torrefied chips, pine	19,900	8,556	0.0%		21,232	9,128
Torrefied pellets, pine	21,000	9,028	0.0%		22,332	9,601
Torrefied pellets, pine	21,600	9,286	0%		22,332	9,601

Mass Balance

		Mass (wet)						M.C. (wet)	M.C. (dry)	m_{H2O}		m_{wood} (dry)	
		Mtpy	Mtpd	Mtph	sh. tpy	sh. tpd	sh. tph	%	%	Mtpd	sh. tpd	Mtpd	sh. tpd
to dryer	Raw Material	**42,503**	**142.9**	**6.0**	**46,851**	**157.5**	**6.6**	**45.6%**	**83.7%**	**65.1**	**71.8**	**77.8**	**85.7**
	Dried Material	25,704	86.4	3.6	28,333	95.2	4.0	10.0%	11.1%	8.6	9.5	77.8	85.7
	Water, drying	16,799	--	--	--	--	--	--	--	56.5	62.2	--	--
	Torrefaction Gas	9,510	32.0	1.3	10,483	35.2	1.5	71.2%	246.6%	22.7	25.1	9.2	10.2
	Volatilized hemicell	6,940	23.3	1.0	7,650	25.7	1.1	60.5%	153.0%	14.1	15.5	9.2	10.2
	Water, drying	2,570	--	--		--	--	--	--	8.6	9.5	--	--
	Torrefied Product	**16,193**	**54.4**	**2.3**	**17,850**	**60.0**	**2.5**	**0.0%**	**0.0%**	**0.00**	**0.00**	**54.4**	**60.0**
	Torr Pellets	16,193	54.4	2.3	17,850	60.0	2.5	0.0%	0.0%	0.00	0.00	54.4	60.0
	Water, drying	0	--	--	--	--	--	--	--	0.00	0.00	--	--

m_{out}	42,503	65.1	78
m_{in}	42,503	65.1	78
Δ	0	0	0

Thermal Energy Balance

$q = m\ Cp\ \Delta T$ $\qquad$ $q = m\ \Delta H$

Demand Required / **Energy Recovery Available**

	m	Cp	ΔH	T_{in}	T_{out}	Q	Cp	ΔH	T_{in}	T_{out}	Sensible Heat	Latent Heat	LHV	
	kg/day	kJ/kg-K	kJ/kg	°C	°C	kJ/day	kJ/kg-K	kJ/kg	°C	°C	kJ/day	kJ/day	kJ/day	
Drying														
Heat wood	142,867	2.5		25	100	2.68E+07								
Vaporize water	56,468		2257			1.27E+08	2.08	2257	100	100	0.00E+00	1.27E+08		
Torrefaction														
Heat wood	86,399	2.0		100	280	3.11E+07								
Vaporize water	8,640		2257			1.95E+07	2.08	2257	280	110	8.04E+06	5.13E+07		
Volatilize hemicellulose	23,328		2000			4.67E+07							1.21E+08	Combustion of torrefaction gases
Pelletizing														
Vaporize water	0		2257			0.00E+00	2.08	2257	100	100	0.00E+00	0.00E+00		
Total						2.51E+08					8.04E+06	1.79E+08	1.21E+08	

Furnace Requirements

If steam is condensed from drying and torrefaction process: 79.2 Mtpd process water condensed

Energy Demand	2.51E+08 kJ/day	1.05E+07 kJ/hr	**297 BHP (delivered)**	Energy Demand	2.51E+08 kJ/day			
Energy Recovery I (combust only)	8.62E+07 kJ/day	34% of demand	**102 BHP (delivered)**	Energy Recovery III (combust+sens	2.07E+08 kJ/day		82% of demand	**244 BHP (delivered)**
Energy Recovery II (combust +sensil	9.06E+07 kJ/day	36% of demand	**107 BHP (delivered)**	**Net Demand**	**4.47E+07 kJ/day**	1.86E+06 kJ/hr		**53 BHP (delivered)**
Net Demand	**1.61E+08 kJ/day**	6.70E+06 kJ/hr	**190 BHP (delivered)**					

Makeup requirement (w/ En Recovery II)									
Pine (green)	20.43 Mtpd	22.5 sh. tpd	8.94E+06 kJ/hr	**253** BHP (boiler rating @) 75%	5.67 Mtpd	6.3 sh. tpd	2.48E+06 kJ/hr	**70** BHP (boiler rating @) 75%
Wood chips (air dry)	13.58 Mtpd	15.0 sh. tpd	8.94E+06 kJ/hr	**253** BHP (boiler rating @) 75%	3.77 Mtpd	4.2 sh. tpd	2.48E+06 kJ/hr	**70** BHP (boiler rating @) 75%
Torr wood	10.78 Mtpd	11.9 sh. tpd	8.94E+06 kJ/hr	**253** BHP (boiler rating @) 75%	2.99 Mtpd	3.3 sh. tpd	2.48E+06 kJ/hr	**70** BHP (boiler rating @) 75%
Torr pellets	10.21 Mtpd	11.3 sh. tpd	8.94E+06 kJ/hr	**253** BHP (boiler rating @) 75%	2.84 Mtpd	3.1 sh. tpd	2.48E+06 kJ/hr	**70** BHP (boiler rating @) 75%
Net production	44.2 Mtpd	48.7 sh. tpd			51.6 Mtpd	56.9 sh. tpd		

No Energy Recovery				
Pine (green)	31.94 Mtpd	35.2 sh. tpd	1.40E+07 kJ/hr	**396** BHP (boiler rating @) 75%
Wood chips (air dry)	21.23 Mtpd	23.4 sh. tpd	1.40E+07 kJ/hr	**396** BHP (boiler rating @) 75%

Thermal Energy Content

	m (dry)	LHV	Q (latent)	
	Mtpd	kJ/kg	kJ/day	
Raw Material	**77.8**	18,980	1.48E+09	
Torrefaction Gas	9.2	13,119	1.21E+08	8.2%
Torr Pellets	54.4	21,600	1.18E+09	79.7%
				87.9%

Q_{in} 1,476 GJ/day

Q_{out} 1,297 GJ/day

Δ 179 GJ/day

Yield calculations

$y_m = (m_{tw} / m_{feed})_{maf}$ 70% (Bergman, 2005)

$y_e = y_m (LHV_{tw} / LHV_{feed})_{maf}$ 90% (Bergman, 2005)

Electric Costs

300	kW peak demand
75%	load factor
225	kW base demand
80%	motor efficiency
180	kWh/hr delivered
72	kWh/t consumed
$112,455	annual energy cost
$10	Demand charge
50	kW base demand adjustment
$2,500	estimated monthly demand charge
$150	Other monthly utility fees
$144,255	**total annual electric costs**
$8.08	/ton production
$0.11224	net cost per kWh

Natural Gas Costs

0.200	mmBtu/hr consumption
$22,313	**total annual natural gas costs**
$1.25	/ton

Diesel Fuel Costs

2.0	gal/hr consumption
$53,550	**total annual diesel costs**
$3.00	/ton

Total Annual Energy Costs

$220,118 total annual energy costs

Material	Property												
	Density		Cp	LHV	HHV	H(vaporiz)		H(form)		H(combus) (LHV)		water of	Notes
	kg/mol	kg/m^3	kJ/kg-K	kJ/kg	kJ/kg	kJ/mol	kJ/kg	kJ/mol	kJ/kg	kJ/mol	kJ/kg	combustio	
Pine (green)		550	2.5								10500		39.9% M.C. (
Wood chips (air dry)			2.0								15,794		15.0% M.C. (
Wood (mf)											18,980	0.59	0.0% M.C. (wb)
Torr wood		230									19900		
Torr pellets		800									21000		
Torr gas			1.005										
$C_2H_4O_2$ (acetic acid)	0.060052							-438	-7295	-832.6	-13864		
CO	0.028010		1.004	10100				-111	-3946	-283.0	-10103		
CH3OH (methanol)	0.032042							-201	-6273	-676.2	-21103		
CH4 (methane)	0.016042							-75	-4667	-802.3	-50012		
$C_5H_4O_2$ (furfural)	0.096082							-151	-1572	-2300.2	-23940		
CO2	0.044010							-394	-8941				
H_2O (l)	0.018016		4.181			40.7	2257	-286	-13423				
H_2O (g)	0.018016		2.08					-242	-15865				
Xylose							2000						

Conversions

4.1868	kJ/kcal	1.308	yd^3/m^3	100,000	Btu/therm
0.239	kcal/kJ	35.31	cu ft/m^3	102,500	Btu/ccf
0.948	Btu/kJ	1.1023	sh. ton/Mt		
28.32	BHP/GJ/hr	2.2046	lb/kg		

all (g)	Reacts				Prods			
CH3COOH + 2 O2 ---> 2 CO2 + 2 H2O	1	CH3COOH	2	O2	2	CO2	2	H2O
2 CO + O2 ---> 2 CO2	2	CO	1	O2	2	CO2	0	H2O
2 CH3OH + 3 O2 ---> 2 CO2 + 4 H20	2	CH3OH	3	O2	2	CO2	4	H2O
CH4 + 2 O2 ---> CO2 + 2 H2O	1	CH4	2	O2	1	CO2	2	H2O
C5H4O2 + 5 O2 ---> 5 CO2 + 2 H2O	1	C5H4O2	5	O2	5	CO2	2	H2O

	amu
carbon	12.0100
hydrogen	1.0080
oxygen	16.0000

wood (pine	4.42	kcal/g	18,506	kJ/kg	Niessen, pg. 675
pine (0% H2O)			21,030	kJ/kg	Klass, pg. 78

Torrefaction gas (daily basis: 100 Mtpd of product)

	Reported wt %	100 g basis	dry to 10 wt% CO2		m (kg)	Hcomb (kJ/kg)	Hcomb (kJ)	
Acetic Acid	4.8%	4.8	14.55%		4650	-13864	-6.45E+07	
CO	0.1%	0.1	0.30%		97	-10103	-9.79E+05	
Methanol	0.1%	0.12	0.36%		116	-21103	-2.45E+06	
Methane, etc	1.0%	1	3.03%		969	-50012	-4.84E+07	
furfural	0.2%	0.2	0.61%		194	-23940	-4.64E+06	
CO2	3.3%	3.3	10.00%		3197			
H20	89.3%	89.3	71.15%		22746			
Total	0.9882		100.00%		31968		burn it all!	
			28.85%				-1.21E+08	kJ/day
				wet basis:	31968	kg/day	-3785	kJ/kg

Gas Phase Composition
CO = 0.1%
CO_2 - 3.3%
H_2O = 89.3%
Acetic Acid = 4.8%
Furfural = 0.2%
Methanol = 1.2%
Formic Acid = 0.1%
Remainder = 1.0%

INL report:
"Even when completely dry biomass is torrefied, it is expected that the torrefaction gas has a water content of over 50% wt and a CO2 content of about 10% wt."

Calorific value of Pine

Water content (wb)	Water	Dry matter	Calorific value HHV	Calorific value LHV	Energy content HHV	Energy content LHV
wt%	kg	kg	kJ/kg	kJ/kg	kJ	kJ
50	0.50	0.50	10,156	8,362	10,156	8,362
45	0.41	0.50	11,171	9,423	10,156	8,567
40	0.33	0.50	12,187	10,485	10,156	8,738
35	0.27	0.50	13,203	11,547	10,156	8,882
30	0.21	0.50	14,218	12,609	10,156	9,006
25	0.17	0.50	15,234	13,671	10,156	9,114
20	0.13	0.50	16,249	14,733	10,156	9,208
15	0.09	0.50	17,265	15,794	10,156	9,291
10	0.06	0.50	18,280	16,856	10,156	9,365
8	0.04	0.50	18,687	17,281	10,156	9,392
5	0.03	0.50	19,296	17,918	10,156	9,431
0	0.00	0.50	20,312	18,980	10,156	9,490

Normalized calculation (Calorific Value)

wt%		Calorific value HHV	Calorific value LHV
52	0.52	9,750	7,937

Figure 1: Calorific value of pine wood as a function of moisture content
source: Topell Energy, "Understanding the mass and energy balance of Torrefaction," January 2011, pg. 2.