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An Economic Analysis of Mobile Pyrolysis for Northern New Mexico Forests

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Abstract

In the interest of providing an economically sensible use for the copious small-diameter wood in Northern New Mexico, an economic study is performed focused on mobile pyrolysis. Mobile pyrolysis was selected for the study because transportation costs limit the viability of a dedicated pyrolysis plant, and the relative simplicity of pyrolysis compared to other technology solutions lends itself to mobile reactor design. A bench-scale pyrolysis system was used to study the wood pyrolysis process and to obtain performance data that was otherwise unavailable under conditions theorized to be optimal given the regional problem.

Pyrolysis can convert wood to three main products: fixed gases, liquid pyrolysis oil and char. The fixed gases are useful as low-quality fuel, and may have sufficient chemical energy to power a mobile system, eliminating the need for an external power source. The majority of the energy content of the pyrolysis gas is associated with carbon monoxide, followed by light hydrocarbons. The liquids are well characterized in the historical literature, and have slightly lower heating values comparable to the feedstock. They consist of water and a mix of hundreds of hydrocarbons, and are acidic. They are also unstable, increasing in viscosity with time stored. Up to 60%

of the biomass in bench-scale testing was converted to liquids. Lower (~550°C) furnace temperatures are preferred because of the decreased propensity for deposits and the high liquid yields.

A mobile pyrolysis system would be designed with low maintenance requirements, should be able to access wilderness areas, and should not require more than one or two people to operate the system. The techno-economic analysis assesses fixed and variable costs. It suggests that the economy of scale is an important factor, as higher throughput directly leads to improved system economic viability. Labor and capital equipment are the driving factors in the viability of the system. The break-even selling price for the baseline assumption is about $11/GJ, however it may be possible to reduce this value by 20-30% depending on other factors evaluated in the non-baseline scenarios. Assuming a value for the char co-product improves the analysis. Significantly lower break-even costs are possible in an international setting, as labor is the dominant production cost.

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1 Introduction

Northern New Mexico Forests are characterized mostly by dense growth of small-diameter conifer trees. Maintenance of forested lands is a significant regional business, and represents an expense to land owners. A big concern is that of wildland fires. Severe fires have a significant negative effect that necessitates the expense to manage the lands. A large fire jeopardizes improvements like residential and commercial structures. Fires alter the quality of the land, promote soil erosion, cause burnt products to pollute downstream waters, and destroy wildlife habitat. Furthermore, fires create landscape blights, which may reduce tourism and require years to recover. Finally, fires create significant air pollution. Long-term land management plans must acknowledge the threat of fires and actively plan for a sustainable land-use model. Thinning helps mitigate the potential for severe fires.

Northern New Mexico has abundant biomass. Growth tends to be small diameter conifers, with little commercial market for the trees of that size. Land owners need to periodically thin the growth to mitigate fire hazards. The thinning products have minimal current commercial value at the scales at which they are generated, and are an added cost to remove from the land. This project was undertaken with the goal of exploring and potentially providing the region with a technology that may allow the waste biomass to be converted to an economical product. The regional issues have been previously studied and source materials inventoried (Zachritz et al, 2000). There is a potential for 20-50 tons of extracted biomass per acre in the region of primary interest.

This project was proposed in 2008, when oil prices reached a record high. A motivating argument is that there must be a point at which the price of fossil fuel is so high that biomass energy technologies become more economical. This focused the project on energy uses of the biomass. Non-energy related uses vary widely, with some of the more common including use as a structural material, for paper, or for furniture. Biochemical processes can result in energy product, an example of which is the corn or sugar cane ethanol industry. Cellulosic ethanol is considered a prospect, but the technology behind this type of conversion is not mature. Thermochemical conversion is the most widely used route to extract energy from biomass.

A significant challenge with biomass is that it has much lower energy density as compared to most fossil fuels. The low energy density is further exacerbated by the shape of the material. Branches and limbs do not pack efficiently, and often the shipping volume of biomass solids is composed of a significant void fraction. Chipped, the biomass still is not compact. Rogers and Brammer (2009) suggest that loading is the primary cost associated with biomass transport until longer distances are driven. There is a finite distance one can transport raw materials before consuming the amount of

energy ultimately recovered from the material in the transportation. Estimates of practical shipping limits vary widely, but normally fall inside of 100 miles (Searcy et al., 2007). This means that a central (immobile) processing plant must have access to copious and continuous raw material nearby if one is to transport the raw materials to a facility for energy extraction.

Additional issues exist. There are numerous thermochemical methods of using wood, each of which has certain advantages and disadvantages. All are used to some extent. First, a wood burning stove or fireplace can convert biomass to residential heat. However, combustion of biomass is regulated in many urban areas due to the emissions. And preparing the wood for a fireplace requires manual labor, as does tending and maintaining the stove or fireplace. From a consumer perspective, refined fossil fuels are typically considered superior because they do not demand as much time to use. Boilers can be used at larger scales, but have clean-up and labor issues as well. Central facilities can pelletize and torrefy biomass, improving the raw material for later combustion. However, the processing requires energy, which may not be recovered depending on final use of the biomass. Second, charcoal can be produced from a slow pyrolysis reaction. It is normally used for cooking since it does not flame as readily and will release heat slowly and evenly. Charcoal can also be used in boilers as a coal equivalent. Third, faster pyrolysis can yield a liquid combustible as the primary product, with char as a secondary. Finally, even more intense thermal processing can produce mostly a gas, known as a synthesis gas. This can be directly combusted, or upgraded through a refining and catalytic process to a liquid fuel.

For reasons further enumerated in the next section, we have elected to focus on on-site pyrolysis of the wood as a solution to the problem stated above. This would produce a combustible liquid as a primary product. Conceptually, this would allow the harvesting process to create a directly usable product, or one that could more efficiently be shipped to a central location for refinement or further processing to a higher-value product.

Pyrolysis is well detailed in the literature. It yields a variable product (Oasmaa et al., 2009; Ringer et al., 2006; Bahng et al., 2009) with a range of properties that depend on the process and the material of origin.

1.1 Concept Solution

This project was initiated at the behest of Northern New Mexico small community wildland management companies. These companies are paid to thin forested lands, but often have no use for the harvested biomass. It consequently is left to rot, or at a cost to the land owners it is hauled away or burnt on the land where it was harvested. None of these solutions is very satisfactory as the product material has potential value. Burning and rotting

materials release gases and particulates to the environment that are considered pollutants. Sizing and selling the product for burning in a fireplace is often done, but there is market saturation, and the emissions of wood burning are not desirable at a large scale without implementing controls.

We elected to evaluate the possibility of field pyrolysis in a portable facility based on an evaluation of the benefits and drawbacks of the technology. Since there were not many studies on this topic in a portable environment, it was prudent to conduct some experimental evaluation. Additionally, it seemed from a list of benefits and challenges that field pyrolysis might provide a beneficial solution to the problem. It holds the promise of being able to generate a locally usable energy product with local labor, thus boosting the local economy.

Pyrolysis of biomass can yield significant combustible liquid products. Because of its abundance and re-growth potential, biomass is an attractive source of renewable energy. Furthermore, there are many sources of waste biomass material, whose low cost facilitates cost-effective conversion to liquid fuel. However, the technology to do this is far from mature. Pyrolysis is one of many technologies for converting biomass to liquid fuels. At present, very few commercial organizations have designed and operate such systems. Consequently, the economics of this technology are not well enough understood for many potential applications. Challenges exist, including a need to minimize transportation and other costs while maximizing fuel quality and product yield. Once pyrolysis is completed, there is a question as to how the material would be used. Liquid products from pyrolysis are often termed pyrolysis oils, or bio-crude. They are acidic, and unstable, increasing in viscosity and molecular weight with time. They can be refined to transportation grade fuels through hydroprocessing, or they can be directly combusted in boilers or low-speed engines. Three fairly recent review articles provide additional background information (Mohan et al. (2006), Bahng et al (2009), and Elliott (2007)).

Traditional and commercial pyrolysis plants process biomass at a centralized facility. The source raw material is inherently distributed, and consequently present commercial application of pyrolysis is as a secondary process. For example, plants are collocated around areas near sawmills and other industry where cost of transport is covered by the major product of the industry. This ameliorates the challenges associated with transportation, and also provides sized material without additional processing costs, as sawmills produce copious product sized well for fast pyrolysis. Alternatively, if one were to convert the biomass through pyrolysis to a more dense liquid at the site of growth, the economical transportation distance could be greatly extended. Pyrolysis products could then be sent for refinement, or the liquids could be used in custom designed applications within the community where they were extracted. This transportation challenge is the primary

motivation behind the model presented in this paper. Because pyrolysis is a comparatively simple process that results in densification of the wood, it may be an optimal solution for the regional problem. On-site conversion in a portable pyrolysis plant could densify materials for more economical shipping to a central location for distribution or to a facility that processes the materials to higher value product (i.e. liquid fuel). Such a process has potential not only for forested land management, as is the primary focus of this work, but also could be used for agricultural land management.

The next two tables list considerations that led to the decision to focus on portable pyrolysis. Table 1 focuses on the potential benefits, while Table 2 focuses on the challenges associated with the proposed solution.

Table 1. Perceived benefits of the proposed technology

Improved transportation model	Densification takes place early in the handling process, allowing much longer economical product shipping distances compared to other biomass use models
Infrastructure cost	One aim is to provide an economic benefit to the rural economies, and portable pyrolysis units may not be too costly for small land management companies to be able to purchase and employ
Local energy source	Having a local energy product provides an economic boost, as small communities often bring in energy products from outside, representing a drain on the local economy
Provides Jobs	Local energy production creates local jobs
Simplicity	Pyrolysis is comparatively simple, may require little external power or chemical input, and may be tractable for a field unit
Environmentally benign	Product streams are mostly similar to products from forest fires, and are therefore believed to be within an acceptable range of naturally occurring product such that they may not be a significant environmental hazard in the event of a spill or under normal waste disposal conditions
Green technology	This has the potential to provide a comparatively clean renewable energy source with a near-neutral carbon footprint and a short (tens of years) renewable cycle
Clean combustion	Pyrolysis oils have reduced mineral content compared to raw wood, and can be burned much cleaner as a consequence
Portability	The dispersed nature of biomass resource is one of the economic and energy challenges to cost competitiveness, which a portable system may help ameliorate
Diversity	A diverse national or regional energy portfolio is less susceptible to market fluctuations from a single or less diversified source
Independence	The U.S. currently imports a significant fraction of energy products used, with economic imbalance and energy security considerations currently resulting in promotion of alternative technologies

Table 2. Perceived challenges associated with the proposed technology

Lack of market for products	Pyrolysis oils do not presently have a high demand, and many of the proposed uses of the materials are immature
Economy of scale	Chemical processing systems are normally challenged by the economy of scale, resulting in higher profitability for larger plants
Technological maturity	Process optimization requires significant work, and a final design requires prototype iterations
Acceptance	Land managers and consumers may be wary of new technologies or departure from traditional management models, and will need to be educated on the benefits of the process before it is likely to be widely accepted
Lack of handling infrastructure	Pyrolysis oils are acidic and unstable, becoming very viscous with time, and require different treatment compared to other liquid fuels

These tables represent only high-level considerations. Many of these considerations are further explored later in this report. In particular, some of the benefits will be further examined, and the economic assessment is targeted to help quantify the potential profitability of a portable pyrolysis model.

Figure 1 shows a crude schematic of the conceptual model being considered in this study. A positive aspect to the pyrolysis process is that there are many potential uses for each of the product streams from the process. Since land management already is paying for the thinning of forests, costs associated with the harvesting of the biomass are not included in the model. Chipping of the cut wood is a requirement for processing, as whole trees or logs would be expected to yield high solid residual mass if they were fed directly into a pyrolysis furnace. This may be due to the insulating nature of the chars, the inability to heat the interior mass effectively, the inability of trapped gases to escape, or a combination of all these effects. Chipped biomass varies widely in shape and depends on the type of chipper used, but a common piece of chipped wood may have a high aspect ratio, and be typically 2-10 cm long, with the other dimensions being smaller than 1 cm. Since a majority of wood is expected to need to be chipped based on an understanding of how thinning operations currently function, this cost is factored in to this model.

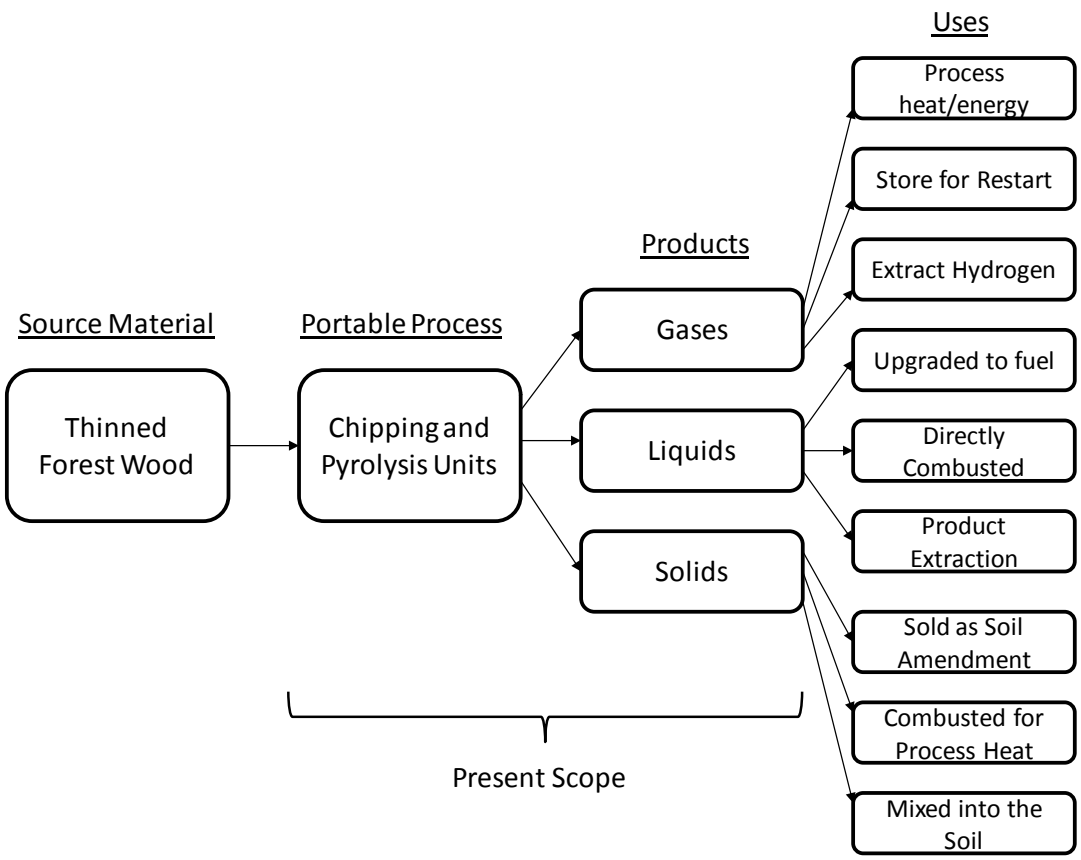

Figure 1. A diagram of the proposed process

The end use of the material will partially influence the economic model. Use of the gases to provide the pyrolysis energy is believed to be ideal, as the viability of a portable system would be challenged if a significant continual source of energy were required to sustain the operations. The experimental section to this report focuses on the prospects for the gases based on analysis of a bench-scale system. The end use of the liquids is not well studied, although it is suggested that the oils can substitute for fuel oils, be upgraded to petroleum equivalent fuels, or be used as tars in asphalt (see for example Czernik and Bridgwater, 2004 and Ringer et al., 2006 who review end uses of the product). Solids are essentially charcoal-like material. Because it lacks the additives that many commercial charcoals contain, bio-char has been proposed as a soil amendment, and is shown in some studies to promote healthy soils (Joyce, 2010; Lehmann, 2011). Understanding of the soil benefit mechanisms is immature, and careful further studies have been proposed to help improve knowledge in this regard (Lehmann, 2011; Brick, 2010). Such use is also proposed as a method to fix carbon. It is presently reported that optimal use of pyrolysis chars as soil amendments requires conditioning, and simply mixing pyrolysis chars into a soil may produce mixed results (Joyce, 2010). Conditioning involves composting with

other organic materials. The chars have a calorific value, and could be used for process energy if the system is designed to be receptive to this, as is suggested by Badger et al. (2011). This would create an ash waste stream, with low or negative co-product value. The solid product materials could also be co-fired with coal or burned alone in a boiler.

Conventional wisdom and much of the existing technical literature suggests 'fast' pyrolysis is optimal for wood pyrolysis if a liquid product is the target of the process. Fast pyrolysis is normally considered any pyrolysis taking place at high (i.e. 100+ºC/s) heating rates. Since biomass is not a good thermal conductor, there is a limit to the size of particles that can be pyrolyzed while still achieving fast pyrolysis conditions throughout the entire sample. In a traditional reactor, 2-6 mm (Bridgwater and Peacocke, 2000) is the largest a sample can be to still retain 'fast' pyrolysis characteristics. Ablative reactors can yield fast pyrolysis characteristics for much larger samples, but are normally considered too energy intensive to operate. The sizing requirement for fast pyrolysis suggests a need for very fine wood particles, and for significant pre-processing. Other characteristics of proper fast pyrolysis systems include a rapid quench, as secondary gas reactions diminish the quality of the product. Temperatures for fast pyrolysis are typically above 500°C, and liquid yields can be in the 50-80% on a dry mass basis. Solid char yields for fast pyrolysis are normally smaller than 20%, and can be below 10%. Slow pyrolysis normally does not yield significant oils (~20-30%) and yields higher char solid fractions (on the same order as the liquid yields or less). Maggi and Delmon (1994) compare slow and fast pyrolysis products and conclude that their differences are more substantial than the feedstock differences. But we propose that there is a continuum of product variations between idealized slow and fast pyrolysis regimes.

The literature only provides hints at performance in thermal and flow regimes that were not part of existing studies, and only very recent complimentary work helps confirm what is also shown in this study: that non-ideal pyrolysis conditions may still give fairly high quality and quantity of liquid yields (Puy et al., 2011). Because there are scarce data in the literature on the performance of pyrolysis systems under conditions idealized for portability, a system analysis was required to populate the economic assessment with data that are thought to be better representative of a system designed with portability in mind. Fluidized bed technology requires large blowers and centrifugal separation. Since these demand energy and for portability it is desirable to minimize the energy requirements, we elected to evaluate an auger system that may have lower energy demands. Fluidized bed system analysis was considered a back-up technology in the event that the auger system we initially designed was not able to produce significant yields.

The existing literature was found to contain insufficient data on the performance of portable pyrolysis systems. Therefore, further study was

required to obtain reliable data for input to an economic analysis. An experimental prototype designed to be representative of a scale portable system was constructed with design principles conforming to how one might construct an optimal portable system. Some of the motivations and considerations for performing the experiments are listed below:

- What yields are possible given a reasonable level of pre-treatment of the biomass?
- What is the effect of performing the pyrolysis in the effluent of the process (i.e., in a continuous gas loop)?
- What are the mechanical and heating energy requirements?
- What kind of condensers work best, can multiple stages provide helpful fractionation, and how should condensers be staged if a series of condensers is used?
- How reliable will the system be both in terms of maintenance and in terms of durability?
- Can the same system be used for significantly different feedstocks?
- What sort of labor and maintenance costs might be associated with the system?
- What are the implications of performing operations under conditions that may not be considered steady-state, like at start-up?
- What conditions produce the best product?

This list was put together prior to performing the tests, and represented the outstanding questions believed to be key to understanding the viability of the proposed solution (see Brown and Jepsen, 2009). The experimental section of this report provides answers to many of these queries, and will be shown to be helpful in populating the economic analysis with credible parameters.

1.2 Economic Analysis Background

The literature (journal articles and technical reports) includes numerous examples of economic analysis studies. Pyrolysis has been evaluated in technoeconomic studies in the past, and these studies contain information relevant to the current study. However, pyrolysis has not been examined for portable application at the scales presently considered and using the design principles presented in this study.

Ringer et al (2006) provide extensive background on technology and economic issues relating to large-scale pyrolysis oil production. They do a fairly comprehensive review of past and existing work on the topic, including health effect issues and cradle-to-grave analysis of issues.

Other relevant studies include the 'transportable' pyrolysis oil system studies (Badger et al, 2011 and Badger and Fransham, 2006). However, their concept of transportable is different from ours, 100 tons per day requiring a crane to assemble. Badger et al. (2011) value pyrolysis oils at $1.65/gallon as a fuel oil substitute, and project generation with year round operations. Char is also valued at "a conservative" $75.00 per ton. A return on investment is possible with $0.94/gallon, providing the process with significant margin according to the study. The earlier study is more focused on the infrastructure required for large-scale pyrolysis. Costs of storage tanks, shipping trucks, etc. are a focus.

Another relevant study is that of Polagye et al. (2007). They are focused on the residual materials from logging and thinning efforts in Washington State. Because their source materials are residual materials from the logging process, the materials are thought to be similar in size to what northern New Mexico forests typically yield. They consider pyrolysis, ethanol production, pelletization, and co-firing with coal. The pyrolysis model fits that of Bridgwater et al. (2002) where they consider diesel co-combustion of the pyrolysis products. They also look at scales ranging from 10 tons per day, up to 500 tons per day. A challenge is that they estimate only 14 tons per acre of biomass (compared to 20-50 tons per acre as suggested by Zachritz et al, 2000). Coal co-firing of the raw biomass is their lowest cost solution until shipping distances become large. The smaller scales are less economically viable, with 10 tons per day performing particularly poorly (worse by a factor of 3-4 compared to the larger scales on a cost per ton basis). Pyrolysis and pelletization are found to be most favorable under certain conditions.

Rogers and Brammer (2009) examine shipping costs for annual miscanthus and perennial wood chips for use in pyrolysis plants. The study estimates costs in British Pounds. Distributed and dedicated models are examined. They find distributed pyrolysis only makes sense for certain conditions. Other factors that were critical to the costs include the number of trips and the unloading times associated with shipping.

Other technoeconomic studies exist for pyrolysis. Cottam and Bridgwater (1994) estimate that upgrading pyrolysis oils to diesel is the most cost-effective use of pyrolysis oils. They also consider using pyrolysis oils as a medium fuel oil, or bio-naptha. Hydrogen extraction from the gas stream is also examined. Performance data are taken from previous work of Scott et al. (1982-1988). A more recent study (Bridgwater et al., 2002) compares biomass gasification, pyrolysis oil generation, and direct combustion. They find generating pyrolysis oils for co-injection in a diesel engine to be the most cost-effective end use for biomass.

A somewhat dated analysis, Gregoire and Bain (1994) examines the vortex reactor and conclude that the minimum viable selling point for pyrolysis oils is $0.11/kg, or converted assuming a density of 1200 kg/m^3 to $0.50/gallon. Another somewhat dated analysis (Solantausta et al., 1992) has some

relevant assumptions and methods to the present economic study. They conclude that pyrolysis oil substitution for fuel oil and zeolite upgrading of pyrolysis oil for transportation fuels have particular promise.

Islam and Ani examined the technoeconomics of rice husk pyrolysis. They found pyrolysis was better than catalytically upgraded pyrolysis, and gave 9.1 $/kg production costs. This looks promising, since this translates to a gasoline energy equivalent of around $1.10/gallon. However, because the study applied to Malaysia, they benefited from labor costs of $1.00/hour, so it is not clear that this technology would be as promising using U.S. standard labor rates that are much higher. The cost-effectiveness finding is particularly remarkable since char yields were around 50%, with liquid yields only 40% of the input mass. Woody biomass is expected to give superior yields, and therefore have better economic productivity.

Pan et al. (2008) examined the costs of harvesting and hauling small diameter trees distances up to 36 miles. They find they can do the harvesting and delivery for around $50-75 per bone dry ton. About half of that was shipping cost, while the other half was harvesting.

Even though the studies are focused on corn stover, Wright and Brown (2007), Wright et al. (2010) and Brown et al. (2011) provide interesting background information. They find that there is not an infinitely increasing economy of scale for biomass, which is primarily due to the distributed nature of the source material. There is a plant size range where return is flat. They also find that if you are upgrading pyrolysis oils to a transportation grade fuel, the source of the hydrogen (purchased on the market or synthesized from the biomass) makes little difference on the outcome of the economic analysis.

A few summary points from the data in the literature described above are highlighted:

- Economies of scale are important: small and mobile systems are not typically found to be cost-effective compared with larger systems[1]
- Use models vary widely, and have an impact on the analysis. Regional studies are important because they take advantage of local strengths and can avoid local weaknesses

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[1] Most of the studies that are significantly critical of the smaller scale pyrolysis models are quite recent, and were uncovered after the present project was proposed and initiated. Some of the subsequent points about regional dependencies and process specifics make the present study still sensible in light of the findings of the previous studies. Had they been available at the time of project inception, this study might have taken a different form.

- Pyrolysis oils generation under optimal conditions can be shown to be economically competitive with fossil sources of energy
- Infrastructure for the end use of pyrolysis oils is not mature, and represents an obstacle to the adoption and adaptation of these technologies
- There are many methods to perform pyrolysis and utilize its products, and fuel sources and products are not all equal
- Performance differences are expected to be found with differing use models
- Many of the historic technoeconomic models are deterministic, and do not assess process and economic uncertainties which might be quite high considering the lack of maturity of the technology and lack of experience with actual processes
- All technoeconomic studies evaluated suggest biomass pyrolysis has use models where it may be profitable

The historical work is important to this study. It provides a source for model assumptions, and allows our results to be compared to other similar work.

Challenges exist with all economic analyses. Because valuations are fluid with time, it is difficult to project accurately to future conditions. It is also risky to use dated valuations for the same reason. Market values drive certain costs, and these are influenced by consumer sentiment and other complex factors. It is not unusual to have years within which the price of fossil fuels varies by a factor of two. Part of the risk associated with capital investments is that economic factors become adverse to the profit goal. As with any risk, the reward when the economic factors cycle positive in favor of a technology can also be significant.

Governmental influence can also play a role in the valuation of products[2]. For novel technologies like pyrolysis, it is anticipated that the regulatory effects of government intervention might be mostly positive. However there could be factors that work against this technology. A significant portion of the lands in Northern New Mexico are federally and state managed forests.

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[2] The state of New Mexico currently requires consumers be offered power from renewable sources, and mandates an escalating fraction (with time) of power generation from renewable sources through the Renewable Energy Act:

http://www.nmprc.state.nm.us/utilities/renewable-energy.html

The American Clean Energy and Security Act of 2009, also known as the Waxman-Markey Bill came close to regulating carbon emissions, passing the U.S. house but failing in the U.S. senate.

The availability of the biomass for pyrolysis will depend on the sentiment of the land management decision process.

The objective of the current study is to examine regionally specific information and to determine if there is a model whereby the businesses that harvest biomass may generate a commercially viable product through pyrolysis. A goal is to outline the major assumptions and to present the techno-economic analysis in a way that facilitates the understanding of the potential of the proposed technological solution.

1.3 Objectives

This report has two distinctive sections. The first focuses on experimental measures designed to uncover operational behavior of a system designed to function in a portable environment. The second portion details the results of an economic analysis designed around the technology employing assumptions and methods that might be consistent with a final design. Attractive economic analysis results could provide incentive for investment in this technology. Ultimately, it may be seen that the two sections of this document are complimentary. Since most previous performance studies on pyrolysis were not done with conditions in Northern New Mexico in mind, it may not be suitable to conduct an economic model directly on the basis of the historical performance data of pyrolysis technology. Previous work typically used different methods than would make sense for a portable system, so performance data from those studies may not be applicable to the present application. Design of a dedicated (non-mobile) plant system would have inherent differences from one designed for portability because the two designs would have different requirements. For example, obtaining electrical power at a fixed plant would not be a difficulty. In the field, designs which minimize external power requirements are more important. This report details experiments that were designed to inform the economic analysis being done with the end goal of understanding the potential for portable pyrolysis processing of biomass.

2 Experimental Methods

The scope of this project did not extend to prototyping or to full-scale demonstration. The experimental work is therefore focused on providing data that can better elucidate the potential function of a portable pyrolysis system. With bench-scale experimental data, there is a risk projecting the performance data to full-scale. However there was a need for data at the start of this study to help answer certain technical questions and to generate baseline performance data.

Liquid yields are understood to be optimized for higher heating rate processes (see for example, Mohan et al, 2006). Rapid quench also helps preserve the yields, as secondary reactions will occur in the gases after pyrolysis, producing additional fixed gases (see for example Evans and Milne, 1988). Conventional wisdom suggests fluidized bed technologies or particle ablation reactors are optimal for pyrolysis. Indeed, these types of reactors tend to be superior at providing high heating rates necessary to optimize liquid yields. However, they require energy to fluidize the system or provide cyclonic motion and tend to result in large amounts of char and ash fines comingled with the product stream. Mineral content of the pyrolysis oils is believed to relate to the stability of the product (Ringer et al., 2006). This is typically mitigated with cyclonic separators at the exit of the furnace, requiring additional energy, yet still allowing some particle pass-through. Since we are considering portability as key to this study, we elected to build and study a system with potentially lower energy requirements. Our auger fed tubular furnace is believed to function with low energy input, the magnitude of which is part of the study. The expected decrease in liquid yield performance compared with a fluidized bed system may be offset by the reduced front-end energy requirements.

For this series of tests, several simplifications were made. Instead of using actual forest slash material, we elected to use commercial wood pellets. The general size and shape is reasonably approximate of what would be expected in the field, and the bulk of the material content is believed to be similar as well. The pellets are around 0.5 cm in diameter, and 1-2 cm long. Pellets are believed to be a superior fuel to slash material, with lower ash and water content than is expected from forest trimmings that would have more bark, leafs and needles mixed in with the core wood. Previous work details the constituency of many forest materials in the Western United States in this regard (Brown et al., 2003). Soft-wood pellets (primarily pine wood from the Show Low, AZ pellet plant) were selected because commercial feeding systems were easy to find and because the pellets were locally marketed and available. The pellets are thought to be similar in origin to the wood that would be found in Northern New Mexico, and reasonably representative of the bulk wood behavior. A full system design would require significant effort to assure consistent feeding of the materials as they are expected to be under field conditions. The feedstock simplification was made to achieve system

performance data under the assumption that the scaled-up system performance could be made similar with further engineering design work.

2.1 Experimental Details

Figure 2 shows a simplified schematic of the general arrangement. Our system was designed with two condensers, two motorized augers (Bodine Electric Company 24 V transport motor and Hansen Corp. 12 V lift step motors), a Thermcraft Inc. 230 V 22 Amp furnace, and a Cole Parmer 12 V 1.0 Amp pump. A Vibco vibrator was normally located on the feed hopper, and was helpful to achieve a steady feed of biomass through the system. Figure 3 shows a CAD rendering of the furnace. Fundamentally, the furnace, two motors and the pump are the minimum required components for this system. A thin-wall steel tube with a 10.16 cm (4 inch) outer diameter was used to house the biomass inside the furnace. Condensers were custom constructed. The condensers require cooling, which could be done passively through natural convection. Contrary to the Figure 2 schematic, for most of the test presented here the re-circulating gases were routed through the first condenser to provide cooling. In a few of the final tests, cooling water was used instead of the gases (the 800°C tests and a few others at lower temperatures). The counter-flow condenser configuration improves the system energy efficiency through a regeneration step. This type of energy management methodology is expected to be replicated for a larger-scale system to manage the energy in the system and improve the efficiency. Refrigerated circulating water was used to cool the second condenser. We report data from a Stage 3, which is a euphemism for product that was recovered that condensed past the end of the second stage. We believe this to be due to fine mist passing through the condenser for lack of collisional coalescence of the aerosol to a size where it would fall out of the flow. The Stage 2 condenser exit temperature was approximately 0°C. Throughout the testing, various passive methods were employed to enhance recovery of these materials, none of which proved sufficiently satisfactory that they merit recommending. Historical work suggests electrostatic precipitators can help enhance recovery (e.g. Ringer et al., 2006). These were not employed, but could be considered in subsequent work.

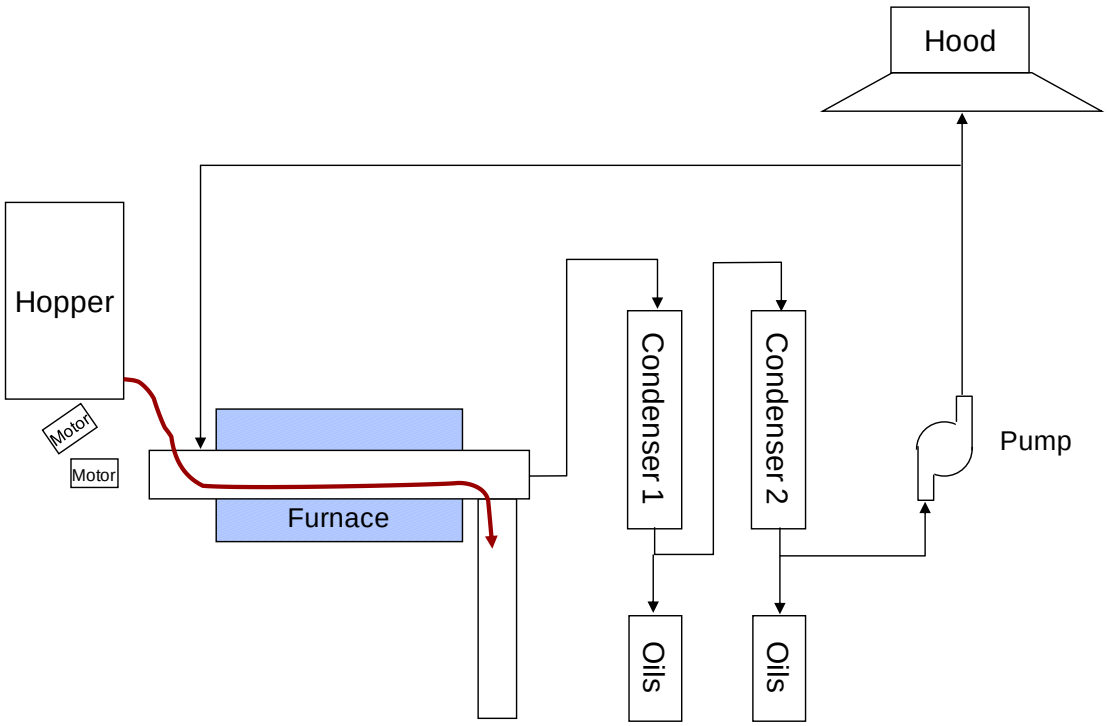

Figure 2. A rough schematic and flow diagram of the pyrolysis system.

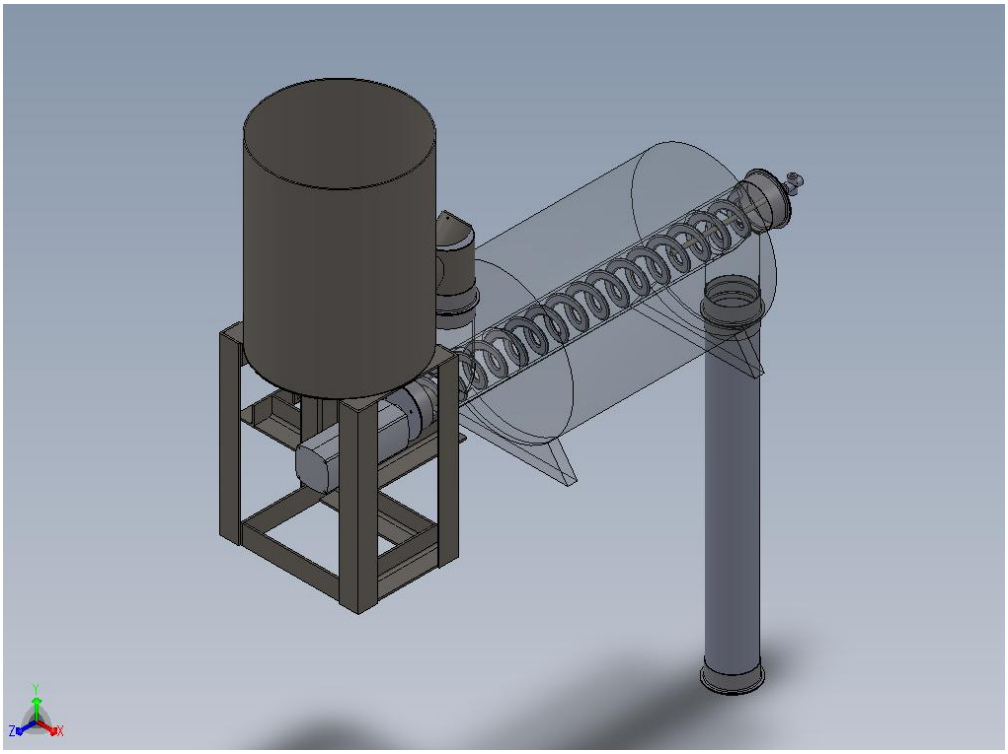

Figure 3. A rendering from a technical drawing of the continuously fed bench-scale system.

Figure 4. Two photographs of the pyrolysis system.

Condensers were arranged on a rack, oriented diagonally, and periodically cleaned. Figure 4 shows photographs of the system. The excess gaseous product from the system was typically ignited so active burning consumed the volatile material as it entered the hood. Flames were typically 10-25 cm long, clean of visible soot, and would vary in color from yellow to blue depending on furnace temperature. They were photographed with a digital camera. Multiple condensers were used as opposed to a single large condenser under the theory that the condensation stages provided a simple way of segregating pyrolysis products that may make sense for a full-scale design. In particular, the water content may be pre-separated. This could provide a high-quality product from one stage, and a lower from another without resorting to any costly post-processing steps.

2.2 Analysis Methods

A variety of methods were used to monitor and to deduce the performance of the pyrolysis system.

Thermocouples (type-K) at various locations were used to monitor the progress of the system during all testing. They were located at various points along the furnace and at several pre- and post-condenser locations. Significant departures from steady state values were good indicators of feeding irregularities, and active monitoring of these allowed for consistent testing. These thermocouples have an ANSI standard accuracy of +/- 2.2°C under 400°C, and +/- 0.75% of the reading above 400°C. They were output along with the current measurements through controller cards to a standard data acquisition personal computer.

Solid material analysis was performed through Proximate and Ultimate Analysis for raw material, chars at several temperatures, and liquids from

the condenser stages for a furnace temperature of 600°C. ASTM standard tests D3172, D3175, D3176, D3302, D5373, D5530, and D6316 were followed. This analysis was performed by Columbia Analytical Services Inc., and has a reported accuracy of +/- 5% of their reported values.

Mass of the products was compared to the initial samples and weighed on an OHAUS EC series lab scale. The resolution on the instrument was 0.1 g.

Electrical Current was monitored for the furnace, the pump, and the two motors. Voltage drop across a known serial resistive circuit was monitored to extract current. The current signal was recorded on the data acquisition system with the thermocouple traces through a series of data acquisition modules and recorded on a laptop personal computer. The power supplies delivered rated voltages. The power requirements were extracted by averaging over time the product of the current and voltage supplied to the various components.

Gas analysis was performed using an Agilent 6890 gas chromatograph equipped with 250 µL gas sample loops on gas sampling valves. Fixed gases were separated using helium carrier gas and a Hayesep A, 10' x 1/8" 80/100 mesh, packed column with thermal conductivity detection, and organic gases were separated using helium carrier gas and a J&W DB-1 60 meter x 0.53µm x 1.5µm df capillary column with a flame ionization detector. In addition, the organic gases were analyzed as total hydrocarbons as methane equivalent by replacing the DB-1 column with a 1 meter x 0.53 µm uncoated capillary column. Hydrogen, oxygen, and nitrogen analysis was performed using an Agilent 5890 gas chromatograph equipped with a 5 mL gas sample loop on the gas sampling valve and were separated using argon as a carrier gas and a Supelco 5A molecular sieve 33' x 1/8" 45/60 mesh packed column with thermal conductivity detection. Where possible, quantitation of gaseous species was determined by comparison to gas standards of known concentration. Gases were extracted for later analysis in evacuated stainless steel containers by opening a bleed valve.

Titration was performed for water in the samples using a Mettler-Toledo DL39 Karl Fischer coulometer autotitration instrument and standard Karl Fischer reagents and methodology.

Liquid analysis was attempted using a modified ASTM D2887, Standard Test Method for Boiling Range Distribution of Petroleum Fractions by Gas Chromatography on an Agilent 5890 gas chromatography equipped with a 5972 mass spectrometer. The GC column used was as a Restek Rxi-5ms 60 meter x 0.32 µm x 1.0 µm. During the analysis it was observed that the sample liquids were largely insoluble in the solvent selected (methylene chloride), and this analysis was not pursued. A few liquid samples were also sent for proximate and ultimate analysis with the raw and char samples.

3 Experimental Results and Discussion

3.1 Conversion

Most tests were performed with 2000 g wood samples. The samples were pre-dried, losing on average 4.4% of their original mass. A few tests were performed with larger samples. In addition to the sample size, furnace temperature was varied. Lift and translation motor speeds were also varied. At higher temperatures, lower solid yields may be achieved for higher motor speeds. At lower temperatures, lower translation speeds were necessary to reduce the char residual mass down to the 20% level that was typically achieved for the other tests. The roughly 20% char yield was experimentally determined to be typical of reasonably full conversion, as a variety of conditions were tested before the standard operating conditions for the tests detailed in this report were finalized. Gas pump speeds were also varied, but to little discernable effect. Figure 5 shows a summary plot including results from various furnace temperatures. Liquid yields were normally a little below 60%, with a decrease at higher temperatures. Char yields were typically around 20%, increasing slightly at lower temperatures. Gas was determined by difference, and generally increased with increasing temperature.

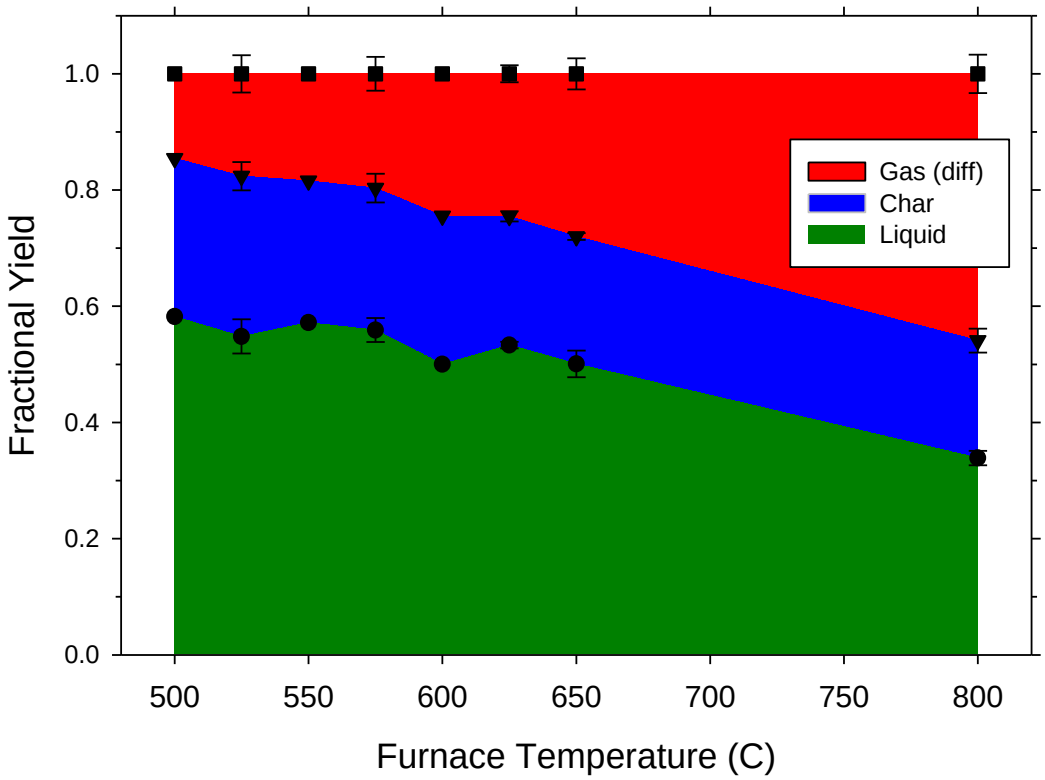

Figure 5. Mass conversion summary for pyrolysis tests.

Standard procedure involved taking apart the Stage 1 condenser and cleaning after a test. There was a propensity to form deposits at the entrance to the first condenser stage. This was mitigated by several design iterations during the early phases of testing, and it is also mitigated by performing the pyrolysis at lower temperatures. The deposits formed more rapidly for the higher temperature tests. This represents a small mass loss in the system that was not quantified in these tests. The gas product as shown in Figure 5 is therefore thought to be a little high on account of the mass lost to deposit formation.

Subsequent analysis will differentiate between liquid products of the condenser stages. Condenser temperatures are therefore important. During the tests, the temperatures typically varied within a narrow range at the exit of the Stage 1 condenser. An increase during the test of 5-10°C was typical. Across all tests, there was a little more variability in temperatures, but Stage 1 exit temperatures were normally 60-80°C with a slight increase during the test when operating Stage 1 with gas cooling. Using water cooling, the exit temperature was closer to 10°C. At the entrance to the Stage 2 condenser, temperatures were typically 30-40°C for most tests (gas cooled Stage 1). The difference is due to thermal loss in the tubing between the condensers, and probably mostly due to conduction through the tubing near the water cooled entrance to the chilled water in the Stage 2 condenser. The chilled water resulted in Stage 2 condenser exit temperatures being very near 0°C.

3.2 Liquid Analysis

Product from the first stage (see Figure 2) of the condenser was the most viscous, and with time there was a tendency for material to sometimes separate to form a more viscous material at the bottom of the container with a less viscous material on top. In some cases, the full sample became very viscous such that it did not flow. Product from the second stage was less viscous, and appeared much like darkened water. With time, this product also exhibited separation. The third stage product did not separate, and was more viscous than the second stage product.

Liquid products from three tests representing three temperatures were analyzed for water content by titration. The products from each condenser stage were analyzed separately. These results are shown plotted in Figure 6. Most of the water was recovered in the output of the Stage 2 condenser. This suggests that staged condensing can indeed be used to provide product of increased quality (i.e. lower water content). Overall, water content was between 30-35% with a slightly increasing trend with increasing temperature. This is high when compared to other pyrolysis studies detailed in the literature (Puy et al., 2011; Mohan et al., 2006). Beaumont and Schwob (1984) suggest that liquid water yields from wood pyrolysis can be mitigated with higher gas flow rates, which may make sense to examine in

subsequent work. Water could also be formed by partial oxidation. These experiments are not sufficiently detailed to distinguish between the proposed water formation mechanisms.

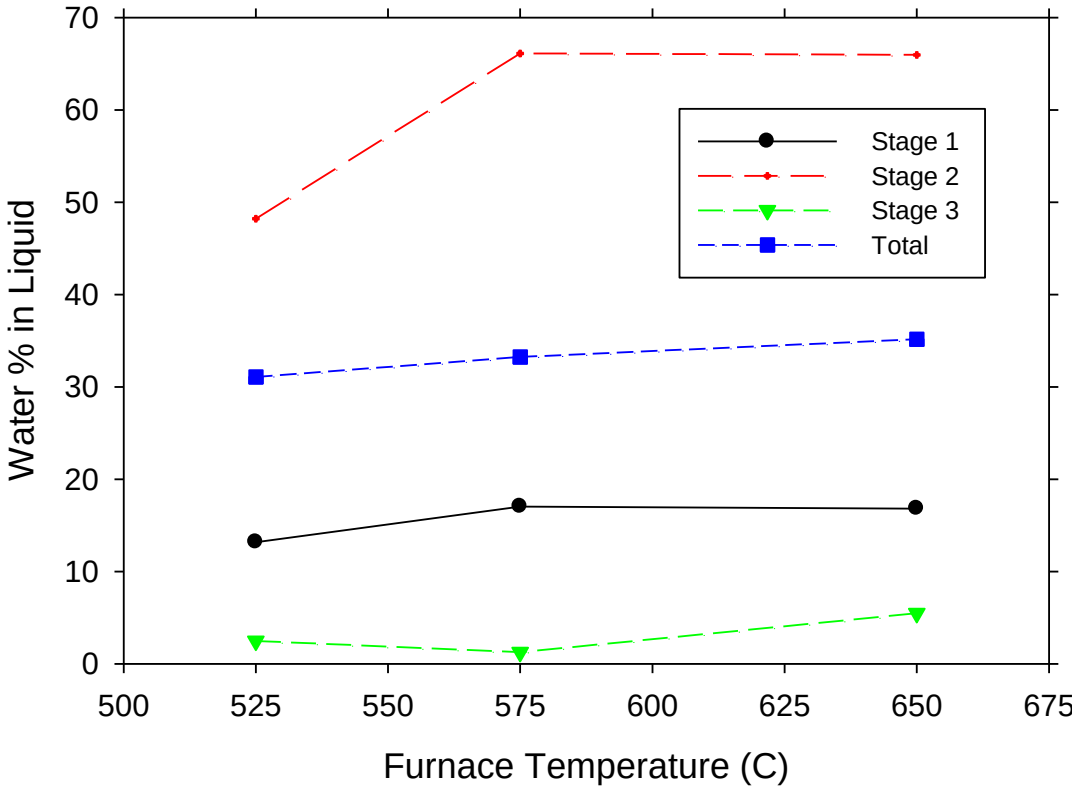

Figure 6. Water yields from three tests on a mass basis.

Further analysis of the liquids was performed as part of this study, but is not reported herein. This is because there are numerous more comprehensive existing studies of this nature, and products can be assumed to be similar in nature (see for example Evans and Milne, 1988; Ingram et al, 2008; Puy, 2011; Ortega et al., 2011).

Further interpretation of the data requires knowledge of the yields in each condenser. Some representative data to this effect are found in Figure 7, and correspond to the cases for which proximate and ultimate analysis were performed. These results are typical of operating conditions; the Stage 3 product never exceeded 30% of the yield. The Stage 1 and 2 products were typically around 40% of the yield. Exceptions are when the chiller was used for Stage 1 and for the 800°C case, where Stage 1 yielded 70-90% of the liquid.

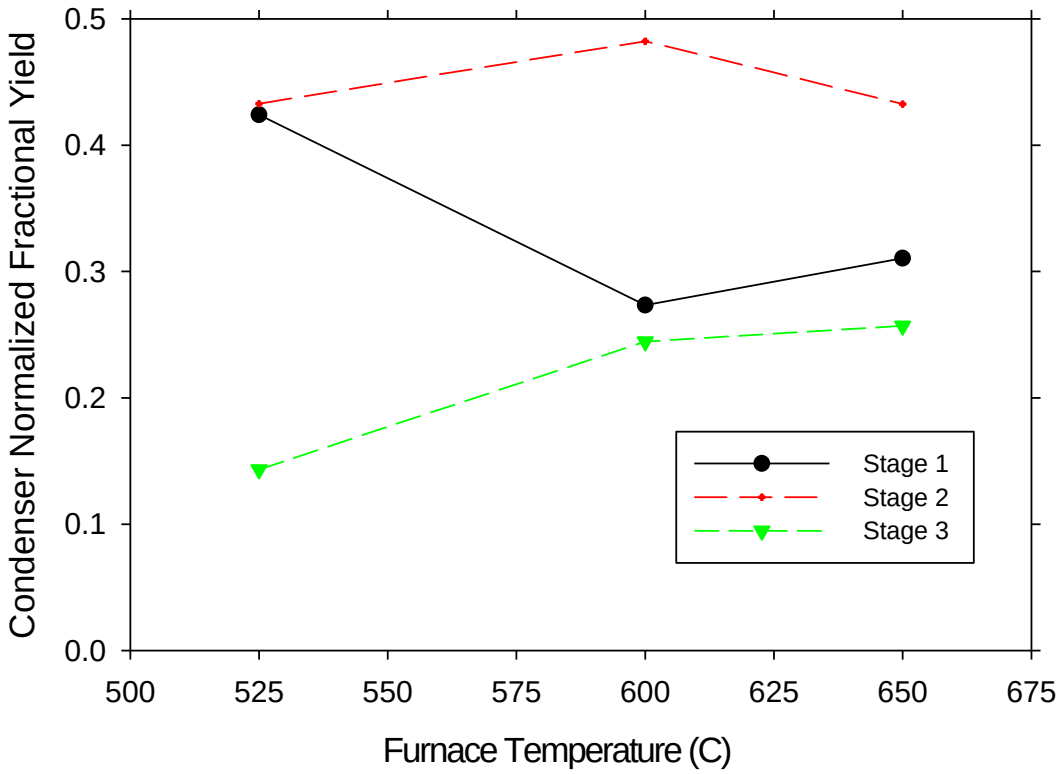

Figure 7. Fractional liquid yields from three tests on a mass basis.

Analysis of heating value was performed for one series of 600°C liquids, as part of the proximate and ultimate analysis by stage. The heating values results reported for Stage 2 were not credible, likely due to the fact that the liquid had separated by the time it was analyzed. The heating value can be projected based on the assumption that the water-free portion has a similar heating value to that extracted from the other two stages. Higher heating value (HHV) results projected back to the mixed product suggest a value of 15.8-18.2 MJ/kg for the heating value of the oils on a wet (as received) basis. The analysis showed that on a dry basis the Stage 1 and Stage 3 oils had a HHV of around 30 MJ/kg. These results are in slight conflict, as the dry basis HHV analysis results are higher than would be expected based on the measured liquid water yields. The differences likely have at their origin the differences in the analysis methods, and are representative of the uncertainty in the heating values of the product.

3.3 Gas Analysis

Emphasis is given to the analysis of the gaseous products. This is because there is less information in this regard in the literature. Also because the gases are being relied upon in the present design model for process energy,

and the recirculation gases are the carrier gases used as the inert for pyrolysis.

Table 3 shows gas analysis results for eight samples taken from the exit of the Stage 1 and Stage 2 condensers, four at 650°C and two at the other temperatures. They were sampled at least an hour into the test, attempting to assure that the gases sampled were representative of steady-state conditions and not of start-up conditions. One 575°C sample had high oxygen and nitrogen compared with the rest of the tests, suggestive perhaps of an increased inflow of air to the system at that time or a leak. No attempt was made to purge the air from around the pellets prior to injection into the system. This was deemed to be typical of how a system like this would function in the field. It may make sense or be worth considering routing the combustion products from the gases through the inlet to reduce oxygen comingled with the biomass feed in a full design. This may ultimately be incorporated in a pre-drying stage that is not a part of the current design. This might help purge the oxygen, which presumably does some indeterminate oxidation of the biomass product in the present system.

Table 3. Average gas molar percent analysis results including standard deviation (σ) from two samples at 525 and 575°C and four at 650°C.

	525°C		*575°C*		*650°C*	
	Avg.	*σ*	*Avg.*	*σ*	*Avg.*	*σ*
Hydrogen	1.29	0.01	1.60	0.48	4.45	0.17
Oxygen	2.23	0.28	4.55	3.97	1.19	0.44
Nitrogen	14.50	1.56	23.20	15.13	9.83	2.14
Carbon monoxide	33.25	1.06	29.90	7.35	42.43	0.95
Carbon dioxide	41.00	1.41	26.45	6.58	18.88	0.87
Methane	3.05	2.05	7.95	2.05	11.80	0.36
Ethylene	0.70	0.00	1.10	0.28	2.60	0.08
Ethane	0.40	0.00	0.75	0.21	1.20	0.00
Propylene	0.45	0.07	0.75	0.21	1.40	0.00
C4's	0.30	0.00	0.50	0.14	0.83	0.05
Total	97.15	1.34	96.75	1.77	94.58	1.42

Since it is proposed that the gases may be combusted to provide the required energy to the portable system, further analysis of the gases is warranted. Interpreting the results of the gas analysis in terms of energy availability requires some assumptions. First, the total gases analyzed were around 3-5% short of full recovery (i.e., total is below 100%). We speculate these missing species may be higher-order hydrocarbons, containing significant energy. Indeed, the gas chromatographs of the trace species in Figure 8 and Figure 9 at two different temperatures suggest furanic and aromatic compounds as trace matter in the gas streams. If this is the major constituency of the unrecovered portion, there might be a significant increase in the heating value of the gases compared to the more conservative

assumption of assuming those to be inert products. Using standard gas combustion energy values, we may approximate the combustion energy for the pyrolysis gas. We are using a lower heating value (LHV) approximation since it would be difficult to design a system that recovers the latent energy in the water vapor. Table 4 shows the species combustion energy calculated from molecular heats of formation found in Kuo (1986). The heat of formation used for C4's was selected from that of n-butane (C_4H_{10}).

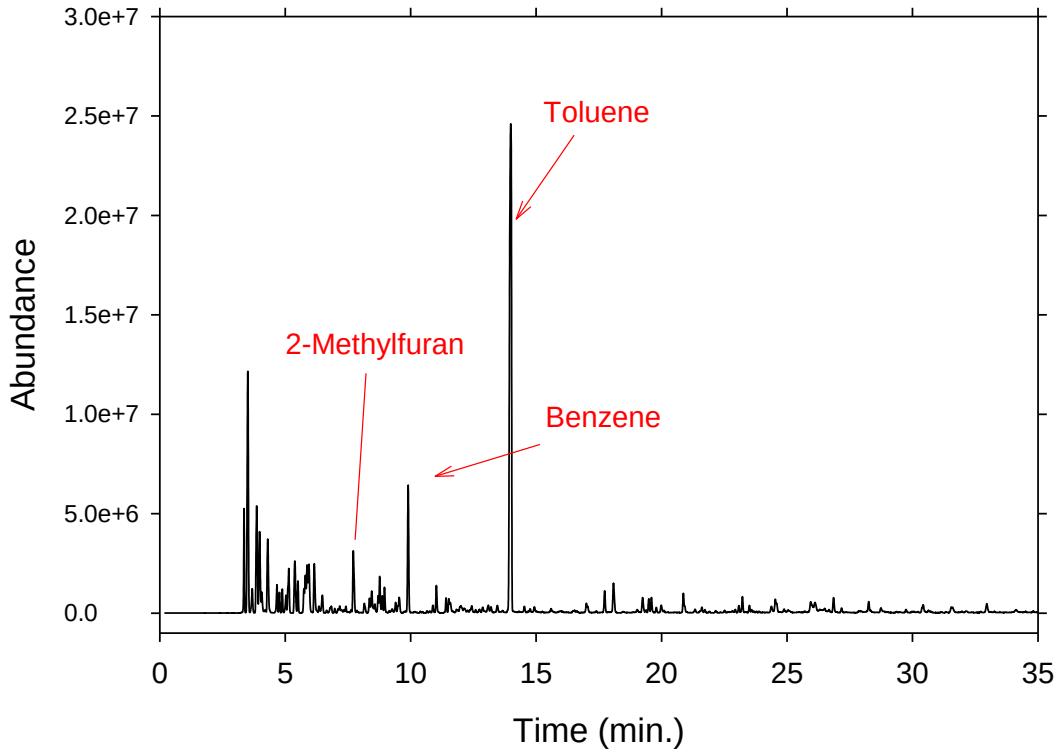

Figure 8. Trace gas hydrocarbons from a 650 °C GC/MS analysis

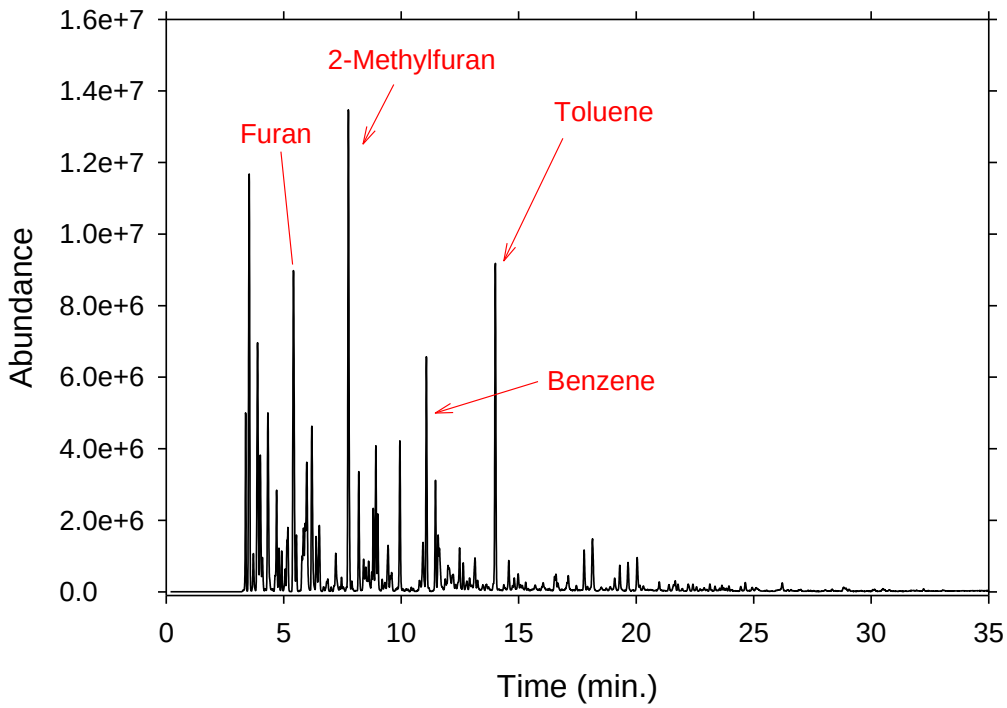

Figure 9. Trace gas hydrocarbons from a 525 °C GC/MS analysis

Table 4. Combustion energy calculated based on heats of formation from Kuo [7].

Species	Energy (LHV) *kJ/mol*
Hydrogen	133
Carbon monoxide	283
Methane	585
Ethylene	1107
Ethane	1103
Propylene	1601
C4's	2117

Since oxygen and nitrogen are not believed to be significant pyrolysis products, their contribution was normalized out, and the bulk normalized reading was assumed to be representative of the typical pyrolysis gas. Figure 10 shows the calculated combustion energy based on this methodology on a percent basis. Carbon monoxide is the most significant contributor to the gas energy, followed by methane at all temperatures. The relative contribution of methane increases significantly from 525 to 575 °C, mostly at the expense of the carbon monoxide. Error bars are plotted with the magnitude of one standard deviation, and are often small enough that they are obscured by the data points in the plot.

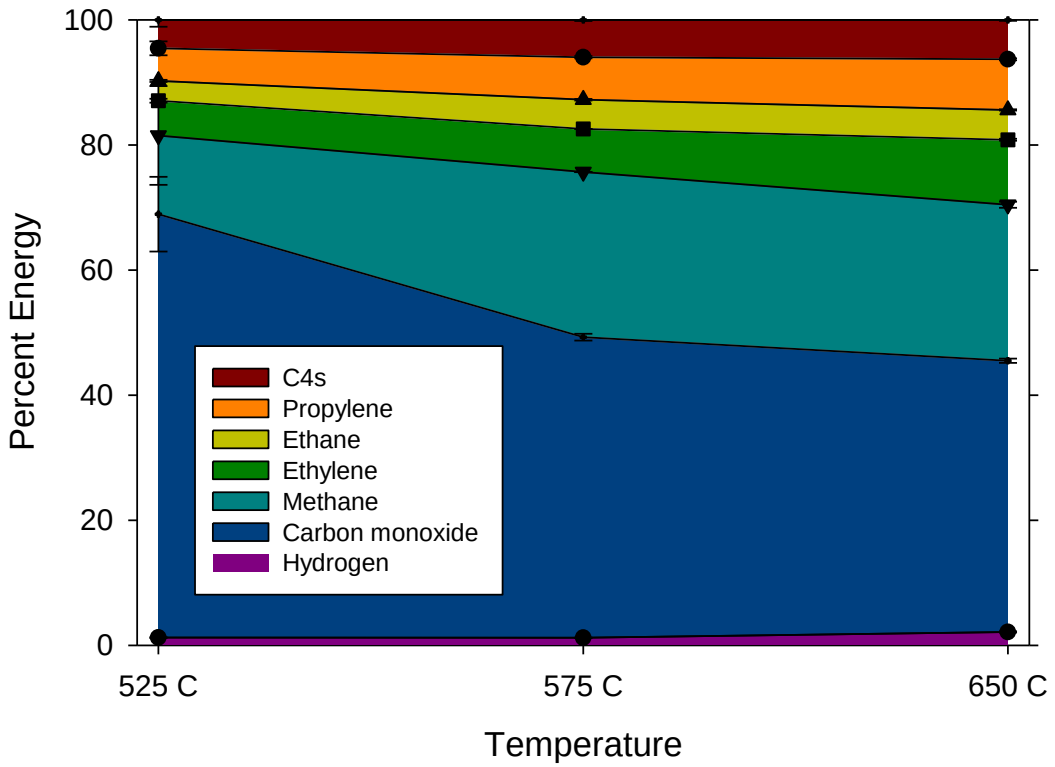

Figure 10. Calculated percent energy in the quantified gas species for three temperatures (Method 1).

There are different ways to deduce energy content of the gases based on the analysis presented here. One way (Method 1) is to simply take the contents of Table 3 and Table 4, and convert the measured molar concentrations to energy per unit mass. This is probably a lower estimate of the energy because it neglects the potentially energetic materials not recovered quantitatively in the analysis shown in Table 3. These are the results plotted in Figure 10. Another way (Method 3) involves assuming all unrecovered hydrocarbons are identical in heating value to that assumed for the C4's. This probably over-estimates the energy in the system, ascribing a conservatively high energy to the unknown. A similar plot of Method 3 energy is found in Figure 11. Samples were also analyzed in separate testing for hydrocarbons as methane equivalent. These data might be expected to give a more realistic estimate of the energy in the gas. The results from this method (Method 2) along with the other two are plotted in Figure 12. These data suggest that the pyrolysis gases from higher temperature pyrolysis are much more energetic in addition to being more abundant (as per Figure 5). Method 2 results fall between Method 1 and 3 results consistently. This is suggestive that the Method 2 results may be more accurate since Method 1 and 3 are thought to under- and over-estimate, respectively, the energy content.

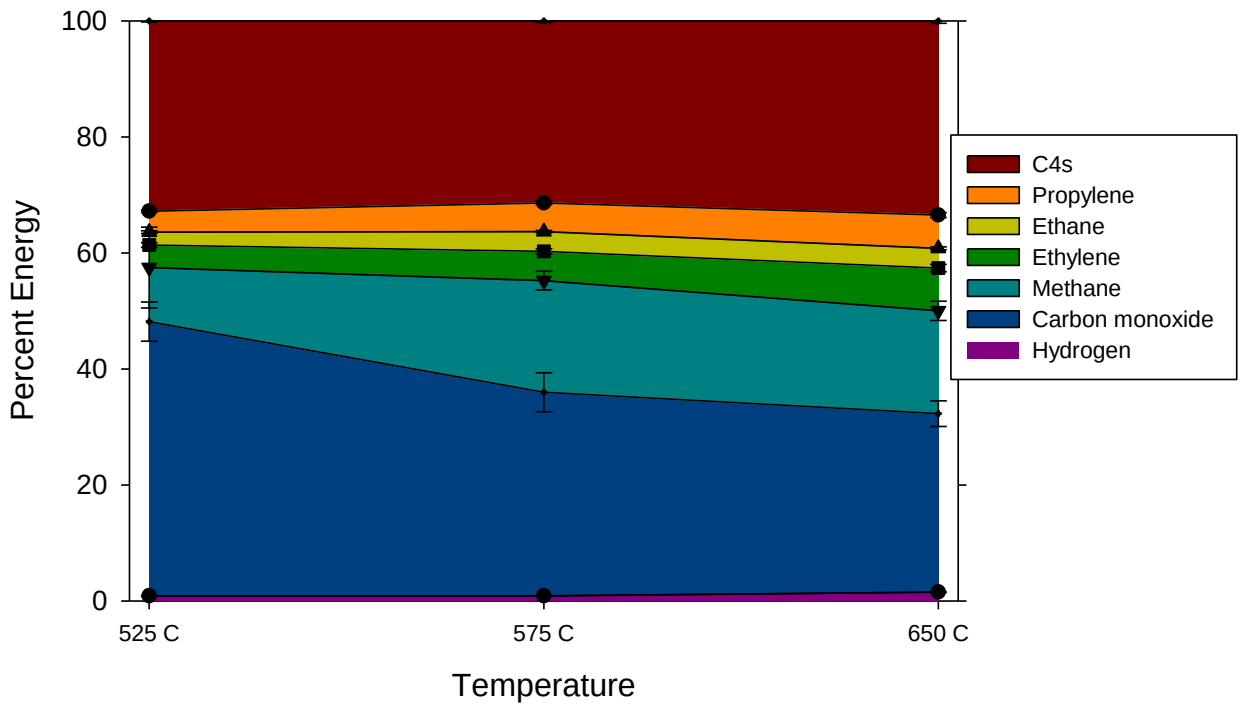

Figure 11. Calculated percent energy in the quantified gas species for three temperatures (Method 3).

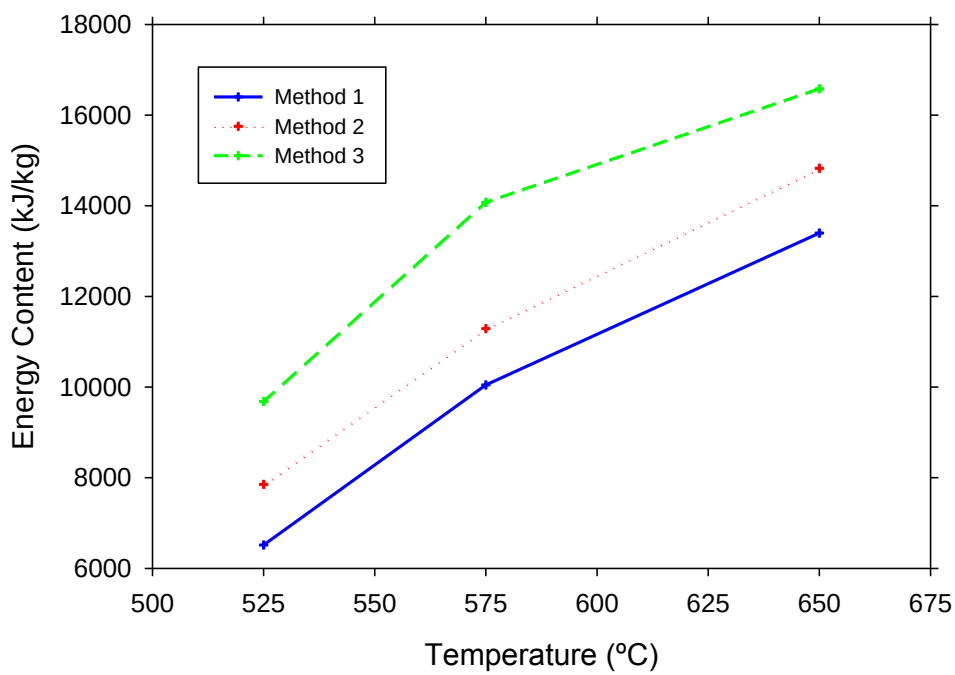

Figure 12. Calculated heating value of the gases using three methods.

The positive slope of the data in Figure 12 is suggestive of a potentially unstable process if the gas is to be combusted to heat the furnace. If temperature increases, gas yields increase, and the energy in the gases increase. This further increases the temperature because product gases are combusted to provide the pyrolysis energy. There is a potential for thermal run-away. This can be ameliorated by implementing system controls to prevent this type of feedback issue. This also suggests that increasing pyrolysis temperatures can provide more system energy from the gases if they are used for energy in the system.

As previously mentioned, the product gas stream was combusted under standard conditions, with a range of observed flames from the pyrolysis. The lowest temperatures produced the weakest flames, blue in color. The strongest flames came from the higher temperatures, more yellow in color. Example flames are shown in Figure 13. Each of these flames had ostensibly the same mass input, as the lift motor was run at the same speed for each. The translation motor in the 500°C case was run at half-speed and the 650°C speed was two times the other two.

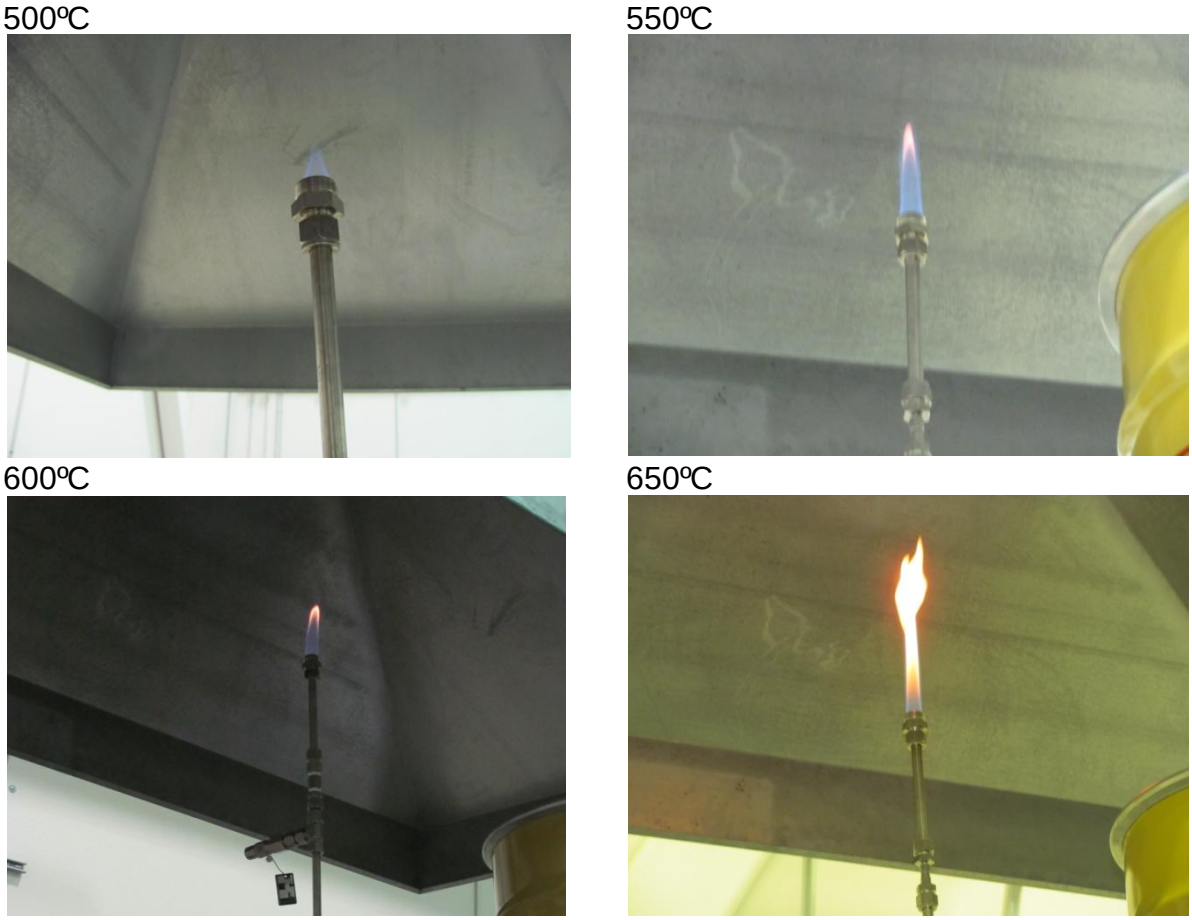

Figure 13. Gas product flames from various pyrolysis temperatures.

A point of uncertainty with regard to the gas products is the orientation of the exhaust tubes. A tee was arranged with a vertical tube allowing gases to escape the system from an otherwise horizontal flow. This configuration might preferentially exhaust more buoyant moieties, like hydrogen. Since the gases were re-circulated, there is a potential that the measured gases are not representative of the pyrolysis gases as is assumed in the above discussion. It is possible based on this theory that the gas analysis in this study may be skewed, resulting in an under-prediction of the lower molecular weight species.

3.4 Char Analysis

Several points stand out in the proximate and ultimate analysis results of the char. By comparing the char composition with the original (raw) material, inferences may be made on the fate of certain products. Table 5 shows selected results.

Table 5. Selected results from the proximate and ultimate analysis of the solids.

Material	Ash (as received) %	Nitrogen (dry) %	Carbon (dry) %	Volatile Matter (dry) %
Raw Pellets	0.49	0.10	51.45	80.84
Char, 525ºC	1.19	0.24	74.80	36.57
Char, 600ºC	2.20	0.26	75.77	33.15
Char, 650ºC	2.31	0.31	82.32	23.34

These results are based on single samples, so there is no indication of the test variability. These results are selected to illustrate a few significant points. First, the ash and the nitrogen found in plant materials are nutrients that originate from and can be difficult to replenish in the soils. Ash originates mostly from the inorganic content of the biomass. Removing these from land potentially creates a nutrient deficit. Over time, this can deplete the quality of the soil. The pyrolysis char samples show increased nitrogen and ash content relative to the raw material. Accurate projections of ash and nitrogen fate are not warranted based on the limited set of four tests shown here, but the data suggest at least 50% of the nitrogen and ash are retained in the char. This is indicative of these minerals and species being predominantly retained in the chars through the thermal process. The char fixed carbon is also potentially helpful as a soil nutrient. Assuming the char materials are strewn uniformly back across the land the biomass was harvested from or mixed back carefully, this process represents a much more sustainable utilization than others that would remove the biomass in its entirety. Because a portable pyrolysis system is designed to be in the proximity of the point of removal, there are much lower replenishment costs than if the biomass were removed and processed. Chars would not have to be shipped, eliminating a potential cost to maintain sustainability. This

represents one of the many potential advantages to the portable pyrolysis model being evaluated in this work when compared to other biomass technologies[3].

Contrasting the pyrolysis char yields with the solid products of biomass combustion, the minerals and nitrogen get hot enough under burning conditions that they volatilize. Ash can also entrain in the plume, and is a potential down-stream pollutant. The residual ash from burning also must be disposed of, and may not be as beneficial if it is mixed back into the soil of origin as ash rather than as char.

The volatile matter in the char samples (reported on a dry basis in Table 5) was surprisingly high. This suggests that longer residence times could result in decreased char yields by as much as 35%. Residence times were varied throughout the testing. However, as shown in Figure 5, the char yields are in good agreement despite the residence time and temperature variations, suggesting that the additional volatile matter fraction may not be easy to liberate.

The fact that the analysis in Table 5 suggests around 80% volatile matter in the raw material should not be misinterpreted as the maximum yield of gaseous products from the wood. Biomass is known to have a variable yield of volatiles depending strongly on the thermal process. Higher liquid yields would be reasonably expected under fast pyrolysis conditions, as has been well demonstrated in past work (Mohan et al., 2006). Credible yields can be as high as 70% for processes designed to optimize liquid yield with lower char yields.

Heating values for the chars were around 30 MJ/kg regardless of processing temperature, which is consistent with previously reported work (Mohan et al., 2006). This suggests that the char generated by this system is typical of char from other pyrolysis systems.

3.5 Power Requirements

In a field unit, it is desirable to minimize reliance on external maintenance including fuel and power. Table 6 shows the average power requirements of the essential components of the pyrolysis system. The furnace electrical power dominates the requirements. Only in the case of the vacuum pump

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[3] Based on colloquial knowledge of New Mexico soils, they are normally heavy in alkali mineral content, so removing some of the mineral would likely be beneficial, or at least irrelevant to future growth. However the nitrogen and carbon in the chars would likely be a helpful addition to the soils. Soil analysis is a complex issue and outside the scope of this study and expertise of the authors, so this assessment should be appropriately and accordingly valued and verified.

was the power draw in these tests steady. The lift and transport motors and the furnace each were cycled on and off to maintain a pre-determined temperature or mass flow rate. Table 6 represents the average values, but does not capture peak requirements based on our current design. Practical scale systems may have different design requirements in this regard. Standard deviations were large for all components, suggestive of a degree of uncertainty in the requirements. There were some trends to the power requirements that could be linked to the operating conditions: the furnace requirements tended to be higher for higher temperature settings, as would be expected. The vacuum pump power requirements increased when flow paths became congested.

Table 6. Average and standard deviation of electrical power requirements (in Watts) for the essential systems in the pyrolysis unit.

	Furnace	Vacuum Pump	Lift Motor	Transport Motor
Average	988	7.52	0.24	2.16
Standard Deviation	219	4.57	0.12	0.84

Figure 14 shows power requirements for the furnace and estimated combustion energy in the gas as a function of furnace temperature as described earlier in the Gas Analysis results section. Trend lines are based on numerical linear and polynomial fits of the data. Most of the tests were performed with about 14 g/min. of biomass fed to the system. To power the furnace from combustion of the gases, the energy in the gases must be at least as high as the furnace energy requirements. This analysis suggests that there is an energy deficit that needs to be made up before the gases can be used to power the furnace.

We performed a series of tests at higher mass feed rates at 650°C, as illustrated in Figure 15. Gas energy for the higher mass feed rates is significantly above the furnace requirements. A point of caution is that the gas product results were only performed on samples collected with the mass feed rate below 15 g/min. In estimating the gas energy in Figure 15, the gases are assumed to be the same quality and relative quantity at higher mass feed rates as they are at the lower condition where there are data. Figure 15 results suggest that the deficit in gaseous energy necessary to power the furnace from combustion of the gases may be closed simply by operating at a higher feed rate. A curious feature to this analysis is that the furnace power requirement was only fractionally dependent on the biomass mass feed rate. There are other energy loss mechanisms in the furnace system than the energy required to heat and pyrolyze the pellets. Two of the largest are probably standard thermal loss to the environment and the heating requirements of the transport gases, which would not depend heavily on the solid mass feed rate. In the current system, these loss mechanisms not dependent on the mass feed rate appear to be significantly larger than the energy needed to heat the additional solid feed. This suggests that by

increasing the mass feed rate it may be possible to reach a point where combustion of the gases can replace the electrically powered furnace for all temperature conditions given appropriate system design. The point at which the furnace can be heated by combustion of the product gases is expected to be easier to achieve for higher furnace temperatures, as gas production is enhanced at higher temperatures according to Figure 5 and energy content is also enhanced according to Figure 12.

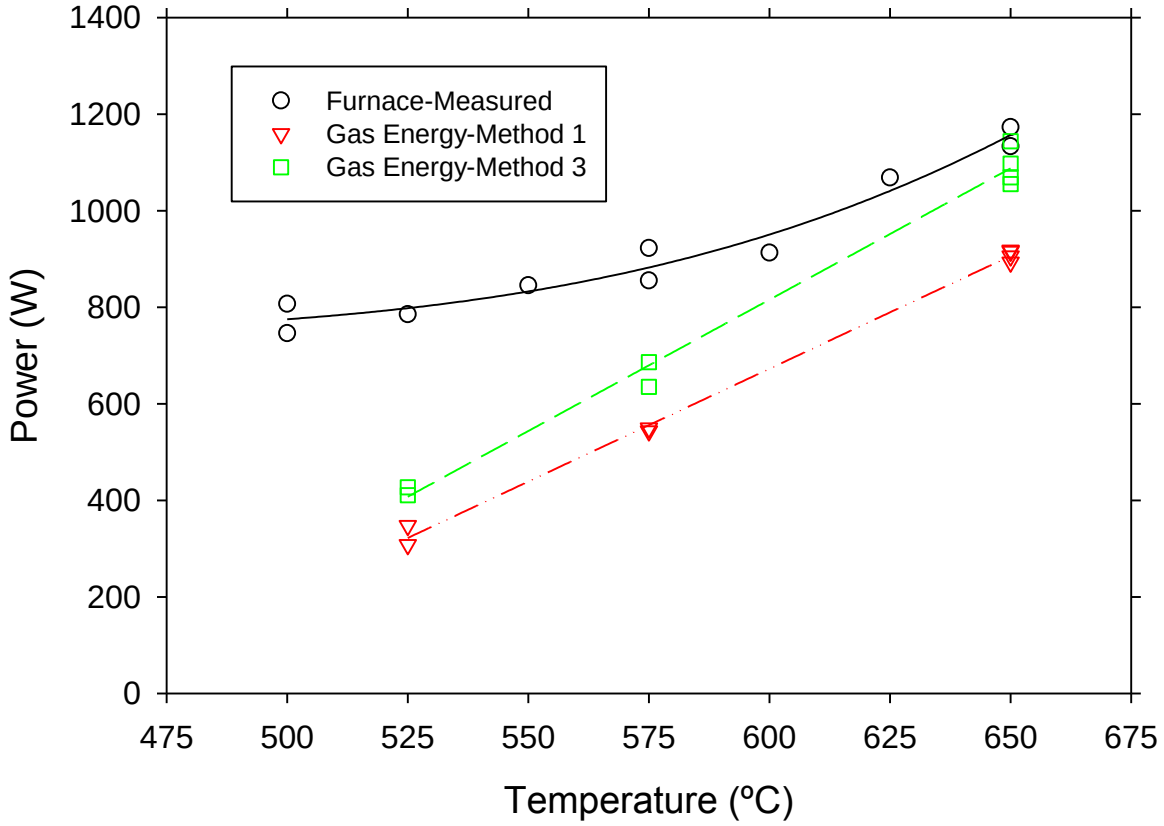

Figure 14. Power requirements for the furnace and power availability in the combustion gases for tests with feed rates of approximately 14 g/min.

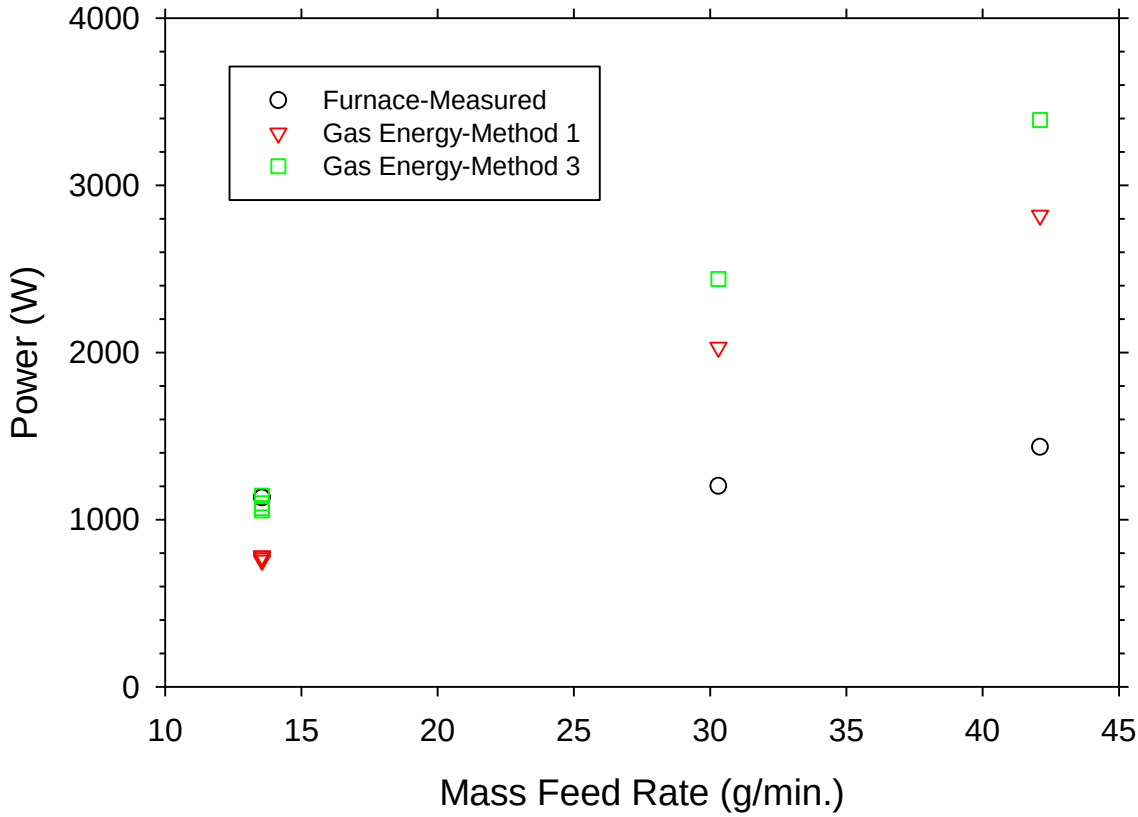

Figure 15. Power requirements as a function of mass feed rate for tests at 650°C furnace temperatures with estimated power from combustion of the gases.

Partial oxidation of the biomass or pyrolysis vapors may also contribute to the heating in the furnace. No special effort was made to purge the air around the incoming solids. This was by design, as a similar challenge of reducing the air intake to the system exists for a field unit. Results in Table 3 suggest that there are low levels of oxygen in the system. Oxidation reactions are expected to be exothermic, and would be expected to contribute to the energy balance in the reaction system. Power requirements may vary in a full-scale design depending on how this feature of the system is ultimately managed.

Badger et al. (2011) report energy requirements for a 100 dry tons per day pyrolysis system. Their source for the data is not easily discerned, whether it originated from a scaled system or from an actual process. They suggest 75% of the char energy needs to be combusted to provide energy to the system. This provides a secondary comparison for power requirements with estimates made in this work. Table 7 shows the data from their report converted to MJ/dry kg in the feedstock.

Table 7. Energy requirements from Badger et al (2011)

Product/Process	Self-generated Energy *MJ/kg-dry feed*	Requirements *MJ/kg-dry feed*
Char	6.7*	
Gas	1.56	
Dryer		2.07
Pyrolysis system total		4.52

*Assuming 100% of the char; 5.02 MJ/kg-dry as reported at 75%

Table 8 shows our similarly plotted estimates using data presented above for our 575°C operating conditions. Our results are not inconsistent with the Badger (2011) results for these conditions. Note that they report that their gas yields were 15% by weight compared to ours at 20%. Consistent with results plotted in Figure 14, there is not enough energy in the gas to power the system under the low average mass feed rate conditions (13.2 g/min average). However, if as demonstrated at 650°C we can operate with double the feed rate and only a marginal increase in the furnace power requirements, we may be close to being able to operate the system with the gas providing the energy to heat the furnace. If the mass feed rate is doubled, the energy requirements for the motors should double under a linear assumption. But the requirement on the furnace as demonstrated would not linearly increase according to the performance data in Figure 15. No data were taken at 575°C with higher mass feed rates, so we can only speculate that the furnace requirement would similarly decrease.

Table 8. Energy requirements from this work, 575°C with 13.2 g/min average feed rate

Product/Process	Self-generated Energy Input *MJ/kg-dry feed*	Requirements *MJ/kg-dry feed*
Char	6.8	
Gas*	2.2	
Vacuum Pump		0.028
Lift Motor		0.0013
Transport Motor		0.0099
Furnace		4.03
Pyrolysis system total		4.07

*Assuming Method 2 data, 20% mean gas yield (from data)

The ability to power the pyrolysis system with its own product will ultimately depend significantly on the system design. The gas energy will vary with yield and with extraction temperature. Higher furnace temperatures favor increasing energy in the gases due to net fractional yield and to the quality of the gases. In the present design, the non-linearity in furnace power

requirements with increasing feed-rates suggests the possibility of a full-system design that can meet energy requirements for the furnace with the gases alone. This would need to be verified, and would likely be a major design consideration that would need to be worked out in a prototyping design stage.

3.6 General Discussion

In preliminary work, a previous paper and at the end of Section 1.1, we described some issues that were intended to be resolved by the testing in this series of pyrolysis experiments (Brown and Jepsen, 2009). These were a series of queries mostly regarding the economic and technical viability of pyrolysis conversion technology under portable conditions, echoed in the introduction. Many of the outstanding questions raised in that work are answered in this experimental section. The subsequent discussion follows roughly the outline of questions as presented earlier.

Yields from a system designed to be portable are of interest to understand system performance. Peak liquid yields are shown to be approximately 60% on a mass basis including the water. Excluding the water, 40% is a more representative approximate value. These total liquid yields are lower than some credible optimized system values from the literature (e.g., Bahng et al., 2009 and Mohan et al., 2006) of 70%. Liquid yields can be improved by enhancing particle heat transfer and performing pyrolysis at higher heating rates. Because the size of the pellets in this system tend to limit both of these mechanisms and the pellet size is close to that of chipped wood from the field, the 60% yields we obtained are believed to be representative and realistic of a field system given our design model and fuel source. The water yields are high compared to other similar experiments (Puy et al., 2011), which is speculated to be because of the partial air environment caused by the biomass feed or due to low gas recirculation rates. A significant finding in this testing is that there is not a dramatic change in product as a function of temperature. Figure 5 suggests a comparatively subtle trend. This means that the control requirements for maintaining the furnace temperature can be relaxed while still maintaining near peak yields.

Using the product gases as an inert seems to be effective. This eliminates the necessity for an inert gas supply to the system, reducing the maintenance requirements. Because the inert gas is mostly methane, CO, CO_2, and other hydrocarbons it makes sense to combust them before releasing them to the environment. Of these products, the CO_2 may be the least hazardous product to the environment and the best form for the product gases, expressing a further benefit to combusting the products. Atmospheric CO_2 is part of the natural plant growth cycle, whereas the other products are not. The energy of combustion may be used to offset power requirements to the bench-scale system given appropriate design to take

advantage of this feature. CO is toxic, and would not be good to release in the proximity of work crews.

Mechanical and heating energy requirements have been evaluated. These are believed to be particularly valuable, since these data are not normally reported in the historical literature. Data presented in the results section are suggestive that the product gases could be combusted to provide the energy for pyrolysis. Since this is by far the largest power requirement, it means that the remaining systems might also be able to be powered from residual energy from the furnace heating. But it may require significant design work to assure the system can function without an external power source; especially during start-up. It is not clear if power requirements scale linearly with the size of the system. However, there is a lot of room for non-linear scaling before the minor component power requirements approach anywhere near 10% that of the furnace. This study did not record the power requirements for the control system or the data acquisition system. For any subsequent prototype work, control system power is expected to be a significant requirement until an optimized system can be built. The reason these were not included in the power analysis for this study is that a final design might be constructed with very low power requirement for a control system once operational details are worked out. Assessing the power requirements of the present laboratory system would not be expected to be representative of the final design requirements.

There remains an open question about optimal condenser type and design. This work was performed with a two-stage condenser system, but since there was liquid product recovered past the second stage, there is a clear need for improvement. The first stage used the re-circulating gases to cool the product gases and pre-heat the carrier gas to minimize system energy requirements. This feature makes sense for future design work. Other researchers have also designed multi-staged condensation systems (e.g., Mohan et al., 2006; Sandvig et al., 2003) with system enhancement and product fractionation in mind. Our results suggest the present system provides water fractionation, as most of the water was recovered in Stage 2. Our test unit used refrigerated water to cool the second stage. Using refrigerated water for the second condenser stage was a simplification assumed for this study that is not representative of what a field system might employ. Passive convection heat exchangers could be used in a final design, but they are not likely to be able to consistently achieve the same final temperatures we obtained through refrigeration. Further improvements to the design of the condensation system and function of the condensers for a portable system remain as a task for future work.

In terms of maintenance and durability, we found the need to periodically clean the entrance to the first condenser stage. This problem was reduced at lower pyrolysis temperatures. Other researchers noted a similar challenge (Sandvig et al, 2003), and suggest that careful design can help reduce or

eliminate this problem. The diaphragm pump required a re-build mid-way through the test series, underscoring that there is a limited lifetime for most components. The vibrator was not essential to the system, but it is expected that maintaining consistent feeding to the system will be a design challenge for a full-scale system. This may be aided by a similar powered agitator, or through manual intervention. Long-term maintenance and system durability would need to be considerations for final design specifications. Because the testing in this report did not involve long-term continuous operation, there are aspects in this regard that may be yet exposed. The experience described with the bench scale system suggests that there will be real maintenance issues for a full system that need to be accommodated in an economic model based on the current design.

Optimal system design has many components to it. The yields shown in Figure 5 are an important consideration. Between 500-600°C there is a slight decrease in liquid yield with an increase in temperature. Lower temperatures give slightly better liquid yields given the current operating conditions. Other work suggests an opposite trend when decomposition is kinetically limited (e.g., Mohan et al., 2006), so these results should not be viewed as universal trends. Other designs might be expected to perform differently. Additional findings from this testing also suggest lower temperatures are better. For example, the water conversion is reduced at lower temperatures, as is the maintenance requirement due to deposition in the condenser. Conversely, the residence time requirements are greater and the energy availability in the gases is lower for lower temperature pyrolysis. Indications are that both of these issues can be managed through system design. So in light of the present testing, we can recommend that the lower furnace temperatures in the range of 500-550°C will result in improved product fraction, higher product value, improved reliability, and therefore represent improved operating conditions. This finding is mitigated by the fact that a design that involves powering the furnace with the gas products may be easier to realize with temperatures towards the higher end of the range. Further testing under different conditions may suggest different optimal conditions, a prospect that suggests that subsequent evaluations may be warranted in this regard.

4 Economic Analysis

Shortly into the economic assessment, it became apparent that the limiting factor in the economic viability of portable pyrolysis was directly related to the productivity and capacity. The only revenue streams come from the material processed. The amount of material processed is controlled in part by operator productivity, and in part by the capacity of the pyrolysis system. With an appropriately designed system, the operator function outside of start-up is to maintain a relatively steady and manageable amount of biomass feeding into the system, and to manage the product. Since we were motivated in this portability model to open up production of the fuel or other product to the land management (thinning) teams, there is a desire to keep the system to a size where it could be towed behind existing work vehicles and access remote sites through existing roads. This limits the volume and footprint available for the system, as well as the weight. Towing weight limitations for 1-ton U.S. trucks are around 5-6 tons depending on manufacturer and model. Trailers are constrained to about 8.5 feet wide, 14 feet high (from ground), and 40 feet long (2.6 m by 4.3 m by 12.2 m). Larger weight capacity trucks are available, but the length limitations are based on the standard road sizes.

Since economic analyses are significantly influenced by their assumptions, clarity and specificity in reporting these is an aim of this study. The next few sections outline the scenarios that were selected for evaluation. They present the assumptions that go into the modeling effort. After the assumptions are presented, a series of scenario predictions is shown that categorize results of the economic estimates.

The cost assumptions are broken out into two categories. Fixed costs, which include those necessary to start, capital equipment purchases, and costs associated therewith are presented first. These only recur when financing is used to make the acquisition. For analysis of the break-even cost of the system, fixed costs are spread across ten years under the assumption that the fixed costs are financed. This implicitly assumes that the hardware has a minimum lifetime of ten years. If the hardware lifetime is longer, it has a positive effect on the outcome of the analysis, with the opposite true for a shorter hardware lifetime. The second category is variable costs, which include those accrued as the system is used. These include labor, maintenance, repair, etc.

Revenue assumptions are fairly straight-forward, with some assumptions being made as to the yields, value of co-products, and properties of the main product.

A series of scenarios are proposed that involve 10 and 50 tons of dry biomass processed per 24 hour working day. These are designed to explore some parameter assumptions with regard to working model and the productivity of

the system. More details on the scenarios are presented in the results section (Section 4.4).

Costs are presented by convention rounded to the dollar, which should not be construed as knowledge to that level of accuracy.

4.1 Fixed Cost Assumptions

The fixed costs involve one-time acquisition of capital equipment necessary to perform the pyrolysis. A full-scale system will look significantly different than the bench scale system. This is because not everything scales directly, and larger-scale systems have increasing requirements to manage product and source materials. Below is a bulleted list of some of the assumptions that guided this assessment:

- An auger driven furnace is used to react the biomass much like the bench-scale system demonstrated in the previous section
- Two scales are evaluated, 10 and 50 tons per day (24 hours of labor)
- The trailer has limited liquid storage capacity, and another trailer is used to hold the product
- Liquid product is separated through three condenser stages and through a mist separator
- The input mass is dried prior to entering the furnace
- The pyrolysis gases are combusted to power the furnace
- The pyrolysis gases can be used to power the auxiliary components; a generator will work off the gases or an auxiliary propane tank to generate the power
- The system has automated control and safety systems (low user input requirements)
- The system is completely mounted on a portable trailer that can be leveled for loading in the field
- A small track front-loader is used to load the biomass in the 50 ton/day system
- The pyrolysis and product trailers can be towed behind commercial heavy-duty pick-up trucks
- A mechanism is required for heating the furnace at start-up

A rough schematic representing the assumed system connectivity is found in Figure 16. The system mimics the bench-scale system with the exception that the condensers are assumed passive, and some assumptions are made with regard to the power requirements for the system.

With these parameters defined, design and fabrication costs can be estimated along with the components needed for operation. Hardware costs are detailed in the appendix. The hardware costs were determined from web catalog searches from standard material supplier data.

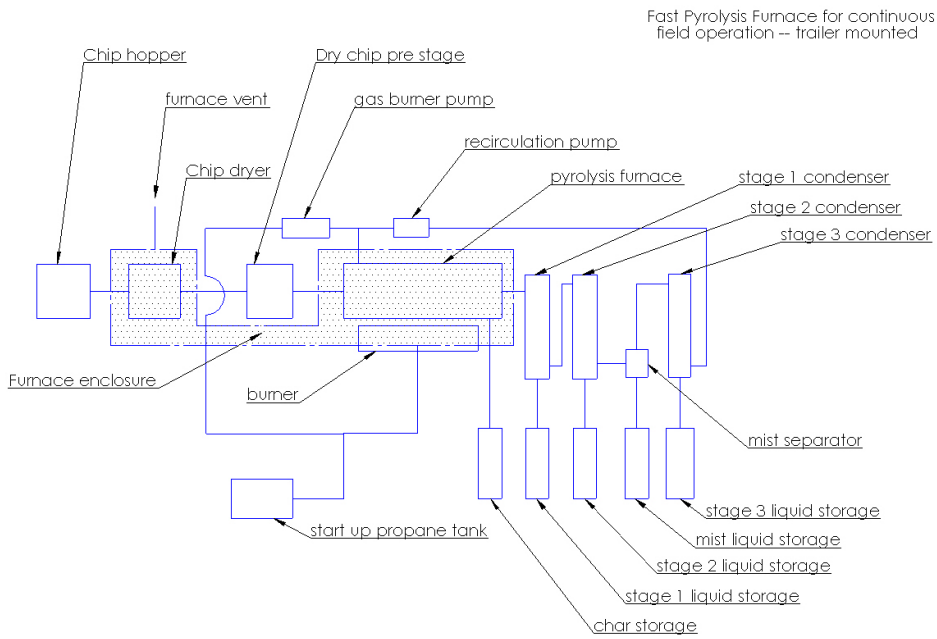

Figure 16. Block Diagram (Major Components).

Process Scaling Factors

Forest residues are assumed to have a density of about 585 kg/m^3. The highest mass throughput of the bench-scale unit was 42 g/min. To get to 10 tons per day a field unit will be scaled by 150 times, whereas the 50 tons per day system will need to be scaled by 750 times.

Pyrolysis Furnace

For 10 tons per day, the furnace was estimated to be constructed with two 25 cm (10 inch) diameter tubes, 2.44 m (96 inches) long. We estimate a 15 cm (6 inch) pitch auger would process sufficient mass at 16 rpm.

For 50 tons per day, the furnace was estimated to be constructed with four similarly sized tubes. The auger is 51 cm (20 inch) pitch, with 16 rpm moving the nominally specified mass.

Gas Recirculation

The bench top experimental unit is assumed to operate as the scale system with pyrolysis occurring in the re-circulated gases. The pump used in the bench-scale system was estimated to move about 1.1 liters per minute. The gas flowed through a 1.3 cm (0.5 inch) OD tubing. Using a scale-up of 150 times for the 10 ton/day system the new blower will be required to move about 150 liters per minute (5.25 cubic feet per minute). The interconnect tubing will need to be at least 7 cm (2.75 inches) diameter. On the 50 ton/day system the blower will need to move 750 liters per minute (26.5 cubic feet per minute) and the interconnect lines will need to be at least 15.2 cm (6 inches) diameter.

Condensers

In the bench top experimental unit the condensers were of an in-house design. The performance of these condensers was somewhat disappointing. In the majority of configurations that were tried, the gas was re-circulated for cooling of the first stage. This methodology proved not to be optimal. Clogging of internal passages on the condensers occurred in virtually every test run. The best thermal performance was achieved when using a liquid cooled condenser. In house design of these small condensers was cost effective, however with the scale factors of 150 or 750 the designing of the condensers would best left to a company with significant experience in this regard. Estimates are made consistent with this assumption. The bench top experimental system used 1,200 W to process 72 cm^3/min (4.38 in^3/min), scaling up by 150 times to process 10,800 cm^3/min (657 in^3/min) would require 180 kW or about 600 kBTU/hr. Since we demonstrated in the experimental section an ability to do product fractionation with a multi-staged condenser system, we are designing the field unit with a three stage condenser system. This is expected to help with fractionation and also with layout, as a large condenser would be expected to be more difficult to accommodate given the volumetric limitations. Generally the first stage should lower the exiting gas temperatures from 525°C to 250°C whereas the second stage should bring the temperature down to just above the point where significant water would condense, thus allowing the final stage to fully condense out the water. Based on this general requirement the first stage needs to be sized for half of the 180 kW with the second and third stages condensing the balance. This would require about 90 kW for the first stage with the second about 60 kW and the remaining 30 kW for the final stage. In determining the cost for these condensers there are losses in this approach that are being neglected. When properly sized condensers were identified based on power loading, the cost of those condensers were doubled for each stage.

The Solid Flow Path

The chips will be lifted into the first stage dryer and transported across the top of the second stage dryer. The chips will be dropped into the second stage dryer which will be on top of the pyrolysis furnace. The chips will move across into a pre-furnace container. This container will help distribute the chips into the augers used in the pyrolysis furnace. The chips will be shuttled into the pyrolysis furnace to minimize the introduction of oxygen into the furnace. The chips will move through the furnace releasing pyrolysis gas that will be pulled through and into the first stage condenser. The char from the furnace will drop into a post furnace shuttle whose function is to move the char out and to minimize the loss of any product gas. The char will then be transported to a holding area via another auger.

The Gas Flow Path

The gas will exit the furnace into the first stage condenser and feed into the second stage condenser which will feed into a mist separator and finally into the third stage condenser. In each step the liquid condensed will drain into storage tanks. The pyrolysis gas will exit the final stage condenser and be routed to the input of a regenerative blower. The output of the blower will feed the gas to the input of the pyrolysis furnace. This gas will be used to inert the pyrolysis furnace. This path will be operated as a closed loop. As the system operates more gas will be produced than can be used to inert the furnace. This excess gas will be siphoned off to heat the pyrolysis furnace in a combustor, and to run the electrical generator. The spent gas from the heating of the furnace (propane or re-circulated pyrolysis gas) will be directed into the chip dryers for three functions; the first being drying of the chips and the second to help transport water vapor out of the dryers and lastly to help minimize the oxygen content going into the pyrolysis furnace.

Pyrolysis Gas Storage

It was originally proposed to store extra gas energy from the pyrolysis gases for re-start. On further analysis, the required storage tank very quickly became too large to transport into the field and operate at a reasonable pressure. Most thin wall gas storage tank operate at a maximum of 150 psi this tank would need to operate at a much higher pressure. Small amounts of external gas will probably be more efficient and effective for re-start. As such, no consideration will be given in this paper to a gas storage system.

Electrical Power Generation

Electrical power is needed to operate various motors (augers, cooling pumps, blowers, compressors) and the control system. Of methods considered: 3

phase power at 240 VAC provides the best flexibility in motor speed control and operation of the control system. The operational control components are proven throughout other industries and meet strict operator safety requirements thus minimizing the development of new safety protocols. Variable Frequency Drive (VFD) systems will be used to control chip movement and gas flow throughout the system. These systems need to be tunable, as the biomass characteristics change from location to location. Sizing of the motors will drive the sizing of the generator. The generator size is also dictated by the interest in having it run off of multiple fuels, including the pyrolysis gas. With this in mind, doubling the generator power will provide a design margin until a unit is fielded to determine if there enough energy in the gas to run the furnace, dryer, and generator during normal operation.

Labor Costs

Engineering and fabrication labor costs are well defined. Typically the fringe benefits include: health insurance, dental insurance, office space, equipment (computers, tools). This information can be found at various sources from government and industry. Professional labor rates for an experienced Intermediate Engineer are in the range of $90-95 per hour. The skilled labor rates will be in the range of $70-75 per hour. For Scenario 4 and 5, this labor rate is not changed under the assumption that the hardware is manufactured locally and exported. Labor time was estimated based on the author's experience with design and construction of mechanical systems.

Systems Cost

The cost comparisons for the two systems are based upon tons per 24 hours. A complete break-down of material costs and fabrication costs is found in the Appendix. Nominal estimates are found listed in Table 9.

Table 9. Fixed cost estimates for the portable pyrolysis system

	10 *ton/24 hours*	50 *ton/24 hours*
Material cost	$ 111,089	$ 374,738
Fabrication cost	$ 119,136	$ 324,120
Design cost	$ 59,940	$ 152,280

Material and fabrication costs are considered baseline costs for a system. A business selling such systems will mark up their product by a factor to pay for the design and prototyping costs, advertising and marketing, and to generate a profit. This is the margin, or loading on the cost of the system.

Assuming many of these units are built, we estimate that factor to be 20% of the cost of material and fabrication. For smaller priced items, this would be expected to be a larger number, as 50-100% mark-up is not unusual. But since these units are large and expensive, there is more room for a smaller margin on a percentage basis.

As larger systems are put in place, the cost per ton quickly decreases. In Table 9 it can be seen that the difference in material processed is a factor of 5, which directly relates to revenue. Conversely, costs are between a factor of 2 and 4 higher, which factor directly into the expense of operating the system. This suggests a clear benefit to processing the most material per unit as is possible.

Truck, Loader, and Chipper

A heavy-duty pick-up truck would be required to haul the system and products. A model employing multiple teams would require multiple vehicles. But since this process would be added to existing infrastructure and probably used in part by teams who do thinning and already have trucks, only one truck was factored in to the model. A web-search suggested a bare-bones model could be currently purchased for around $31,000.

The loader is assumed to be required for the 50 tons per day system, as moving that much material manually is not realistic. The loader is not a requirement for the 10 tons per day system, as this could probably be managed manually. Close examination of the tables in the Appendix will affirm that the loader is included as part of the material costs for the 50 ton system. Operating costs of the loader are factored in as part of the variable costs for the 50 ton system analysis.

A good chipper capable of 2 tons per hour is assumed to cost $35,000 based on data conveyed by the Northern New Mexico thinning companies. Labor for the chipper is estimated on this basis in the next section.

Amortization

Fixed costs are amortized over 10 years at an interest rate of 6% annual. An initial payment would probably be required to secure the loan. This fact is ignored since the intent is to cost the system and amortize the costs over the life of the system. The monthly payment is found through the following equation:

$$Payment = AmtBorrowed\left(\frac{r(1+r)^n}{(1+r)^n-1}\right)$$

Supplying an interest rate r (on a monthly basis) and a number of payments n (on a monthly basis), the amount of the recurring payments is found. The amount of total interest paid can be deduced from the same equation, and is

presented later on as one of the system costs. This is not expected to be the most probable model for financing an operation, but it is a simple way to factor in the potential burden financing places on the system model in the likely event that a good portion of the initial costs are financed. Financing costs are tracked as the interest paid at the assumed rate. For reporting annualized costs, the mean annual interest payment is used. Money down proportionally reduces the cost of interest to the present model to the percent paid down on the loan.

4.2 Recurring Cost Assumptions

Recurring costs are costs that accrue as the process is utilized. It consists of labor, maintenance, transportation, fuel, parts, insurance, administration and marketing. A lot of uncertainty exists in nominally selected parameters, as they depend on market fluctuations and on system reliability, as well as other factors. The scale of the system does not significantly affect the recurring costs, except that the front loader is not required to load the 10 ton/day system and the transportation costs are slightly lower since product will not need to be shipped with the same frequency.

Labor

Even if a single person could operate the system alone, it is unrealistic to have a crew of one working in a remote setting. For safety and for operational management, it is assumed that a crew of two laborers is always present. Labor is estimated at $24/hour, the loaded labor rate for standard thinning forest crews[4]. A standard work year of 2,000 hours per individual is assumed. Product is assumed to flow for 90% of their working time. Weather interruptions and other such factors are ignored, as it is assumed that the crews will work rotating shifts while the weather is appropriate for these operations. Currently, thinning crews work a higher fraction of hours during the winter months because the cold ambient temperature limits the potential for unwanted fire spread when they burn the harvested material.

The labor and transportation costs for the chipper are taken to be proportional to that required to process the chipped biomass in the pyrolysis unit. For a pyrolysis team that processes 2 tons per hour, there is 1 hour of chipping costs for 2 tons. For a pyrolysis team that processes 1 ton every two hours, there is 1/4 hour of chipping labor costs for each hour of pyrolysis labor. The processing rate of 2 tons per hour is conservative, as thinning companies have indicated 2-3 tons per hour is a typical productivity rate.

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[4] Based on conversations with Taos, New Mexico area businesses.

Maintenance and Repair

The system is expected to require periodic repair and maintenance. This is factored in at the standard labor rate, with 40 hours of maintenance per year and 40 hours of repair. This equates to about 50 hours up for every 1 down for repair or maintenance. Cleaning supplies are estimated at $2,000 per year, and annual maintenance materials are estimated to be 3% of the construction cost of the system as per Islam and Ani (2000). The cost for waste disposal was estimated at $5000 per year. This might include disposal of cleaning chemicals, or disposing of residual matter. This could be much higher or lower depending on many factors difficult to assess at this point.

Transportation

It is assumed that there are 20 basic sites worked each year (100 hours per site), with the need to move the trailer ten times per site. This is consistent with a model assuming 2 tons per hour and 20 tons per acre, assuming one move per acre harvested. Since labor is already factored into the costs, the transportation expense is the cost of operating the trucks, which is estimated at $0.75 per mile. Site trips are assumed to average 20 miles distance, and within-site relocations are estimated to cost $5 per move. Shift change involves a new crew arriving and the hauling away of the previous shift's product. The 20 mile average distance is assumed, and based on the operational hours it is assumed that there are 167 shift changes per year. Chipper transportation costs are assumed to be proportional to those of the pyrolysis system based on the number of hours the chipper is used.

Insurance

The system is assumed to be insured for loss and liability to prevent catastrophic losses. The assumption made is that the insurance is 3% of the fixed capital investment (FCI) annually. This is also as per Islam and Ani (2000).

Marketing/Admin

The teams involved in chipping and harvesting are expected to be managed with the rest of the thinning operations. Much of the marketing and administration is covered as part of the thinning process. An additional six weeks (240 hours) is applied to cover the extra costs of managing up to two additional crews. The hourly loading for this is two times that of the labor.

Operations

These costs include the fuel to operate the pyrolysis system generator and start-up fuel. It also includes fuel for the loader and chipper (if factored in based on the scenario). A large cost is incurred for testing product, as customers will likely want to be assured that the product meets a minimum specific energy value. This is estimated at $50 per work shift. Significant fuel will be required for the 50 tons per day system to power the front-loader. Less will be required for the 10 tons per day system. A gallon per hour is the estimated fuel consumption for the loader, with it assumed to be running 67% of the time the process is running. This equates to 1,200 gallons of fuel, assumed at $3.50 per gallon. The chipper is assumed to consume 1.25 gallons of fuel per hour of operation.

4.3 Revenue Assumptions

Revenue is obtained strictly from sale of product produced in the pyrolysis unit. There are other potential scenarios that involve carbon credit, alternative energy governmental incentive, and consumer premiums that could alter the estimates in favor of the technology. Since none of these is currently in place, they are omitted entirely from the study. If any of these were implemented, there would be an adjustment that reduces the break-even cost.

The products of the system are pyrolysis oils and char (biochar, or charcoal). The char is nominally assumed to be 20% mass basis yield from the process. It will be a low density solid, and will have to be actively managed as part of the system process. The present assumption is that the char is periodically removed to bags, which can be left for later extraction or shipped out with the liquid. Various sources estimate the value of char being over a wide range: as high as $500/ton[5] and as low as $75/ton (Badger, 2011). It has use as a solid fuel, and has been shown to be comparable to coal chars in terms of reactivity and combustion properties (Wornat et al., 1995, 1996). This suggests that the wood chars might be used in existing coal burners with little to no modification to the current systems. It also has use as a soil amendment. A web-survey of fuel prices suggests coal in the last few years trades in the $20-$150/ton range depending on quality and source, so the cited $500/ton figure is likely only achievable in a retail environment as a soil amendment. It is not clear if this figure factors in some kind of subsidy, or a regional demand based on temporary scarcity. Based on data from our analysis of the char, it could be sold as a low-sulfur high-volatile bituminous coal equivalent based on calorific values found in this report and ASTM standards as referenced in Smith et al. (1994).

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[5] http://www.biochar-us.org/; accessed October 2011

Revenue is reported on a price per Giga-Joule equivalent. This facilitates comparisons between fuels since the specific energy density on a mass or volume basis is significantly different. It also facilitates comparisons with other studies that use the same metric. To compare pyrolysis oils with a typical refined fossil fuel, gasoline as an example is assumed to have 44 MJ/kg and a density of 720 kg/m^3, which at $3.50 per gallon equates to approximately 30 $/GJ. Since the price per gallon of fuel is highly variable, a plot of the price per gallon of gasoline and the comparable price per Giga-Joule is shown in Figure 17. One GJ is about 950,000 BTU. Comparing pyrolysis oils to gasoline directly isn't a completely fair comparison, since gasoline values are retail and it is a higher quality refined fuel. Fuel heating oil and other such liquid fossil fuels are expected to be approximately the same as gasoline in terms of price per unit energy. Natural gas for the decade of 2000-2010 has varied in futures value from around $2-15/GJ, with residential delivery for New Mexico in the range of $7-20/GJ[6,7]. Diesel fuel has about the same heating value as gasoline per unit mass, and this equates to slightly lower prices per unit energy than gasoline for equivalent prices because it has a higher density. Diesel volumetric prices usually are similar to gasoline prices, but in recent years have tended to be slightly higher.

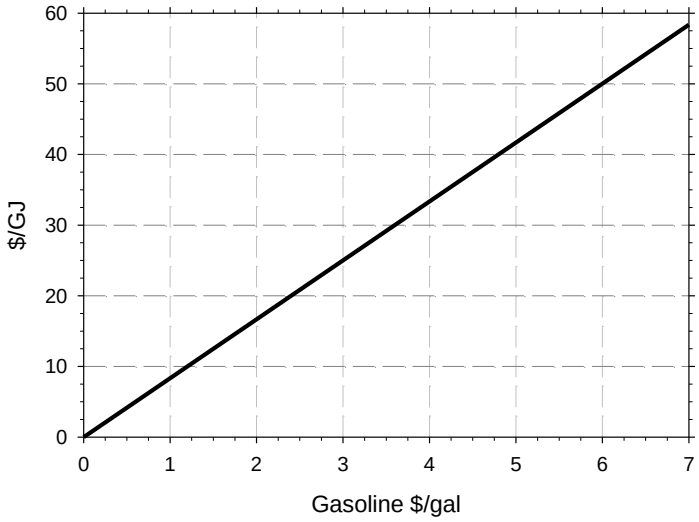

Figure 17. Equating the price per unit energy to price per gallon of gasoline for interpreting the results of this study.

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[6] http://205.254.135.24/; U.S. Energy Information Administration web-page, accessed October 2011

[7] Data for natural gas are often listed in $/million BTU or $/thousand cubic feet. This report uses $/GJ. All of these unit systems are approximately the same, varying only by a few percent.

Pyrolysis oil has been evaluated in Diesel co-injection scenarios, in which case a direct comparison with the price of refined fossil liquid fuels on a specific energy basis is warranted. If it is assumed to be competing for residential heating market, it is more appropriate to compare to the price of natural gas (in Northern New Mexico) or other common regional heating energy sources like fuel oil or electricity. It may also be refined to a transportation grade fuel. Those costs will not be estimated as part of this study, but is briefly discussed in an historical context in a discussion section (4.5) later on in this report.

Since this study has not decided the best way to use pyrolysis oils and this is not a focus of the study, the information on their production prices is presented. The potential for pyrolysis oils will be evaluated based on the current prices. However, the volatility in the fuels markets makes it very difficult to project to the future economic viability. This fact needs to be weighed when considering the application of the results of this technical study.

4.4 Scenario Estimates

It is impossible to know with accuracy many of the performance values that are critical to the accuracy of an economic model. To better represent the uncertainty in the process, a series of scenarios is developed. The scenarios are hoped to capture the effects of some potential variations in the way a mobile pyrolysis system might be used. An attempt is made to capture the bounds of uncertainty. The range of uncertainty is captured by ascribing a nominal value to model parameters, and by varying those parameters over a credible range. Scenarios factor in other potential assumptions.

Table 10. A description of the analyzed scenarios for this study

Scenario	Description	Ton/24hr	With Uncertainty?
1	Best estimate	50	Yes
2	Best estimate	10	Yes
3	Double work crew	50	No
4	Low labor rate	50	No
5	Low labor rate	10	No
6	No chipper	50	No

Table 10 gives a scenario number and a brief description of the distinguishing features of the particular scenario. Scenario 1 and 2 are considered baseline scenarios, one each for 10 and 50 tons per day. The 10 ton per day system is believed to be easily achievable. Whether a 50 ton per day system can be designed to be portable is considered moderately uncertain, as a full lay-up and design would be required to assess this with

accuracy. Since, as mentioned earlier, the economies of scale are expected to result in the higher throughput giving better performance, the 50 tons per day scenario is used as the nominal case from which other variations are evaluated. Scenario 3 is like Scenario 2 except the assumption is made that two full time equivalent crews are able to operate the system on shifts each year instead of just one crew. The net effect of this assumption is that the variable costs double, revenues double, but the fixed costs remain constant. There are places in the world where another two shifts would be possible, but the seasonal weather and other considerations in Northern New Mexico probably will inhibit full-time operation of the portable generation plant. Scenarios 4 and 5 evaluate the system with a quarter-scaled labor rate. The reason for this is that many countries of the world have much lower labor rates (often lower by an order of magnitude, so this is a conservative estimate). This technology would be more easily profitable with lower manufacturing and operations costs from lower labor rates. Scenario 6 omits the chipper, which was originally the nominal case. This is a reasonable assumption if the transportable unit is located by a saw mill or a wood product manufacturer where the residual wood is already small in size. This might also be the case for crop residue processing if the residues are already size-appropriate. There are also instances of thinning where chipping is paid for by the customer. These, however, are too few to consider as a base scenario under the current business conditions. Costs for the chipper and labor are wrapped into the cost of the system for all the other scenarios, even though the businesses targeted as part of this study already have them and are presently trained to use them. Labor and other costs for thinning are not wrapped into this study, as they are considered necessary and already paid for costs. The break-even point would increase if these costs were added in.

We assume that the wood chips are congregated on the forest floor, and of moderately low moisture content (seasoned, not green). This implies that chipping takes place weeks or months before pyrolysis conversion, not simultaneously. We assume that we can access them at no purchase cost (negotiated as part of the thinning agreement). The end point for the model is when the product is delivered to a distributor or to a customer (local) equipped to handle the quantity of bulk material potentially generated by the systems operating in the region. Costs associated with distribution and storage longer than one day are not figured into this analysis.

To facilitate the analysis, the break-even price will be calculated. The profit or margin required will be left to the reader to determine the viability of this technology. All costs will be represented in current dollars, with no attempt to assess the effects of inflation or time value of money.

For Scenario 1 and 2, an attempt is made to assess the uncertainty in the predictions. Since the technology is immature, the real uncertainty is quite high and very difficult to assess. The method used is to apply moderate

variations to parameters within realistic ranges to get a sense for the effect on costs.

The uncertainty estimates are very difficult to make for any level of significance since there are so many parameters with high uncertainty. The objective is to provide a realistic bound to the outcome. Without resorting to very involved statistical methods, this can be achieved by propagating uncertainties through the model in a systematic way. The method used is to select a few of the parameters believed to have the most uncertainty, and to apply a small and credible range of variation. These are propagated in concert with parameters selected to give what is believed to be a realistic low and high cost range for the output parameters. Thus, costs are varied higher for the high cost estimate, and revenues are varied lower for the same. Table 11 shows the parameters selected for variation and their magnitude of variation.

Table 11. Parameter variation for the uncertainty estimates

Property	Nominal	High	Low
Fixed Costs:			
System Margin Loading	20%	25%	15%
System Unloaded Cost	Baseline	+10%	-10%
Interest Rate	6%	6.5%	5.5%
Variable Costs:			
Maintenance	3%FCI	3.2%FCI	2.8%FCI
Fuel ($/gal)	$3.50	$4.00	$3.00
Transportation	Baseline	+5%	-5%
Waste Disposal	$5,000	$10,000	$2,000
Operations Testing ($/shift)	$50	$100	$25
Revenues			
Conversion Fraction	0.55	0.50	0.60
Wet Product Heating Value (MJ/kg)	16.7	15.0	18.0
Char value ($/ton)	75	50	125

The meaning of the bounds holds no statistical relevance (i.e. confidence bounds, etc.). It rather is an approximation of potential variations based on a customized series of parametric changes.

Scenario 1

Scenario 1 represents the best estimate of this study with assumptions for use in Northern New Mexico. Results are summarized in Table 12.

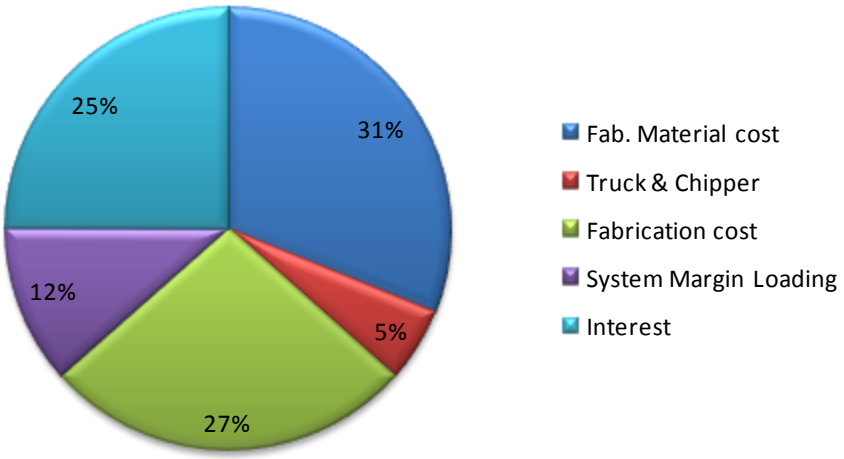
The break-even selling price is based on the assumption that there are two products of the process, one the char and the other the oil. The char price is set as described above, and the oil price is the price that must be obtained to break even on the costs. The $11.17/GJ break-even price is estimated to be approximately $ 0.85/gal or $170/ton based on conversions. Since energy

basis analysis is more meaningful for comparing to other fuels, the subsequent results are presented in those terms. The relative break-down of the fixed costs is shown in Figure 18A, and the relative break-down of the variable costs is shown in Figure 18B.

Table 12. Scenario 1 results

	Baseline	High	Low
Annualized Fixed Costs	$120,519	$139,927	$102,794
Annual Variable Costs	$285,820	$309,447	$269,184
Break-even Selling Price ($/GJ)	11.17	16.14	7.56

A.



B.

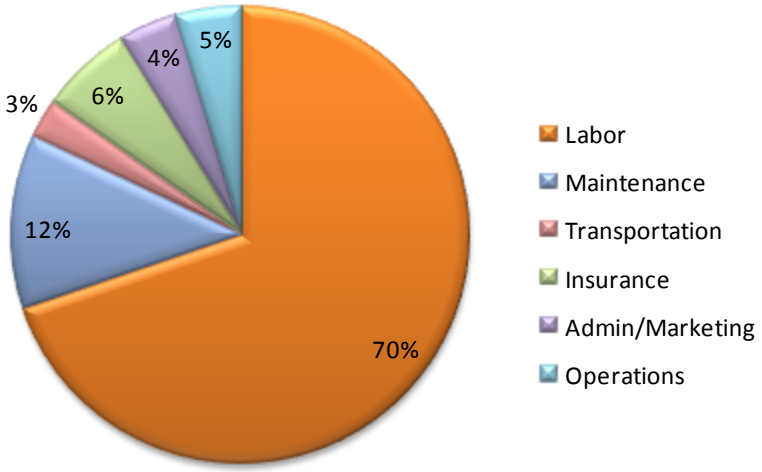


Figure 18. Scenario 1 percent contribution to the fixed (A) and variable (B) costs.

What stands out in the Scenario 1 analysis is that labor is by far the largest component to the costs. The other component of the variable costs that is large is maintenance. The remaining categories are small by comparison. The two largest components of the fixed costs are the materials and fabrication costs, with interest a close third.

Annualized fixed costs are less than 1/3 the total annual costs. Figure 19 shows a similar plot of the total annualized costs for Scenario 1. It shows about half of the costs being related to labor.

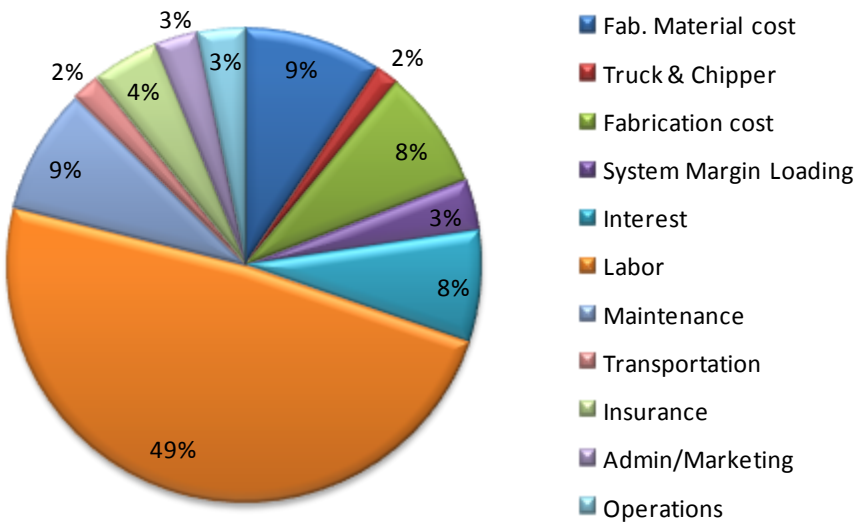


Figure 19. Categorization of Scenario 1 annualized costs.

Scenario 2

Scenario 2 was selected as a best estimate for a system designed to produce a lower quantity of product per hour. Processing 10 tons in a 24 hour day, it will be easier to design, will not require a loader, and has lower fixed costs. Table 13 shows the principal results.

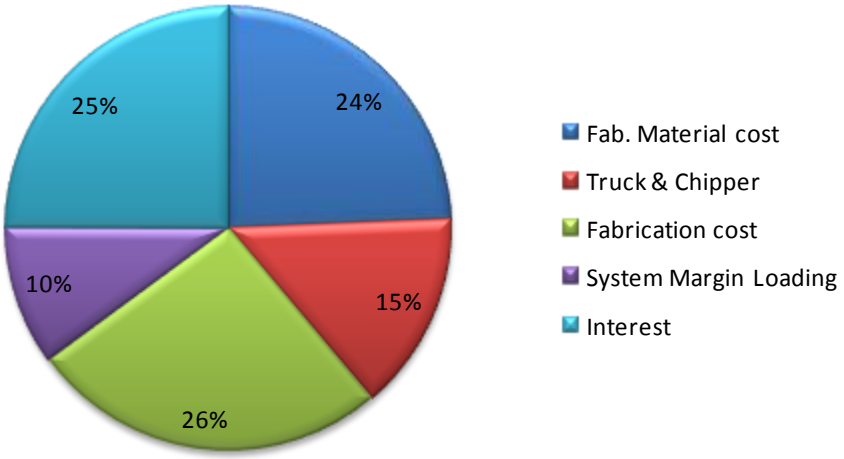
Table 13. Scenario 2 results

	Baseline	High	Low
Annualized Fixed Costs	$45,599	$52,127	$39,627
Annual Variable Costs	$173,661	$191,148	$162,614
Break-even Selling Price ($/GJ)	34.99	47.67	24.94

The importance of economics of scale is evident, as the break-even selling price is above that of any current standard commercial fuel presented earlier. This model for producing pyrolysis oils is not expected to be economically

viable except in an extreme situation where other fuels are very expensive or heavy weighting is given to other factors. As a percent of total annual costs, the fixed costs are lower than for Scenario 1. The break-down of the fixed costs is shown in Figure 20A, and the break-down of the variable costs are shown in Figure 20B.

A.



B.

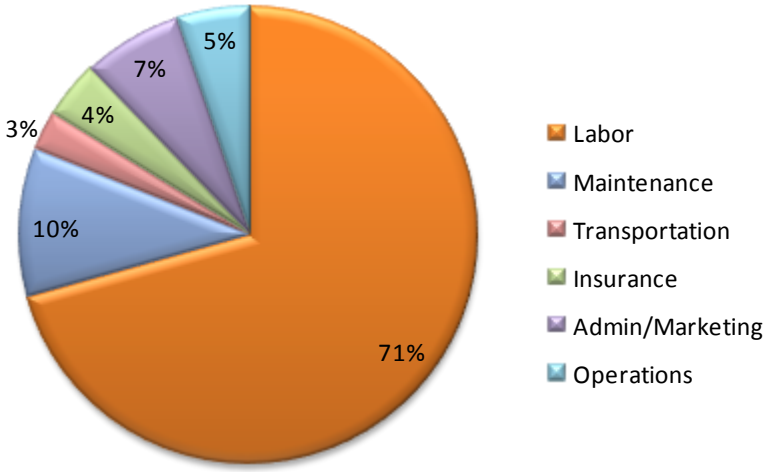


Figure 20. Scenario 2 percent contribution to the fixed (A) and variable (B) costs.

What stands out in the Scenario 2 analysis is that labor is an even larger fraction of the total costs than in Scenario 1. The next largest component of

the variable costs is maintenance. The others are small by comparison. The two largest components of the fixed costs are the materials and interest costs, with fabrication a close third.

Annualized fixed costs are less than 1/3 the total annual costs. Figure 21 shows a similar plot of the annualized costs for Scenario 1. It shows over half of the costs being labor. Part of the reason that economies of scale work is that for larger systems the labor is able to be much more productive.

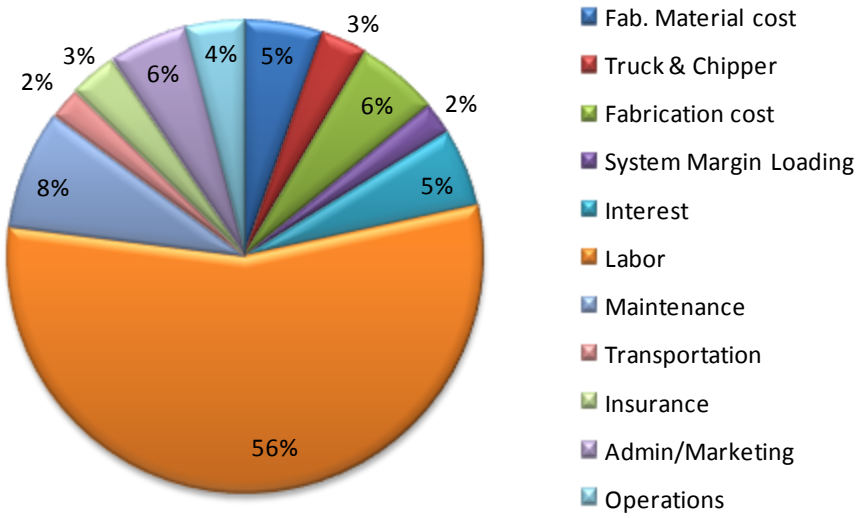


Figure 21. Categorization of Scenario 2 annualized costs.

Scenario 3

Scenario 3 assumes that the mobile system is used by two full-time equivalent crews each year. This means that the system is used more productively, minimizing the relative contribution of the fixed costs. A summary of the results is shown in Table 14.

Table 14. Scenario 3 results

	Baseline
Annualized Fixed Costs	$120,519
Annual Variable Costs	$571,640
Break-even Selling Price ($/GJ)	9.25

Adding an extra annual shift on the hardware has a positive effect on the baseline break-even selling price for the pyrolysis oils, dropping it by about $2/GJ, or roughly 17%. This is because fixed costs are a smaller percent of the total cost. A break-out by category of the annualized predicted costs is

found in Figure 22. These results can be compared to the baseline results from Scenario 1 found in Figure 19.

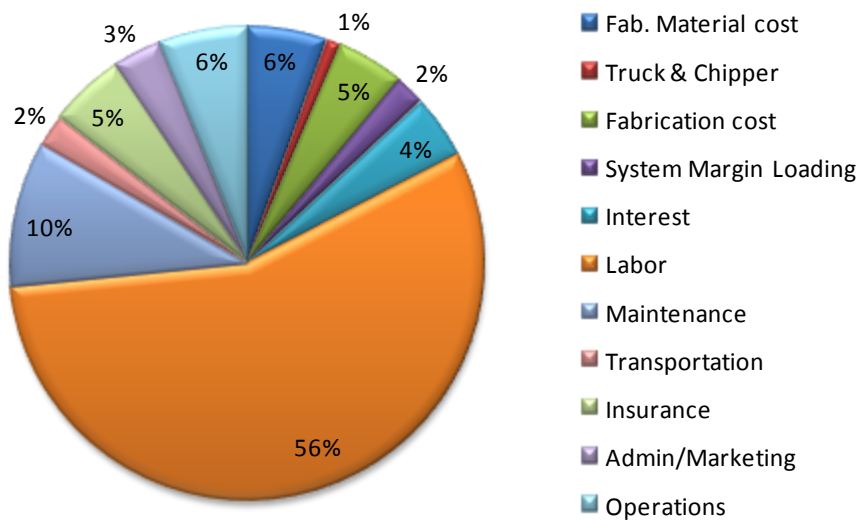


Figure 22. Categorization of Scenario 3 annualized costs.

The use of a second or third shift on the hardware is a realistic way of improving the break-even point for the technology. Although it will increase the wear on the system, the maintenance costs are proportionally increased. As long as the system is designed to operate within the lifetime and maintenance bounds, this is thought to be a credible way of reducing costs compared to the baseline scenario.

Scenario 4

Because labor is such a significant cost in the nominal Scenario 1 case, it is sensible to evaluate this technology for a case with lower labor rates. This is probably not a realistic assumption for Northern New Mexico, but represents an opportunity for other parts of the world where prevailing minimum labor rates are typically less than one tenth of those assumed nominally for this study. Since a higher percent of the population of the planet lives in these conditions, there are likely models whereby labor and a combination of other factors could make this technology much more economically viable than in Northern New Mexico. We only assume a factor of 4 difference in labor, and the labor rates assumed here for New Mexico were significantly above minimum labor rates. Thus, under the assumptions of this scenario, we are providing jobs that pay well above the minimum labor rate in many countries. Developing the technology in a region with lower economic risk makes sense, so this scenario can be looked at as an analysis helping provide motivation to develop the technology to the point where there are

mature systems and costs can be minimized. A summary of the results is shown in Table 15.

Table 15. Scenario 4 results

	Baseline
Annualized Fixed Costs	$120,519
Annual Variable Costs	$131,740
Break-even Selling Price ($/GJ)	6.26

The break-even selling price of $6.26/GJ is a value that might put this fuel source on par with other low-cost energy sources. Fixed and variable annualized costs are close to being equal. A break-out by category of the predicted costs is found in Figure 23. Because of the significantly reduced labor rates, labor is no longer as significant of a factor in the costs, even though it is still the largest component to the annual costs. These results can be compared to the baseline results from Scenario 1 found in Figure 19 to see the effect of a lower labor rate on the cost fraction by category.

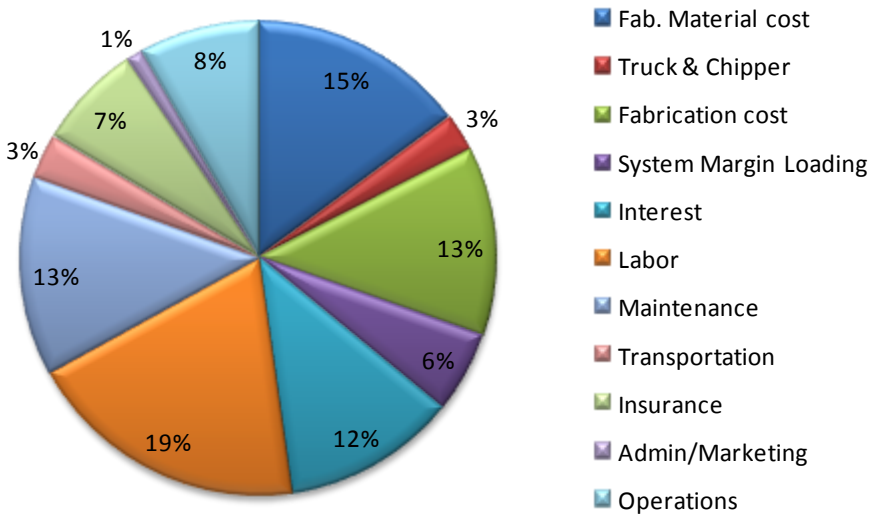


Figure 23. Categorization of Scenario 4 annualized costs.

It should be noted again that this study is assuming that the labor rate of operating the system and the maintenance, administration and marketing are the only rates adjusted. The fabrication cost is still at US standard levels. Were this manufactured at a reduced rate, there is room for further reduction in break-even costs.

Scenario 5

Even though the significance of economies of scale is already demonstrated, it is sensible to perform the low labor rate analysis with the 10 tons per day system. The reason why is because other countries do not have similar infrastructure. The 50 tons per day system might not fit on roads or might weigh too much in other countries. Maximum system capacity might fall between the two nominal systems for this study. The 10 tons per day system predictions are provided because they give data that can be used to estimate the viability of a system scaled between 50 and 10 tons per day if the existing infrastructure cannot support a 50 tons per day system. The 10 tons per day system is used because fixed costs have been estimated at that processing rate and is therefore easier to analyze this way. It is probable that the costs will not vary linearly for pyrolysis systems ranging between 10 and 50 tons per day, the exact nature of the variation is left for future work. Table 16 shows primary results from this scenario.

Table 16. Scenario 5 results

	Baseline
Annualized Fixed Costs	$45,599
Annual Variable Costs	$81,382
Break-even Selling Price ($/GJ)	18.47

The break-even selling price of $18.47/GJ is much better than that for the baseline Scenario 2 case, but is still probably not competitive with other energy sources except in extreme scenarios. A break-out by category of the predicted costs is found in Figure 24. Because of the significantly reduced labor rates, labor is no longer as significant of a factor in the costs. In this scenario, labor is significantly minimized to only 23% of the costs from 56% in Scenario 2. These results can be directly compared to the other 10 ton per day baseline results from Scenario 2 found in Figure 21.

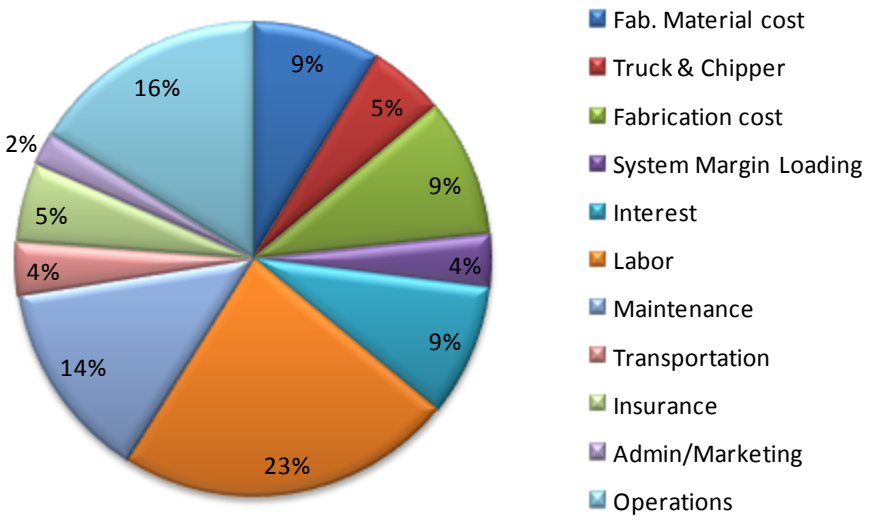


Figure 24. Categorization of Scenario 5 annualized costs.

Scenario 6

This final scenario omits the costs associated with the chipper. The chipper hardware represents a comparatively small cost in all previous analyses. Fixed costs change marginally based on this modification. However, it significantly affects the variable costs, as running the chipper essentially doubles the labor costs. There are also additional fuel and transportation costs that arise from the need to power and transport the chipper and the work crews.

Table 17. Scenario 6 results

	Baseline
Annualized Fixed Costs	$115,856
Annual Variable Costs	$176,394
Break-even Selling Price ($/GJ)	7.53

The break-even selling price of $7.53/GJ is considerably lower than that of the baseline Scenario 1 price of $11.17/GJ. This suggests that the chipping is a significant fraction of the costs to Scenario 1. The chipping is mostly different in the variable costs, as labor and transportation are the most significant costs associated with chipping. The chipper machine is inexpensive by comparison. A break-out by category of the predicted costs is found in Figure 25. In this scenario, labor is significantly minimized to only 34% of the costs from 49% in Scenario 1. These results can be compared to the similarly annualized baseline results from Scenario 1 found in Figure 19.

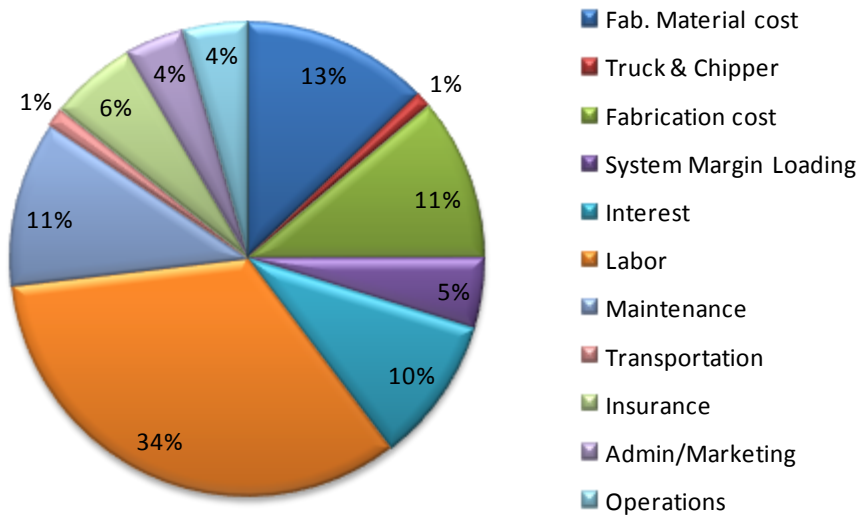


Figure 25. Categorization of Scenario 6 annualized costs.

4.5 Economic Analysis Discussion

Figure 26 summarizes the break-even prices for the various scenarios. In this figure, the break-even price ignoring the char as a co-product is also plotted, data for which were not presented in the previous section. The above presentation data all utilized the nominal price per GJ for selling char to illustrate the potential costs. It can be seen that assuming approximately $75/ton for the char almost uniformly results in a $2/GJ reduction in break-even costs. This price for the char is probably reasonable based on previously presented data on the value of biochar and coal fuel. But if much higher estimated values for the char are in fact possible, it might significantly improve the break-even point for the pyrolysis system.

It can also be seen that the 10 ton/day scenarios (2 and 5) appear unlikely to be economically viable, and an increase in productivity to 50 ton/day will make a significant improvement. The only concern with regard to the 50 ton/day system is that a final design will likely be challenged to meet all the function, size, weight, and processing productivity criteria simultaneously.

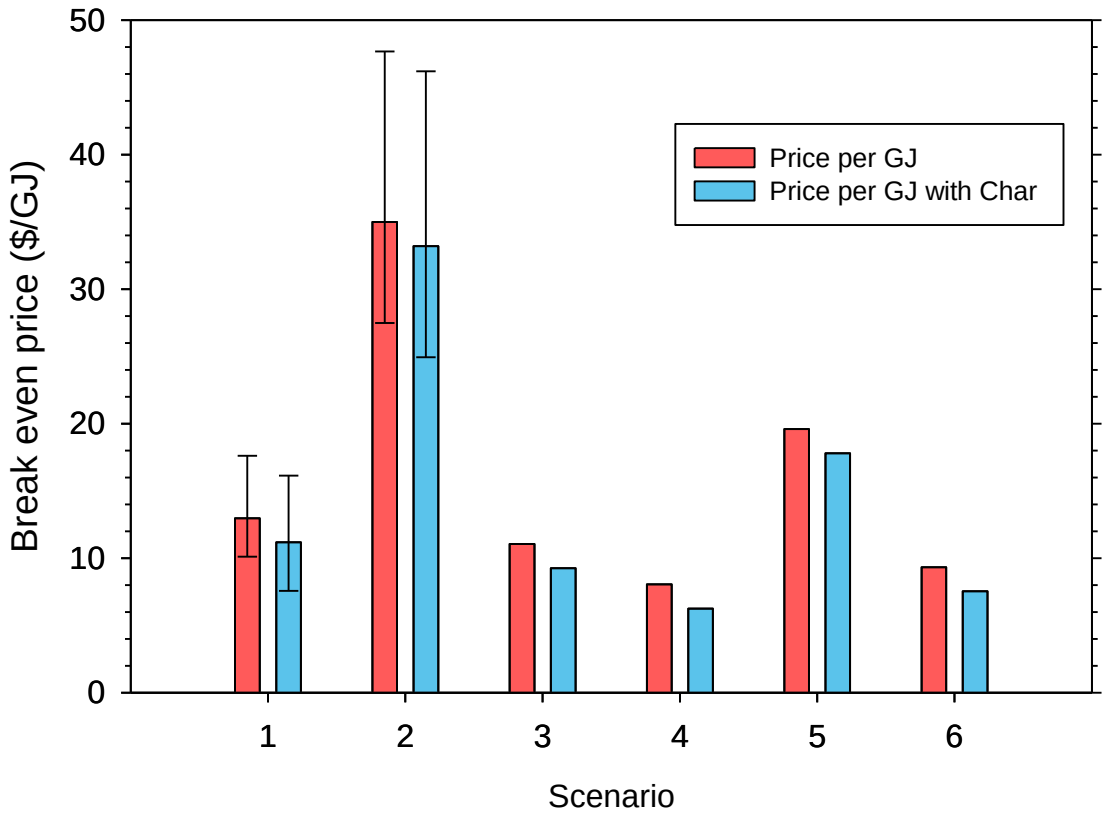


Figure 26. Break-even pricing summary.

Scenario 1 presents the best estimate break-even costs for mobile pyrolysis technologies, with just over 11 $/GJ. Scenario 3 and 6 both show lower costs than the Scenario 1 baseline, and represent potentially realistic ways the break-even price of mobile pyrolysis can be reduced. Unless a continual supply of no-cost chipped or shredded biomass can be secured, it is likely that Scenario 1 is closer to true costs assuming a single work crew compared to Scenario 6. It is possible that a portion of processed biomass could come from sawmills and wood product industries, in which case break-even costs would fall between those suggested by Scenario 6 and 1. The difference between Scenario 1 and 6 costs represents the estimated cost of chipping, which is approximately $3.6/GJ. Similarly, if multiple full-time crews were used with hardware annually and some portion of the biomass did not require chipping, a further combined reduction might be possible.

Scenario 4 shows the lowest break-even pricing of all the scenarios at about 6¼ $/GJ. Labor rates common to other parts of the world make a clear difference in the ability to profit from a system as is proposed in this work. At 19%, labor is not as dominant of a factor to the overall costs. Further reduction in the break-even price is realistically possible too. Interest is 12% of the cost with 100% of the fixed costs financed. Putting money down reduces the interest costs. Fabrication was assumed at U.S. labor rates. The operations labor rate assumed was only 25% of the loaded US value to

provide quality income to the labor. One could reasonably assume 10% or less, since minimum labor rates in many parts of the world are different from U.S. rates on that order, and our analysis assumed a labor rate that is quite a bit above U.S. minimum. One can also consider similar strategies evaluated with Scenario 3 and 6 by working double crews and finding pre-sized source material for further reductions. At 6 $/GJ for break-even, pyrolysis oils may be competitive with other energy sources. This may be more particularly true in fossil fuel energy importing countries.

Some comment is warranted on the uncertainty estimates made for Scenarios 1 and 2. In magnitude, they are a fairly high percentage of the total value, in the 25-50% range. There is no particular confidence interval value that can be placed on their magnitude. But because the variations selected were all realistic representations of possible outcomes, they represent a real range of prospects for the performance of a system. Even though the nominal break-even values may show that there is profit margin for the technology, the potential for some issues arising could very easily result in the costs being significantly higher or lower than the baseline predicted costs. It will probably require additional experience with more appropriately scaled prototype systems before more accurate data can be presented. Actual costs could be anywhere in the range that has been presented.

The annualized categorization plots presented above with each scenario help suggest the fraction the break-even prices can be reduced for a similar reduction in the individual category. Changing labor to zero (assuming penal or volunteer labor), for example, can only result in a 19% decrease in the break-even price for Scenario 4. To further decrease that value, savings would need to come from other categories. Other costs as estimated will be difficult to change, like materials costs, transportation, maintenance, and insurance. To significantly reduce the break-even price for Scenario 4, one would need to find savings across many categories, as there is not one dominant category. Reducing costs for other scenarios where labor is the dominant factor are more easily attained through reductions in the largest (labor) cost.

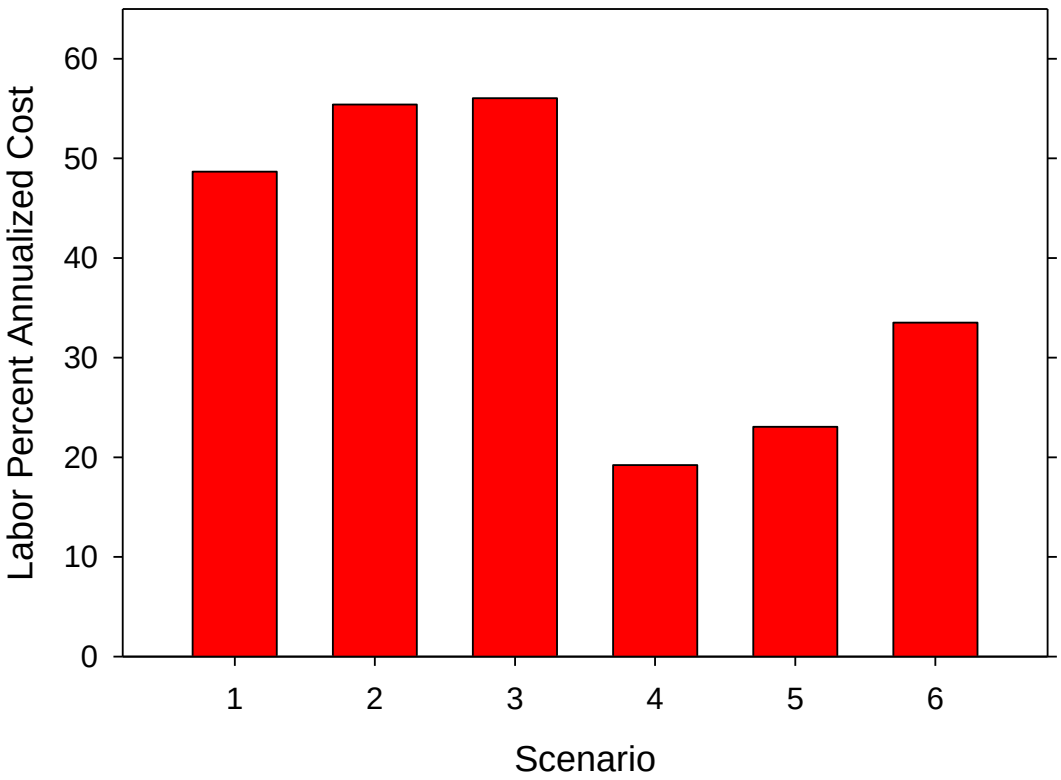


Figure 27. Labor percent costs by scenario.

Probably one of the clearest findings from the economic analysis as a whole is that the labor costs are the most significant driving factor in the potential for pyrolysis fuels at the scales considered. Figure 27 shows the labor percent of annualized costs plotted for the six scenarios. Since the peak portable scale is believed to be limited by volume and weight of the system, the peak production assumed in this paper (50 tons per day) is thought to be close to that which can be achieved using the portable model. Further increase in scale changes the dynamics completely, requiring the biomass to be moved to a central location for processing. This is a dramatic change in system model, and would require significant modifications to the current assumptions. Assuming further increase can ameliorate the labor cost penalty, but would mean that the biomass must be purchased at the point of processing. This is accepted in previous work as an assumption, that the biomass is assumed to 'cost' around $50-75 per ton, which is essentially the price for delivery (e.g. Ringer et al. 2006).

Figure 28 shows a graphical break-out of annualized fixed and variable costs by scenario. Already knowing labor costs are the largest sub-category expense, it is not surprising that variable costs for all scenarios are the highest. Perhaps the most illustrative points from this figure are that the capital expenses in the fixed cost category can be heavily minimized by

operating multiple shifts (Scenario 3), and that for Scenario 4, the capital costs are maximized as labor becomes less of an expense.

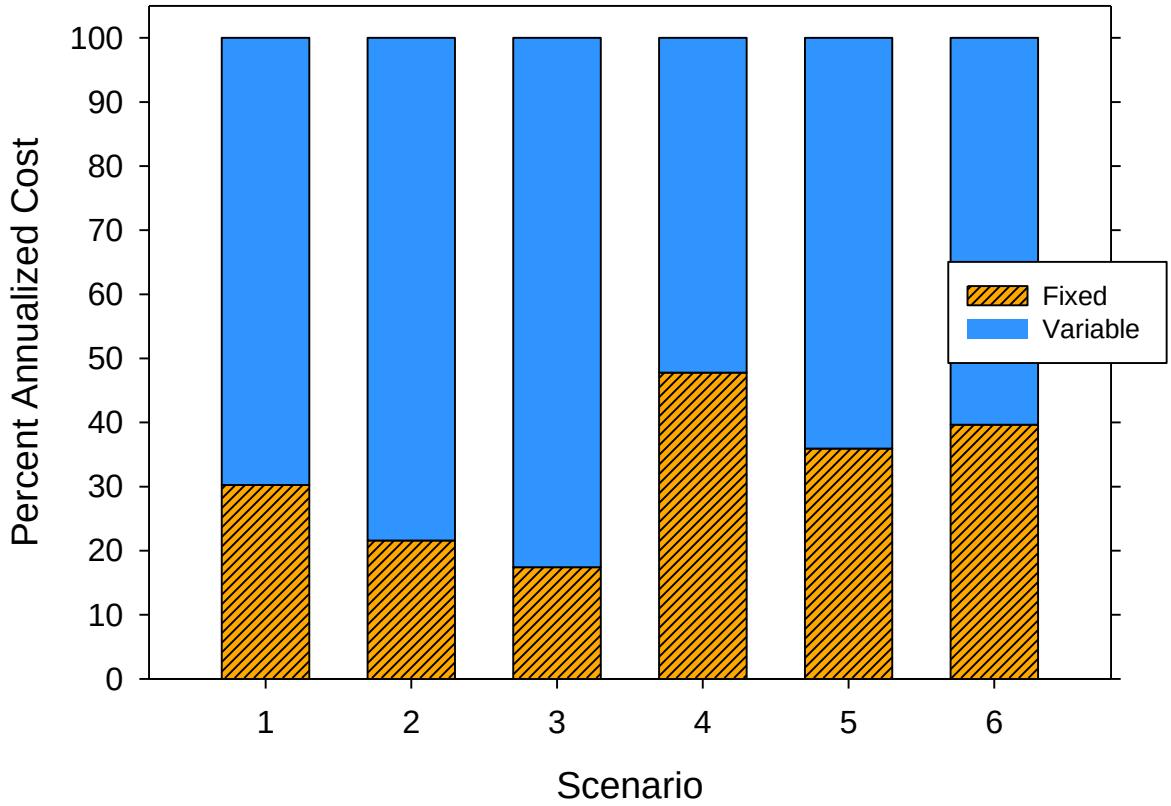


Figure 28. Fixed and variable percent costs by scenario.

Other studies have evaluated various models for pyrolysis systems. Ringer et al. (2006) summarize several previous analyses with varying scale and model assumptions. Analyses were conducted over a range of years, a fact which was not accounted for by weighting the costs to inflation. Also, a variety of feed-stocks and models were assumed, which are presumably contributors to the spread in predicted production costs. For comparison, historical production costs in that report ranged from $5.00-$30.00/GJ for pyrolysis oils. A more recent estimate (Badger et al., 2011) suggests that by valuing pyrolysis oil at $10.4/GJ for a 100 ton/day fixed plant operated full-time in shifts that a 37% profit could be realized. Some previous work dismisses the viability of smaller-scale fully transportable operations. However, our price estimates under some reasonable operating assumptions can fall within the range of the Badger et al. (2011) price, suggesting that the largest transportable system may be cost competitive with a small fixed plant under favorable operating conditions.

An advantage of centralized processing is that more efficient techniques could be used, like electrical power, fluidized bed reactors, and higher processing rates. A fluidized bed reactor might be made portable, but they

normally are vertical in design, and might be difficult to design for 50 tons per day given the vertical constraints of a trailer based system. The auger system we are evaluating is believed to have the advantage of compactness. Fluidized bed systems under idealized conditions have been able to yield 70% liquids, which would have a positive effect on the economic viability of the process. With a fluidized bed system, aerodynamic cyclone-type char separators are considered a requirement. There is also a need for increased energy to fluidize the bed. The scope of the current project did not provide enough data to appropriately assess the differences. A subsequent study on the optimal method for portable pyrolysis would be very interesting, and could find auger or fluidized bed systems to be more optimal, if not equivalent. Ultimately, the driving factor for either system may be the productivity of the labor, or in other words the maximization of the mass processing rate.

The end use of the pyrolysis oils has been generally neglected in this study as being beyond the scope of the work. A serious hurdle for implementing a regional biomass management model involving pyrolysis oils is that there is not a mature market for the product. They cannot necessarily be directly mixed with fossil fuel in refineries, or directly used in fossil fuel energy systems without custom modification. Some modifications to existing systems like fuel oil heaters or Diesel engines have been proposed, and might be moderately simple to implement. But without a commercial source for the pyrolysis liquids, there is limited motivation to provide a commercial product that can use them. This is a challenge, in that new product development and investment involving risk and potential short-term loss is required on both the supply and demand side before the product can be produced and sold productively in a market environment.

Burners and combustors provide a direct use of the pyrolysis oils. The catalytic upgrading pathway is also a potential use for the oils, which involves hydrotreating and refining. Solantausta et al (1992) show primary oil and refined product costs. The refined product under varying assumptions is $5-9/GJ more than the primary oils to produce for wood feed-stocks. These estimates are almost 20 years old, so there is an inflation adjustment that should be made to the costs. If as a general rule the break-even price is doubled for the pyrolysis oils after refining, there is some potential for wood pyrolysis oils to compete with liquid transportation fuels directly at current market prices.

5 General Discussion

The previous two sections included their own discussion sections. However, considering both together, some further discussion is warranted to help explain and summarize the results of the study. There is also a need to provide a discussion around what makes sense as follow-on research.

The experiments were an important aspect of the final goal of this work, the economic analysis. The economic analysis would not have been as credible without having performed the experiments. The experimental work gave some confidence in the methods proposed that would not have been possible by simply examining reports from previous work. Even though this research is not the first to consider features such as auger driven pyrolysis, portable pyrolysis, gas recirculation, staged condensation, and other methods believed to be ideal for the distributed pyrolysis process, there was not appropriate and sufficient data in the literature at the commencement of this study to confidently proceed with an economic analysis. Even considering the comparatively rapid publication of relevant studies, there were and still are significant uncertainties with the performance and ideal nature of a design as is being considered in this work. The next two sections summarize some of the uncertainties and present some ideas for potential follow-up efforts.

5.1 Risks and Uncertainties

The techno-economic analysis has suggested production costs for pyrolysis oils including their delivery immediately following production to a storage tank. There are additional costs for fuels that have not been factored in to this analysis. These include whatever margin is required by the processing companies that process the wood to liquid. There may be distribution costs, refining costs, delivery costs, etc. that need to be factored in. The values presented should not be considered retail prices. Even though there is this clear need for including other factors that increase costs to the consumer, this study deliberately avoided assessments of those costs. This is because there are many different potential end applications for the materials generated by pyrolysis. They can compete in the energy market in many different ways, each one having a different target price for viability that changes as energy markets fluctuate. There is clear benefit to find a use for the materials that will maximize the selling price. Since there are so many potential uses of the product, it was decided to estimate the production cost and leave the rest of the economic modeling to future investigators with a clearer idea of the exact use of the materials generated. If there were infrastructure such as refineries, domestic or commercial burners, or power stations that had the ability for immediate use of the material, it would have made sense to factor that in to the study. But since work is needed on both the supply and demand side to make commodities of the products and

production equipment, there will need to be follow-on work before uncertainties in this regard are reduced.

With the work described above as background, it is worthwhile to discuss where the biggest uncertainties are believed to be. We have suggested that the pyrolysis gases could fuel the furnace, contrary to formerly published results (Badger et al., 2011). However the validity of this assumption is not clear, and requires significant controls design at a minimum to effect. We suggest and assume in the economic model that the furnace can be powered by direct combustion of the gases. However this does not simply require that the energy in the gases be equal to the furnace requirements, as it would be nearly impossible to exhaust the gases at ambient temperature having removed all their energy. Significantly more energy from the gases is required than the minimum electrically required energy. At 575°C and 14 g/min, we were not close to meeting that requirement. Our operations suggest higher mass feed rates can help obtain this. But this was only demonstrated for the 650°C operating temperature, which is not considered the ideal set-point for operations. This problem is anticipated to be one of the largest issues with a full-scale design. It is curious that Badger et al. (2011) suggest the need for char combustion to power the furnace and dryer. Their numbers are based on some assumed flow and furnace effectiveness, which is not discussed in detail with the dialog surrounding the documentation of the energy requirements. A more detailed presentation of the assumptions that go into the model would be helpful, as would additional assessments by different research groups.

Another couple of problems with our bench-scale system that will likely remain issues for a full-scale system are the deposits in the condensers and the effectiveness of the condensers. In reviewing the literature, both of these are acknowledged as issues, but there is not a lot of emphasis on their resolution. In our testing we never well resolved either of these. They are therefore fitting to remain as points of caution. If energy intensive measures are required to deal with these issues, they have not been factored into the current model.

Another large uncertainty is whether the performance of the bench scale system described herein is representative of what would be obtained from a full-scale system. It is well known that many physical processes do not scale linearly, and accommodation will be required to deal with non-linear aspects. Unfortunately, it is not obvious what will directly scale and what will not. For example, the small furnace may be more or less effective at heating the biomass moving through the system compared to a large furnace. This single uncertainty probably is cause to consider an intermediate-scale prototype before investing fully in the full-scale 50 ton/day system. The intermediate-scale system would not be expected to produce cost competitive product, but would be a helpful intermediate step for a lower investment cost that could be used work out some of the scaling issues in the system design.

Also related to the bench-scale testing, the pellets used are not identical to the proposed forest feed-stock. Being wood, the pellets are likely in ways a good surrogate. But there may be some performance change as different feedstocks are fed to the pyrolysis system.

There is no reason the pyrolysis system must only be used for woody biomass. Other agricultural residues can be processed through the same system, although they may have different yields. There are probably lifetime, control, and maintenance issues related to the types of biomass used in the system.

An energy balance on the flow of materials was never performed. Such analysis might be a helpful step towards providing a designer with good information on sizing and performance of parts to the full-scale system. Some thermal energy remains with the chars, and there will need to be a holding area that can hold the material until it cools to the point where it can be safely managed. As we showed, there are regeneration opportunities with counter-flow condensers. The optimal system design may need to take advantage of many of these types of opportunities to meet the requirement that it demand minimal external input as it is operating in the field.

Another risk that has not been well discussed is that of acceptance. If land owners and managers are leery of the technology or safety, they may not permit harvesting. Or they may try to sell access, which would adversely affect the present model. Pyrolysis liquid generation is not well understood by the public. There would be benefit to having studies performed on regional land use cycles using a pyrolysis system too to assuage some potential concerns.

5.2 Recommended Path Forward

Compared with other renewable biomass energy technologies pyrolysis processes are proven and significant additional research or developments to yield a working technology is not required. With information currently existing, a capable engineer could design and have constructed a reactor. Some controls, material selection, and process optimization would be required, but the core technology exists and is well documented. The same is true for end-use applications for pyrolysis liquids. Systems could be generated to combust the liquids for energy, and existing systems could be moderately easily modified to function with the pyrolysis liquids as a fuel. Most of the efforts in this regard can be focused on process refining, optimization, and improving utilization methods. If a focus is made on cost reduction, the technology might be demonstrated to be more efficient than that assumed in the baseline analysis.

Some continuing research on pyrolysis oil systems would be profitable. Issues with the technology such as the acid content and stability of the

pyrolysis products are present research topics. More detailed work on fractionation of the products using multi-staged condensers would be helpful. Handling and transport issues for large-scale systems could also be an issue, and some effort in understanding these issues would be helpful.

Mentioned earlier, there is need for infrastructure on both the supply and demand side for pyrolysis oils to become a viable market product. Until uses for the products exist, there is no need to make the product. Because of the significant cost benefit to operating in other parts of the world, it seems to make sense to identify a good candidate location, or several, where the economic model has more flexibility and profit margin. One would start by building both production and utilization prototypes that meet the supply and demand requirements. The economic model would further benefit if there were governmental support through subsidies or other incentives, as exist in some regions. If the methods prove productive, significant business growth may ensue. Once profitable designs exist, it is to the financial benefit of businesses to sell as many as they can. It is likely that multiple prototypes will be required for a portable pyrolysis system before a mature and optimal version exists. For use of the liquid products, combustors might not be as complicated as wood to liquid production plants, but would need to be tested to make sure that they are fully compatible with the fuel and to understand lifetime issues. The refined fuels route is also interesting, but the infrastructure to refine pyrolysis oils would need to be acquired and well tested.

This study makes no direct argument for or against the viability for the portable pyrolysis technology in the Northern New Mexico region, except for the 10 ton/day model that clearly cannot compete at current prices. The production costs presented do not directly suggest viability for any of the cases, as the end market for the products has a significant impact on the profitability. Although the recommended rout to commercialization of this technology is through more cost-effective locations, this can be circumvented. An investor who is willing to take the effort to build and field prototype units and to design end use equipment for using the oils might be able to build a profitable business. Among the literature reports on pyrolysis, there may be some active commercialization effort presently ongoing. A Canadian company is presently marketing a product for performing mobile pyrolysis[8]. Profitability would be more likely if fossil fuel prices continue to rise. Profitability compared to the fluctuating fuel markets is expected to be one of the major risks of the endeavor, unless long-term contracts or other mitigating factors exist.

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[8] http://www.agri-therm.com/; accessed October, 2011

6 Conclusions

A bench-scale pyrolysis test unit was designed to evaluate the performance of a biomass pyrolysis system concept proposed for a model where woody biomass from thinned forests is processed to a liquid fuel near where it was grown. Assumptions were selected to be representative of current Northern New Mexico conditions. The experimental results were combined with estimates and information from other studies to provide a techno-economic assessment of the break-even cost of generating pyrolysis oils using portable processing hardware. This model minimizes the transportation costs that tend to be high in other studies, where costs are associated with shipping raw biomass to a central processing plant. Shipping of the liquid pyrolysis products can be more effective than shipping raw biomass because of the increased density of the liquid being shipped.

Major experimental findings include:

- Pyrolysis of wood pellets in an auger system resulted in 55-60% liquid yields with temperatures in the range of 500-650°C.
- Liquid yields of pyrolysis oils of around 60% with a water content of 30% were found at the best thermal conditions of around 525°C furnace temperature. Liquids have calorific values in the expected range based on historical work.
- Gas yields are mostly CO, CO_2, methane and other hydrocarbons. An energy analysis suggests that there may be enough chemical energy in the non-condensable gaseous products to power some or all of the systems necessary for the process as long as the wood mass feed rate is sufficiently high.
- There is a controls issue with using the gas for pyrolysis energy, as increasing temperature will increase both the quantity of gas and the energy in the gas evolved creating a potential for thermal run-away.
- Pyrolysis in the re-circulated gases worked well for the bench-scale system, reducing or eliminating the necessity for an external supply of an inert carrier gas.
- Nutrients such as inorganic compounds and nitrogen are mostly retained in the char. This suggests that the char may be valuable as a soil enhancement co-product, representing a significant benefit to this model of biomass utilization. The char could be shipped to farms, or left behind to maintain soil quality. It also suggests the pyrolysis oils can be reacted much more cleanly than raw whole biomass that has higher nitrogen and mineral fraction.

- Multi-staged condensation provides a simple means to fractionate the products, and should be further explored as a way to improve the process and product.

Major findings of the techno-economic analysis include:

- Nominally, pyrolysis oils can be produced in Northern New Mexico for a break-even cost of around 11 $/GJ. Reductions of several $/GJ are possible by increased utilization of the fixed cost components, and by finding supplies of pre-chipped or pre-sized biomass.
- High uncertainty exists around pyrolysis system costs.
- Labor is the dominant cost to a portable pyrolysis model.
- The technology may be more profitable internationally, as labor costs can be significantly reduced. Break-even production costs using generous international labor rates might be as low as 6 $/GJ, or lower depending on operational conditions.
- Economies of scale arguments apply and suggest that the largest portable system that can be constructed will probably be the most cost-effective to operate.
- Char co-products help the viability of this process, with the sale of char at $75/ton resulting in around a 2 $/GJ reduction in price over a model where the char is not considered a profitable product.
- Chipping represents a significant cost, estimated at approximately $3.5/GJ of energy product produced.

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8 Appendix

Suggested parts list and costs for 10 ton/day system:

				20 ton / 24 hr					
pyrolysis furnace		unit price	unit	num need	multiplier	material cost	labor	design	notes
	auger	$ 250.00	per foot	2	9	$ 4,500.00			2- 16" open cent augers
	inner furnace body	$ 200.00	per foot	2	10	$ 4,000.00			2- 16" schedule 10 pipe 10' long
	outer furnace body	$ 490.00	per sheet	5	1	$ 2,450.00			
	furnace design	$ 125.00	per hr	200	1			$ 25,000.00	design dependant on burner and chip dryer
	furnace build	$ 75.00	per hr	200	1		$ 15,000.00		
	flue	$ 144.24	ea	2	1	$ 288.48			McMaster Carr 1716k136
	insulation	$ 58.04		2	1	$ 116.08			aluminum face insulation 3" thick McMaster Carr 93315k88
	auger pillow blocks								dual bearing shaft that mates to auger, each end of oven
	bearing	$ 28.53	ea	4	1	$ 114.12			McMaster Carr 5709k17 + 5709k56
	motor coupler	$ 50.01	ea	2	1	$ 100.02			McMaster Carr 2306k14
	furnace connector	$ 187.00	custom	2	1	$ 374.00			8" weld on pipe flange
	motor support	150	custom	2	4	$ 1,200.00			
	bearing support housing	$ 139.00	custom	4	1	$ 556.00			8" pipe flange blank - machine for bearing / motor support
	rope seals - high temperature	$ 3.71	per foot	2	1	$ 7.42			McMaster Carr 8828k72
	design	$ 125.00	per hr	40	1			$ 5,000.00	design / drawing
	manufacture	$ 75.00	per hr	60	2		$ 9,000.00		manufacture
	chip inlet connection		custom						connectors to shuttle valve
	design	$ 125.00	per hr	25	1			$ 3,125.00	
	manufacture	$ 75.00	per hr	45	2		$ 6,750.00		
	materials	$ 800.00	custom	1	2	$ 1,600.00			
	char outlet connection		custom						connectors to shuttle valve
	design	$ 125.00	per hr	25	1			$ 3,125.00	
	manufacture	$ 75.00	per hr	45	2		$ 6,750.00		
	materials	$ 800.00	custom	1	2	$ 1,600.00			
	chip lift auger	$ 20,000.00	COTS	1	1	$ 20,000.00			COTS system inclined with input agatior , 8' rise
	dryer auger	$ 200.00	per foot	2	9	$ 3,600.00			
	dryer shell	$ 150.00	per foot	2	10	$ 3,000.00			
	design	$ 125.00	per hr	40	1			$ 5,000.00	
	manufacture	$ 75.00	per hr	60	1		$ 4,500.00		
	additional materials								
	Interconnect lines	$ 76.73	per foot	40	1	$ 3,069.20			1.5" thin wall staniless steel tube
	install	$ 75.00	per hr	100	1		$ 7,500.00		
	burner	$ 406.67	ea	4	1	$ 1,626.68			66.000 btu/hr drilled pipe gas burners flame tube 60"

				20 ton / 24 hr					
pyrolysis furnace		unit price	unit	num need	multiplier	material cost	labor	design	notes
	recirculation blower	$ 250.39	ea	1	1	$ 250.39			10 cfm
	gas burner blower	$ 250.39	ea	1	1	$ 250.39			10 cfm
	furnace motor	$ 649.80	ea	1	1	$ 649.80			60 rpm @ 476 # in / torque
	furnace motor speed controller	$ 369.00	ea	1	1	$ 369.00			speed controller for furance motor
	trailer	$ 8,560.00	ea	1	1	$ 8,560.00			size based on solid model of system
	build of unit on trailer								
	design solid model	$ 125.00	per hr	480	1			$ 90,000.00	need to model all compoents and then place on trailer
	assemble field unit	$ 150.00	per hr	960	1		$ 144,000.00		
System monitors:									
	main panel display	$ 1,090.98	ea	1	1	$ 1,090.98			digi key t-55621d175j-lw-a-aan-nd
	logic system								
	PAL design	$ 125.00	per hr	16	1			$ 2,000.00	
	hardware design	$ 125.00	per hr	40	1			$ 5,000.00	
	software design	$ 125.00	per hr	80	1			$ 10,000.00	
	hardware build	$ 75.00	per hr	80	1	$ 6,000.00			
	full system wiring	$ 125.00	per hr	80	1		$ 10,000.00		
	VFD speed controller								
	2 hp	$ 766.71	ea	3	1	$ 2,300.13			
	1/2 hp	$ 697.43	ea	6	1	$ 4,184.58			
	VFD speed controller								
	2 hp	$ 766.71	ea	6	1	$ 4,600.26			
	1/2 hp	$ 697.43	ea	4	1	$ 2,789.72			
	O2/CO in recirculation system	$ 1,000.00	ea	1	1	$ 1,000.00			mcmaster carr 3937k21 + 3937k29
	Furnace temperature	$ 62.00	ea	4	1	$ 248.00			thermocouple
	Chip dryer temperature	$ 62.00	ea	4	1	$ 248.00			thermocouple
	Liquid level tank 1, 2 , 3, 4	$ 226.72	ea	4	1	$ 906.88			ultra-sonic --- mcmaster carr 5354k24
	Furnace rpm	$ 211.93	ea	1	1	$ 211.93			shaft endcoder + read out mcmaster carr 14215t11 + 14215t22
	Dryer – chip feed rpm	$ 42.32	ea	1	1	$ 42.32			shaft endcoder
	Feed / dump shuttle rate	$ 42.32	ea	1	1	$ 42.32			shaft endcoder
	Recirculation flow rate	$ 42.32	ea	1	1	$ 42.32			shaft endcoder
	Gas burner flow rate	$ 42.32	ea	1	1	$ 42.32			shaft endcoder
	Air charge flow rate	$ 42.32	ea	1	1	$ 42.32			shaft endcoder
	Inlet cooling water temp stage 1 condenser	$ 62.00	ea	1	1	$ 62.00			thermocouple
	Inlet cooling water temp stage 2 condenser	$ 62.00	ea	1	1	$ 62.00			thermocouple

				20 ton / 24 hr					
pyrolysis furnace		unit price	unit	num need	multiplier	material cost	labor	design	notes
generator									
	8000 watt propane generator	$ 2,195.00	ea	1	1	$ 2,195.00			Genrac 5870 8kw propane / natural gas generator
	convert to run on bio-gas	$ 500.00	ea	1	1	$ 500.00			
Flow control valves:									
	Propane / pyrolysis gas	$ 409.09	ea	2	1	$ 818.18			switch between bio-gas to propane mc master carr 8117k35
	Recirculation / gas burner	$ 711.85	ea	1	1	$ 711.85			flow control to bio-gas compressor mc master carr 8117k56
bio-gas compressor									
	tankless compressor	$ 902.48	ea	1	1	$ 902.48			mcmaster carr 8280k14
	tank regulator	$ 106.86	ea	1	1	$ 106.86			low pressure gas regulator 4677k51
Stage 1 condenser (gas to liquid)									
	Condenser	$ 15,000.00	ea	1	1	$ 15,000.00			
	Heat exchanger	$ 528.11	ea	1	1	$ 528.11			57000 BTU/hr cooling @ 36 gal/min 3525k41
	Heat exchanger fan	$ 51.10	ea	1	1	$ 51.10			7713 cfm @ 1725 rpm
	Cooling Pump	$ 374.55	ea	1	1	$ 374.55			35 gpm water pump
	Interconnect lines	$ 76.73	per foot	20	1	$ 1,534.60			1.5" thin wall staniless steel tube
	Drain valve	$ 360.94	ea	1	1	$ 360.94			mc master carr 2.5" ball valve
	drain vent	$ 11.59	ea	1	1	$ 11.59			20 gpm drain vent with SS screen mc master carr 4473k21
	Lift pump	$ 1,169.94	ea	1	1	$ 1,169.94			stainless housing , stainless gears 43095k26
Stage 2 condenser (gas to liquid)									
	Condenser	$ 15,000.00	ea	1	1	$ 15,000.00			
	Heat exchanger	$ 528.11	ea	1	1	$ 528.11			57000 BTU/hr cooling @ 36 gal/min 3525k41
	Heat exchanger fan	$ 51.10	ea	1	1	$ 51.10			7713 cfm @ 1725 rpm
	Cooling Pump	$ 374.55	ea	1	1	$ 374.55			35 gpm water pump
	Interconnect lines	$ 76.73	per foot	20	1	$ 1,534.60			1.5" thin wall staniless steel tube
	Drain valve	$ 360.94	ea	1	1	$ 360.94			mc master carr 2.5" ball valve
	drain vent	$ 11.59	ea	1	1	$ 11.59			20 gpm drain vent with SS screen mc master carr 4473k21
	Lift pump	$ 1,169.94	ea	1	1	$ 1,169.94			stainless housing , stainless gears 43095k26
Stage 3 condenser (gas to gas)									
	Condenser (simple finned radiator)	$ 7,000.00	ea	1	1	$ 7,000.00			
	Interconnect lines	$ 76.73	per foot	20	1	$ 1,534.60			1.5" thin wall staniless steel tube
	Drain valve	$ 360.94	ea	1	1	$ 360.94			mc master carr 2.5" ball valve
	drain vent	$ 11.59	ea	1	1	$ 11.59			20 gpm drain vent with SS screen mc master carr 4473k21
	Lift pump	$ 1,169.94	ea	1	1	$ 1,169.94			stainless housing , stainless gears 43095k26
Mist separator									
	Separator	$ 5,000.00	ea	1	1	$ 5,000.00			
	drain vent	$ 11.59	ea	1	1	$ 11.59			20 gpm drain vent with SS screen mc master carr 4473k21
	Drain valve	$ 56.94	ea	1	1	$ 56.94			1" drain valve
	Lift pump	$ 1,169.94	ea	1	1	$ 1,169.94			stainless housing , stainless gears 43095k26

				20 ton / 24 hr					
pyrolysis furnace		unit price	unit	num need	multiplier	material cost	labor	design	notes
Storage tanks									
	Chip hopper	$ 890.46	per sheet	3.3	1	$ 2,938.52	$ 3,000.00	$ 3,000.00	marco steel
	Chip pre stage	$ 890.46	per sheet	2	1	$ 1,780.92	$ 1,500.00	$ 2,000.00	marco steel
	Gas storage: 20 gal @ 200psi	$ 2,038.64	ea	1	1	$ 2,038.64			mc master carr 9934k37
	Propane storage 40 # tank	$ 94.58	ea	1	1	$ 94.58			mcmaster carr 79955a39
	Char tank	$ 890.46	per sheet	2	1	$ 1,780.92			marco steel
	Stage 1 storage 400 gal	$ 890.46	per sheet	3	1	$ 2,671.38	$ 1,875.00	$ 3,125.00	marco steel
	Stage 2 storage 400 gal	$ 890.46	per sheet	3	1	$ 2,671.38	$ 1,875.00		marco steel
	Stage 3 storage 200 gal	$ 890.46	per sheet	1.5	1	$ 1,335.69	$ 1,000.00	$ 1,500.00	marco steel
	Mist storage 20 gal	$ 890.46	per sheet	0.5	1	$ 445.23			marco steel
					total	$ 157,566.49	$ 212,750.00	$ 157,875.00	
					total M/L	$ 528,191.49			
				oops @ 20%		$ 633,829.79			
System motors:		watts							
	Chip auger	745.70							COTS
	Chip dryer	372.85							
	Feed shuttle	186.42							3.5 sec index
	Dump shuttle	186.42							3.5 sec index
	Furnace auger 1,2	372.85							17 rpm
	Recirculation pump	372.85							30 cfm
	Gas burner pump	186.42							10cfm
	Cooling pump stage 1	559.27							
	Cooling pump stage 2	559.27							
	Bio-oil agitators stage 1	186.42							10 rpm
	Bio-oil agitator stage 2	186.42							10 rpm
	Make up air for furnace burner	186.42							
	Lift pump for stage 1 , 2 , 3 , mist	372.85							3.3 gpm gear pump mcmaster carr 43095k26
	Heat exchanger fan 1, 2	372.85							
	bio-gas compressor	745.70							
		5592.74							

Suggested parts list and costs for 50 ton/day system:

			50 ton / 24 hr						
pyrolysis furnace		unit price	unit	num need	multiplier	material cost	labor	design	notes
	auger	$ 600.00	per foot	4	9	$ 21,600.00			4 - 20" augers
	inner furnace body	$ 400.00	per foot	4	10	$ 16,000.00			4 - 20" schedule 10 pipe 10' long
	outer furnace body	$ 490.00	per sheet	6	1	$ 2,940.00			
	furnace design	$ 90.00	per hr	400	1			$ 36,000.00	design dependant on burner and chip dryer
	furnace build	$ 73.00	per hr	800	1		$ 58,400.00		
	flue	$ 144.24	ea	4	1	$ 576.96			McMaster Carr 1716k136
	insulation	$ 58.04		3	1	$ 174.12			aluminum face insulation 3" thick McMaster Carr 93315k88
	auger pillow blocks								dual bearing shaft that mates to auger, each end of oven
	bearing	$ 28.53	ea	8	1	$ 228.24			McMaster Carr 5709k17 + 5709k56
	motor coupler	$ 50.01	ea	4	1	$ 200.04			McMaster Carr 2306k14
	furnace connector	$ 200.00	custom	8	1	$ 1,600.00			pipe flange
	motor support	$ 300.00	custom	4	2	$ 2,400.00			
	bearing support housing	$ 139.00	custom	8	1	$ 1,112.00			machine for bearing / motor support
	rope seals - high temperature	$ 3.71	per foot	2	1	$ 7.42			McMaster Carr 8828k72
	design	$ 90.00	per hr	100	1			$ 9,000.00	design / drawing
	manufacture	$ 73.00	per hr	200	2		$ 29,200.00		manufacture
	chip inlet connection		custom						connectors to shuttle valve
	design	$ 90.00	per hr	60	1			$ 5,400.00	
	manufacture	$ 73.00	per hr	120	2		$ 17,520.00		
	materials	$ 800.00	custom	1	4	$ 3,200.00			
	char outlet connection		custom						connectors to shuttle valve
	design	$ 90.00	per hr	60	1			$ 5,400.00	
	manufacture	$ 73.00	per hr	120	2		$ 17,520.00		
	materials	$ 800.00	custom	1	4	$ 3,200.00			
	chip inlet auger	$ 75,000.00	COTS	1	1	$ 75,000.00			COTS system inclined with input agatior , 8' rise
	dryer auger	$ 600.00	per foot	4	9	$ 21,600.00			
	dryer shell	$ 300.00	per foot	4	10	$ 12,000.00			
	design	$ 90.00	per hr	200	1			$ 18,000.00	
	manufacture	$ 73.00	per hr	400	1		$ 29,200.00		
	additional materials								
	Interconnect lines	$ 200.00	per foot	50	1	$ 10,000.00			4" thin wall stainless steel tube with welded interconnects
	install	$ 73.00	per hr	360	1		$ 26,280.00		Tig welded
	burner	$ 406.67	ea	16	1	$ 6,506.72			66.000 btu/hr drilled pipe gas burners flame tube 60"
	recirculation blower	$ 428.80	ea	1	1	$ 428.80			27 cfm blower
	gas burner blower	$ 428.80	ea	1	1	$ 428.80			27 cfm blower

			50 ton / 24 hr						
pyrolysis furnace		unit price	unit	num need	multiplier	material cost	labor	design	notes
Flow control valves:									
	Propane / pyrolysis gas	$ 409.09	ea	2	1	$ 818.18			switch between bio-gas to propane mc master carr 8117k35
Stage 1 condenser (gas to liquid)									
	Condenser	$ 18,000.00	ea	1	1	$ 18,000.00			
	Heat exchanger	$ 3,000.00	ea	1	1	$ 3,000.00			57000 BTU/hr cooling @ 36 gal/min 3525k41
	Heat exchanger fan	$ 51.10	ea	1	1	$ 51.10			7713 cfm @ 1725 rpm
	Cooling Pump	$ 1,500.00	ea	1	1	$ 1,500.00			35 gpm water pump
	Interconnect lines	$ 153.00	per foot	20	1	$ 3,060.00			1.5" thin wall staniless steel tube
	Drain valve	$ 360.94	ea	1	1	$ 360.94			mc master carr 2.5" ball valve
	drain vent	$ 11.59	ea	1	1	$ 11.59			20 gpm drain vent with SS screen mc master carr 4473k21
	Lift pump	$ 1,169.94	ea	1	1	$ 1,169.94			stainless housing , stainless gears 43095k26
Stage 2 condenser (gas to liquid)									
	Condenser	$ 18,000.00	ea	1	1	$ 18,000.00			
	Heat exchanger	$ 3,000.00	ea	1	1	$ 3,000.00			57000 BTU/hr cooling @ 36 gal/min 3525k41
	Heat exchanger fan	$ 51.10	ea	1	1	$ 51.10			7713 cfm @ 1725 rpm
	Cooling Pump	$ 1,500.00	ea	1	1	$ 1,500.00			35 gpm water pump
	Interconnect lines	$ 153.00	per foot	20	1	$ 3,060.00			1.5" thin wall staniless steel tube
	Drain valve	$ 360.94	ea	1	1	$ 360.94			mc master carr 2.5" ball valve
	drain vent	$ 11.59	ea	1	1	$ 11.59			20 gpm drain vent with SS screen mc master carr 4473k21
	Lift pump	$ 1,169.94	ea	1	1	$ 1,169.94			stainless housing , stainless gears 43095k26
Stage 3 condenser (gas to gas)									
	Condenser (simple finned radiator)	$ 12,000.00	ea	1	1	$ 12,000.00			
	Interconnect lines	$ 152.00	per foot	20	1	$ 3,040.00			1.5" thin wall staniless steel tube
	Drain valve	$ 360.94	ea	1	1	$ 360.94			mc master carr 2.5" ball valve
	drain vent	$ 11.59	ea	1	1	$ 11.59			20 gpm drain vent with SS screen mc master carr 4473k21
	Lift pump	$ 1,169.94	ea	1	1	$ 1,169.94			stainless housing , stainless gears 43095k26
Mist separator									
	Separator	$ 5,000.00	ea	1	1	$ 5,000.00			
	drain vent	$ 11.59	ea	1	1	$ 11.59			20 gpm drain vent with SS screen mc master carr 4473k21
	Drain valve	$ 56.94	ea	1	1	$ 56.94			1" drain valve
	Lift pump	$ 1,169.94	ea	1	1	$ 1,169.94			stainless housing , stainless gears 43095k26

			50 ton / 24 hr						
pyrolysis furnace		unit price	unit	num need	multiplier	material cost	labor	design	notes
Flow control valves:									
	Propane / pyrolysis gas	$ 409.09	ea	2	1	$ 818.18			switch between bio-gas to propane mc master carr 8117k35
Stage 1 condenser (gas to liquid)									
	Condenser	$ 18,000.00	ea	1	1	$ 18,000.00			
	Heat exchanger	$ 3,000.00	ea	1	1	$ 3,000.00			57000 BTU/hr cooling @ 36 gal/min 3525k41
	Heat exchanger fan	$ 51.10	ea	1	1	$ 51.10			7713 cfm @ 1725 rpm
	Cooling Pump	$ 1,500.00	ea	1	1	$ 1,500.00			35 gpm water pump
	Interconnect lines	$ 153.00	per foot	20	1	$ 3,060.00			1.5" thin wall staniless steel tube
	Drain valve	$ 360.94	ea	1	1	$ 360.94			mc master carr 2.5" ball valve
	drain vent	$ 11.59	ea	1	1	$ 11.59			20 gpm drain vent with SS screen mc master carr 4473k21
	Lift pump	$ 1,169.94	ea	1	1	$ 1,169.94			stainless housing , stainless gears 43095k26
Stage 2 condenser (gas to liquid)									
	Condenser	$ 18,000.00	ea	1	1	$ 18,000.00			
	Heat exchanger	$ 3,000.00	ea	1	1	$ 3,000.00			57000 BTU/hr cooling @ 36 gal/min 3525k41
	Heat exchanger fan	$ 51.10	ea	1	1	$ 51.10			7713 cfm @ 1725 rpm
	Cooling Pump	$ 1,500.00	ea	1	1	$ 1,500.00			35 gpm water pump
	Interconnect lines	$ 153.00	per foot	20	1	$ 3,060.00			1.5" thin wall staniless steel tube
	Drain valve	$ 360.94	ea	1	1	$ 360.94			mc master carr 2.5" ball valve
	drain vent	$ 11.59	ea	1	1	$ 11.59			20 gpm drain vent with SS screen mc master carr 4473k21
	Lift pump	$ 1,169.94	ea	1	1	$ 1,169.94			stainless housing , stainless gears 43095k26
Stage 3 condenser (gas to gas)									
	Condenser (simple finned radiator)	$ 12,000.00	ea	1	1	$ 12,000.00			
	Interconnect lines	$ 152.00	per foot	20	1	$ 3,040.00			1.5" thin wall staniless steel tube
	Drain valve	$ 360.94	ea	1	1	$ 360.94			mc master carr 2.5" ball valve
	drain vent	$ 11.59	ea	1	1	$ 11.59			20 gpm drain vent with SS screen mc master carr 4473k21
	Lift pump	$ 1,169.94	ea	1	1	$ 1,169.94			stainless housing , stainless gears 43095k26
Mist separator									
	Separator	$ 5,000.00	ea	1	1	$ 5,000.00			
	drain vent	$ 11.59	ea	1	1	$ 11.59			20 gpm drain vent with SS screen mc master carr 4473k21
	Drain valve	$ 56.94	ea	1	1	$ 56.94			1" drain valve
	Lift pump	$ 1,169.94	ea	1	1	$ 1,169.94			stainless housing , stainless gears 43095k26
Storage tanks									
	Chip hopper	$ 890.46	per sheet	3.3	1	$ 2,938.52			marco steel
	Chip pre stage	$ 890.46	per sheet	2	1	$ 1,780.92			marco steel
	Propane storage 40 # tank	$ 94.58	ea	1	1	$ 94.58			mcmaster carr 79955a39
	Char tank	$ 890.46	per sheet	2	1	$ 1,780.92			marco steel
	Stage 1 storage 1000 gal	$ 800.00	ea	1	2	$ 1,600.00			mcmaster car 3764K36
	Stage 2 storage 1000 gal	$ 800.00	ea	1	2	$ 1,600.00			mcmaster car 3764K36
	Stage 3 storage 400 gal	$ 800.00	ea	1	2	$ 1,600.00			mcmaster car 3764K36
	Mist storage 20 gal	$ 150.00	ea	1	2	$ 300.00			mcmaster car 3764k31
	agitator motor/blade	$ 985.00	ea	1	3	$ 2,955.00			mcmaster carr drum mixer 3484k48

			50 ton / 24 hr							
pyrolysis furnace		unit price	unit	num need	multiplier	material cost	labor	design	notes	
					total	$ 354,737.72	$ 324,120.00	$ 152,280.00		
					total M/L	$ 831,137.72				
									design hours	1218
									build hours	4322
System motors:		watts							load rate = hour*2.33	
	Chip auger	2237.10							COTS	
	Chip dryer	745.70								
	Feed shuttle	745.70							3.5 sec index	
	Dump shuttle	745.70							3.5 sec index	
	Furnace auger 1,2	745.70							17 rpm	
	Recirculation pump	559.27							30 cfm	
	Gas burner pump	186.42							10cfm	
	Cooling pump stage 1	745.70								
	Cooling pump stage 2	745.70								
	Bio-oil agitators stage 1	186.42							10 rpm	
	Bio-oil agitator stage 2	186.42							10 rpm	
	Make up air for furnace burner	186.42								
	Lift pump for stage 1 , 2 , 3 , mist	372.85							3.3 gpm gear pump mcmaster carr 43095k26	
	Heat exchanger fan 1, 2	745.70								
		9134.81								

9 Distribution

1	MS 0899	RIM-Reports Management, 9532 (electronic copy)