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Methods for Producing Biochar and Advanced Biofuels in Washington State

Part 4: Literature Review

Sustainability Issues, Business Models, and Financial Analyses

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Methods for Producing Biochar and Advanced Bio-fuels in Washington State

Part 4: Literature Review of Sustainability Issues, Business Models and Financial Analyses

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This report is the last of a series of four reports available on the Department of Ecology's website at: www.ecy.wa.gov/beyondwaste /organics. The reports are titled: *Methods for Producing Biochar and Advanced Biofuels in Washington State*. They are as follows:

- *Part 1: Literature Review of Pyrolysis Reactors*. This report reviews the technologies that have been developed for kilns, retorts and pyrolysers. It can be found at: http://www.ecy.wa.gov/biblio/1107017.html.
- *Part 2: Literature Review of the Biomass Supply Chain and Preprocessing Technologies, (From Field to Pyrolysis Reactor)*. This report reviews biomass sources, collection, and pretreatment. It can be found at: http://www.ecy.wa.gov/biblio/1207033.html.
- *Part 3: Literature Review of Technologies for Product Collection and Refining*. The report describes technologies and methods for bio-oil products recovery and characterization, biochar activation, bio-oil refining strategies and regulatory issues related with deployment of pyrolysis technologies. It can be found at: http://www.ecy.wa.gov/biblio/1207034.html.
- *Part 4: Literature Review of Sustainability Goals, Business Models, and Economic Analyses*. This report focuses on the criteria that need to be followed to integrate these technologies into sustainable business models. The last report presents sustainability criteria and several business models that could be used to build sustainable enterprises based on biomass pyrolysis technologies. It can be found at: http://www.ecy.wa.gov/biblio/1207035.html.

Some figures and photos in this report can be seen in color in the online file. Additional project reports supported by organic Waste to Fuel Technology sponsored by Ecology are also available on this web site. This report is also available at the Washington State University Extension Energy Program library of bioenergy information at www.pacificbiomass.org.

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Beyond Waste Objectives

Turning organic waste into resources, such as compost and biofuels, and the recovery of stable carbon and nutrients along with other products, promotes economic vitality in growing industries, and protects the environment. This creates robust markets and sustainable jobs in all sectors of the economy, and facilitates closed-loop materials management where a by-product from one process becomes feedstock for another with no waste generated.

Disclaimer

This is the fourth in a series of publications on thermochemical (pyrolysis) products and processes to recover energy, fuels, and stable carbon from organic waste. The objective of this series of reports is to describe existing technologies to create clean, non-polluting pyrolysis units. The Department of Ecology and Washington State University provide these publications to the public to help individuals interested in the development of a biomass pyrolysis industry in order to identify suitable technologies for bio-oil condensers, pyrolysis vapor combustion, removal, cooling, briquetting, pelletization and activation of biochar and bio-oil refineries. These reports also summarize the analytical techniques needed to characterize bio-oils and biochar and the permits needed to implement a biomass pyrolysis industry in Washington State. Another major goal of this project is to identify what new technologies need to be developed or what hurdles need to be overcome to convert organic waste resources available in Washington State into valuable products. This review does not represent an endorsement of the processes described and is not intended to exclude any technology or company offering similar services, that due to time and space limitations was not cited.

Executive Summary

This is the last report of a series reviewing the technologies that need to be put together to build a sustainable biomass economy to convert waste lignocellulosic resources into fuels, chemicals and engineered biochar using pyrolysis. The first three reports of this series were descriptions of technologies for: biomass supply chain, pre-processing, pyrolysis reactors, products collection, heat production, bio-oil refining and biochar activation. This report focuses on the criteria that need to be followed to integrate these technologies into sustainable business models. It discusses several sustainability criteria and summarizes cost data needed by engineering practitioners to conduct enterprise-level financial analyses of different biomass economy models based on pyrolysis technologies. Finally we present some approaches to continuously improve these technologies and develop new products. The continuous innovation, evolution and improvement of technologies and products are critical for the success of a sustainable biomass pyrolysis industry.

1. A Sustainable Biomass Economy

During a memorable speech at the Jorburg Summit, the United Nations Secretary, Kofi Annan, discussed the challenges humans face to secure a sustainable future (Annan 2002). He pointed out the existence of two extreme schools of thought about economic development. While the first one focuses on economic gains without regards for the environment, the second school positions itself on the other extreme, downplaying any economic progress because of its potential impact on the environment. He pointed out that, instead of positioning ourselves in one of these two extremes, humans should look beyond these two paradigms and try to live in harmony with their natural environment. Due to our high standard of living, ever-growing population, and the rate at which resources are being consumed, it will be difficult to expand the prosperity that has been enjoyed by one fifth of the humans to the rest of the population with current paradigms. In the past years, humans have destroyed over one third of the natural world. We are today consuming 20% more natural resources than the world can produce sustainably. On one hand, we are destroying much of Nature and on the other, given the current economic structures we must maintain or accelerate development, or market forces will create even greater damage (AtKisson 2001). It seems that our choices are limited to industrial growth destroying the environment, or deceleration of our economic growth with disastrous social consequences. In his speech Annan stresses that the solution is not “ecology versus economy”, it is actually how to integrate these two paradigms (Annan 2002).

And, although science and technology are needed as tools to achieve human sustainability, a renewed sense of spirituality and the sacred in our actions is imperative to life in harmony with our environment (AtKisson 2001). He calls for a new sense of the sacred that is inclusive of our historical heritage, the scientific quest and the technological imperative (AtKisson 2001). In this regard AtKisson (2001) proposes to reinvent the sacred word “sustainability” in such a way “that fascinates the hungry mind, satisfy the heart in search of a meaningful life, draw people to it the way athletes are drawn to compete, the way artists are drawn to create, the way lovers are drawn to each other.” AtKisson (2001) recommends to use the word “sustainability” only when it carries the “full radiance of a dream” that will allow the transformation of the “industrial capitalism or capitalism at all cost” into a more mindful “capitalism conscious of all costs” that is able to function within the earth’s limits (AtKisson 2001, Boyd 2004). Within this new type of capitalism, nature would have a higher value and ecosystems services (regulation of atmosphere and climate, pollination, maintenance of bio-diversity, and cycling of nutrients and water) will have a value to be accounted for (Lovins et al. 2004). Moving towards a sustainable capitalism will require a revolution comparable to the Agriculture Revolution of the late Neolithic and the Industrial Revolution of the past two centuries (Boyd 2004, Flora et al. 2010a). Growing and developing a biomass carbonization industry, to sequester carbon and provide environmental services and energy could be a key component in a transformation into a society that is more sustainable.

Extensive debate occurred in the late 1990’s regarding the appropriate valuation of natural capital (the global stock of natural resources) and ecosystem services in response to an article by Constanza et al. (1997) published in Nature. Perspectives on this debate, published by Constanza (1998) formed the basis for much of the recent societal debate on the issue of sustainability. The essence of these debates is best captured in an article by Daly (2005). Daly states that "the global economy is now so large that society can no longer safely pretend it operates within a limitless ecosystem" and that "the biosphere is finite, non-growing, closed (except for the constant input of solar energy), and constrained by the laws of thermodynamics." He argues that "any subsystem, such as the economy, must at some point cease growing and adapt itself to a dynamic equilibrium, something like a steady state." Daly's three-point plan articulates the principles of transitioning to an ecologically-based economy:

> *The economy must be transformed so that it can be sustained over the long run. It must follow three precepts:*
>
> 1. *Limit use of all resources to rates that ultimately result in levels of waste that can be absorbed by the ecosystem.*
> 2. *Exploit renewable resources at rates that do not exceed the ability of the ecosystem to regenerate the resources.*
> 3. *Deplete nonrenewable resources at rates that, as far as possible, do not exceed the rate of development of renewable substitutes* (Daly 2005).

It is now a common, if controversial, proposition that the development of biomass feedstock-based fuels, chemicals and materials is a key strategy for realizing larger sustainability goals. Anex et al. (2007) wrestled with these concepts of sustainability in the context of the emerging biomass feedstock-based economy, stating that:

> *Whether this is a positive impact or a negative impact will depend largely on how biomass feedstocks are produced and converted, and the extent to which these two activities are integrated. As in any managed ecosystem, nutrient management in industrial biomass … must address multiple criteria, including air and water quality, nutrient use efficiency, and … economics* (Anex et al. 2007).

This fourth report focuses on commercial financial considerations (i.e. business models) for the application of pyrolysis technology as a strategy for sustainable recovery of energy, carbon, nutrients and products from organic wastes. The authors think it is critical to consider the available literature presented below on business models through the larger lens of sustainability which was not necessarily an explicit goal in all the studies reviewed. The authors also recommend that further analyses of the larger sustainability issues presented above be conducted on the implementation of biomass feedstock-based industries to determine whether this emerging industry is actually achieving outcomes consistent with stated sustainability goals.

One of the ways sustainability is being incorporated in today's corporate culture is through triple bottom line analyses (McDonough & Braungart, 2002). The triple bottom line can be understood with a triple E' triangle. Economic profitability, Environmental protection and social Equity are presented as variable indexes on the legs of an equilateral triangle (McDonough and Braungart, 2002). This concept has been used recently for corporations as a tool to improve the environmental performance while maintain economic goals. This tool has resulted in strategies to improve resource use efficiency and drive down waste production while minimizing environmental and social liabilities (McDonough & Braungart, 2002). Sustainability represents an opportunity to build business value through the following drivers: reduced risk and liability, operating efficiencies and cost savings, synergies with stakeholders, and enhanced reputation and brand differentiation (MBDC, 2010).

Moreover, McDonough & Braungart (2002) recommend a stronger focus from the beginning of a project which they call the triple top line. The authors differentiate "top line" (targeting ambitious achievable sustainability goals) versus "bottom line" (targeting minimum sustainability and social requirements). To incorporate "top line" criteria, project designers must consider how to "enhance the well being of nature and culture while generating economic value." http://www.mcdonough.com/writings/beyond_triple.htm, retrieved 1/18/2013) The authors argue that "if one approaches the design process asking, right from the start, how to grow prosperity, celebrate my community, and enhance the health of all species, the result is likely to be far more positive and enriching than measuring performance against a bottom line standard." Introducing positive aspirations in each of our designs and actions is critical to build a sustainable biochar industry. The authors suggest that rather than balancing equity, ecology and economy, an intelligent design should use the dynamics among these three points to create business opportunities and maximize values and services in each of these areas (http://www.mcdonough.com/writings/design_for_triple.htm, retrieved 1/18/2013, http://www.renegademedia.info/books/william-mcdonough.html, retrieved 1/18/2013). The design of sustainable business models based on pyrolysis technologies should adhere to these concepts and should be able to offer beneficial environmental services, enhanced well being to people, while producing economic value in the form of heat, power, transportation fuels and chemicals. Communities in Washington State value a rural lifestyle and access to open spaces, and enjoy seeing healthy agricultural lands, wild lands and wildlife (Flora 2010a). Sensitivity to these values is important for developing a biomass economy in our state (Flora 2010a, McDonough & Braungart 2002).

A sustainable business model perpetuates conditions that allow for the fulfillment of economic, social, and environmental requirements of current and future generations (Figure 1) (US DOE 2010). In the sections that follow each of the components to building a sustainable business model for pyrolysis will be reviewed.

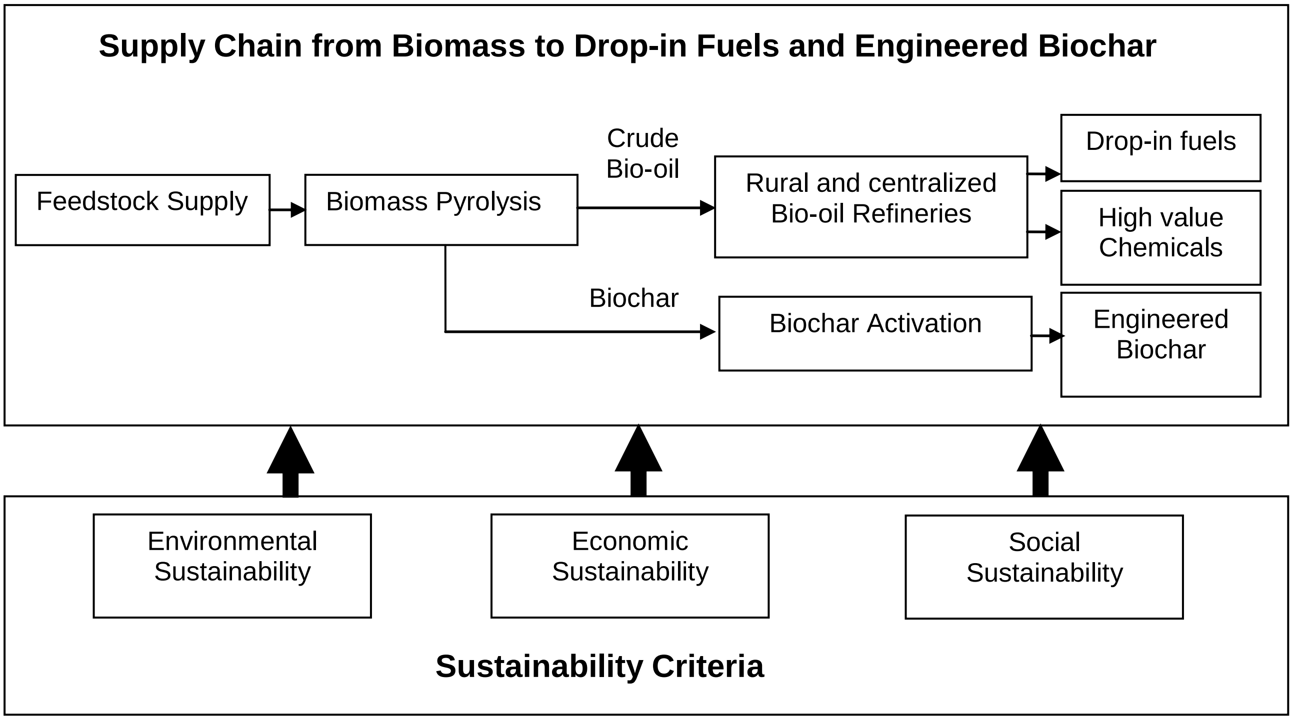

Figure 1. Sustainability criteria affect all aspects of the biomass to bioenergy supply chain (modified from US DOE 2010).

1.1 Environmental sustainability

The International Biochar Initiative (IBI) presents an excellent discussion on biochar production and sustainability (http://www.biochar-international.org/sustainability, retrieved 1/18/13). It is very difficult to provide a complete review of all the issues associated with biochar and bio-oil sustainability (feedstock and land use, personnel production safety, environmental applications and potential impacts, transportation, application, economics, soil and crop sustainability, carbon sequestration ability, stability of carbon in soil, and energy use and output). The number of publications in this area is growing dramatically, so in this section we discuss some of the most important documents published recently. Biochar sustainability principals prepared by the International Biochar Initiative (2012) can be found at: http://www.biochar-International.org/sites/default/files/IBI_Biochar_Sustainability_Principles_September_2012.pdf, retrieved 1/18/2013).

Deploying a biomass pyrolysis industry could be an important component of building a sustainable future because this is one of the few alternatives to sequester carbon. In fact a biomass carbonization industry offers an excellent opportunity to reproduce the natural process of carbon fixation similar to the one responsible for the formation of coal deposits. Though most people look to the improvement in soil fertility and other environmental services that biochar provides as the primary benefit of building a biomass carbonization industry, the use of pyrolysis vapors to produce heat (electricity) or the production of bio-oil to replace fossil fuels are also important components that must be considered when evaluating the sustainability of this industry (Woolf et al. 2010).

Current pyrolysis technologies can recover heat for combined heat and power (CHP), conditioning building space, for thermal industrial applications and oil, and for further refining. However, bio-oil refineries do not currently exist. So, commercial biochar production will likely occur as a result of pyrolysis for heat production. In the future, condensable liquid fuel recovery may be supported by bio-oil refinery capacity. Although, there are very few studies on the combustion of pyrolysis vapors, its combustion products are expected to be much cleaner than those generated when the whole biomass is combusted just as natural gas burns more cleanly than coal.

Small pyrolysis CHP distributed systems could have many advantages over large systems. Half of the energy is contained in the biochar produced and half can be used for heat and electricity production. Lovins (2002) listed 207 benefits of distributed production systems that should be leveraged to develop more competitive systems. Typically small distributed CHP systems sized for the needs of local markets shorten construction period, lower capital and interest costs. These small units can be built on a "pay-as-you-go" basis which can match gradual changes in demand. One of the major advantages of small systems is that they can be integrated well within existing infrastructure. Because these units will use distributed resources, which do not need to be transported long distances, they could produce heat at lower prices. Small systems lower local impacts and they tend to be inherently benign. This would reduce construction risks. These small units could shorten the development and production times which could allow exploitation of rapid learning to develop several generations of the technology in shorter times than is possible when a single large unit is built. Lessons learned during the operation of these systems can be applied incrementally and immediately to a new generation of the product. These small CHP units can be more easily adapted to changes in local feedstock composition and can be adapted to produce biochar for targeted local environmental services. The portability of small systems offers advantages because these units can be more readily sold, with higher salvage value than large centralized units which tend to have high demolition costs at the end of their useful lives (Lovins 2002).

The use of biomass waste resources from recycled and reclaimed wood materials is intrinsically more sustainable that the use of energy crops. However, the ability and reliability of supplying waste materials the whole year is an issue that could be solved by combining the processing of clean processed waste biomass generated by industries, agricultural and forest operations and cities as well as biomass produced as energy crops to create a steady stream of feedstock. Soil quality, biological diversity, and minimal negative land use impact during the feedstock production are critical considerations of a biomass business model that can also be minimized when relatively small systems are used. Replenishing, maintaining, and enhancing soil organic matter is very crucial to develop a sustainable biomass economy. Maintaining a soil cover with biomass provides soil protection from water erosion and wind (Flora 2010a). To help bring biochar into the market, its potential as an ecological sorbent, mediator, and facilitator of environmental services must be more thoroughly demonstrated. The economic value associated with heat, fuels, chemical and biochar provide huge opportunities to develop a sustainable biomass economy based on pyrolysis.

Globally, biochar is being explored to improve soils for crop production, retain soil moisture, remediate polluted sites, and to sequester carbon by storing atmospheric carbon dioxide (CO_2) fixed by plants in stable form in soil. Biochar has also been demonstrated to have numerous environmental applications and ecosystem uses. Recent applications of biochar are evolving and new markets are being created. A spray on fiber mat and seed layer, PermaMatrix, was used to help establish vegetation on an industrial site with drastically disturbed soils (Figure 2). Biochar was admixed (10%) with the fiber mat. The area without vegetation (center, Figure 2) did not receive the biochar mixture. Biochar is currently being used as a filter media to adsorb contaminants in rainwater and stormwater runoff (Figures 3). Kearns (2012) used biochar as a final media in a potable water system.

Figure 2. Soils reclaimed with PermaMatrix mixed with 10% biochar. (Miles 2010, http://www.futureenergyconference.com/2010/FECWA-Presentations/4D_Miles.pdf).

Figure 3. Roof drain using biochar for filtering zinc from roof runoff. (Miles 2010, http://www.futureenergyconference.com/2010/FECWA-Presentations/4D_Miles.pdf).

Biochar is an excellent vehicle to develop robust environmental services. It has been identified as a soil amendment and as a tool for carbon sequestration (Woolf et al., 2010). Studies have indicated that biochar can reduce greenhouse gas off-gassing from soils; CO_2 and nitrous oxide off-gassing for example can be reduced by 60 to 70% (Felder et al. 2005, Taghizadeh-Toosi, et al. 2011). Excellent reviews and report on the effect of biochar on climate change and soil can be found elsewhere (Sohi et al. 2009, Bracmort 2009, Verheijen et al. 2010). Environmental services supplied by soil organic matter can be provided by specially designed biochar thereby contributing to the importance and viability of this industry as well.

Although there may be several mechanisms that allow biochar to be considered as a soil amendment, the direct supply of nutrients to plants and the improvement of nutrients uptake by improving soil quality are considered the two main mechanisms of biochar action (Chan & Xu 2009). Other environmental services that biochar could provide include: (1) the sorption and removal of nutrients (Nitrogen-N, Phosphorous-P) or contaminants (Zinc-Zn, Cooper-Cu, Lead-Pb) from liquid waste streams, (2) odor sorption (such as hydrogen sulphide-H_2S, and organo-sulfur and nitrogen compounds) and removal from gaseous streams and (3) cleanup of contaminated soils.

The practice of payment for ecosystem or environmental services is typically implemented in the form of incentives to farmers and landowners in exchange for use of their land to provide environmental services that benefit households, communities and economies. The Millennium Ecosystem Assessment (Millennium Ecosystem Assessment, 2005) report" (http://www.millenniumassessment.org/documents/document.356.aspx.pdf, retrieved 1/18/13) defined categories of ecosystem services:

1. Food production
2. Fiber production
3. Genetic resources
4. Fresh water
5. Air quality
6. Climate regulation
7. Water regulation
8. Erosion regulation
9. Water purification
10. Water treatment
11. Disease regulation
12. Pest regulation
13. Pollination
14. Natural hazard regulation and cultural services

There are very few studies on the use of biochar as means to provide some of these environmental services. Biochar sorbs nutrient compounds, and may reduce the quantity of fertilizers needed while achieving equal or better crop production. Consequently, biochar mitigates the detrimental effects of nutrients leaching to the surrounding ecosystems.

Likewise urban storm water poses a serious threat by degrading surface water bodies, both in the United States and worldwide. The U.S. National Research Council has named urban storm water a leading source of water quality impairments due to the amount of pollutants it carries into receiving waters; these pollutants include heavy metals, nutrients (P, N), pesticides and industrial organic pollutants. In order to reduce the affect of storm water pollution, green storm water infrastructures (GSIs) are being constructed. These infrastructures are made to filter, and detain and allow runoff – essentially mimicking natural landscapes with predevelopment hydrological conditions. One technique of the GSIs that is particularly popular in the Puget Sound area is the bioretention system (or rain garden). Likewise the use of biochar in living roof systems captures and holds rainwater, putting it to beneficial use while capturing pollutants and reducing run-off. The potential use of biochar in these GSIs and green roof applications, and its effect on the water purification efficiency should be thoroughly studied. This application could greatly increase the markets for engineered biochar.

Biochar could also be an important component of the carbon offset markets (either the compliance or the voluntary market), however, it is not currently recognized as an official method of producing carbon credits but many experts believe it will be soon accepted (De Gryze et al. 2010, Baranick et al. 2011, Diamant 2011, Weisberg et al. 2010). The International Biochar Initiative is working to obtain recognition of biochar in the United Nations Framework Convention on Climate Change (UNFCCC) as a tool for emission reduction and carbon credits for emission reductions that are measurable, reportable and verifiable.

The Climate Trust (Weisberg et al. 2010) conducted an assessment of biochar to determine its appropriateness as a terrestrial carbon sequestration offset and concluded that attractive projects must meet the following criteria: (1) Projects must use waste biomass, that in the absence of the project, will be left to decompose. (2) Projects must account carbon credits by producing 25,000 tons (or more) of biochar in 20 years. This capacity is only related to minimum size for which the carbon credits will be counted and has nothing to do with the scale needed to ensure the economic viability of the business. (3) Projects must consistently monitor the place where the biochar produced is incorporated into the soil.

Biochar is currently being investigated for reclamation of abandoned mines. Over 161,000 abandoned mine sites exist in 12 western U.S. states, with at least 33,000 degrading the environment according to the Government Accountability Office's 2011 report on the subject. Biochar is being evaluated as an additive to animal feed to reduce methane emissions, as an additive to animal bedding to reduce methane and ammonia and control the run-off of nitrogen. Dow Chemical is evaluating biochar soil amendments to reduce the uptake of mercury in the aquatic plant and fish food chain near brownfields. Unpublished results suggest reductions in uptake of up to 85% (personal communication, 2012).

The payment for ecosystem services can be executed as contracts between consumers or ecosystem services and the suppliers of these services. These payments require an assessment of the range and value of ecosystem services flowing from a particular locale or region, the beneficiaries, and a policy, subsidy or market capture value. Biochar can be designed to offer one or more of these environmental services (see list on page 7). The payment for the environmental benefits of sequestering carbon by biochar addition to soils could be articulated by either carbon credits in emission markets or carbon taxes. Several excellent presentations on biochar sustainability issues can be found elsewhere (Roberts et al. 2010, Amonette 2010, Fournier 2012, Steiner et al. 2010, Verheijen and Montanarella 2010, Cowie et al. 2010, Flora 2012).

1.2 Social sustainability

Social sustainability is frequently overlooked yet critical for developing a business model. It is critical that business models reflect society’s needs, and support improvements and benefits to the regional culture. It is not enough to build an enterprise, in economically depressed settings, providing positive impacts is critical. Supporting nearby living wage jobs with tangential benefits, such as remediation of brownfields, or providing community access to clean water, or processing waste materials generated by the community should also be considered to build sustainable business models. Some aspects of a socially sustainable business model include: 1) ensuring that the technology contributes to the creation of healthy, satisfying jobs in communities, 2) demonstrating a positive net energy balance compared to fossil fuels, 3) increasing access of isolated communities to affordable clean energy and 4) improving energy densification and security (e.g. reducing the dependency on fossil fuels and increasing the diversity of energy supplies) (Flora 2010a).

The opportunity to support communities is one of the most important social values of creating a pyrolysis industry. According to Baranick et al. (2011) the social benefits of pyrolysis plants can be summarized in four categories: Pyrolysis plants would: 1) provide livable wages to its workers, 2) provide year round employment, 3) provide workers with the opportunity to work outdoors, and 4) create partnerships between local industries (for example: composters, nurseries, urban gardens and farms).

Another less considered but necessary societal benefit would be developing production practices that produce less waste or in fact zero waste for future generations to manage. As previously noted 90% of materials used to make a product end up directly landfilled. This social objective would be to maximize cultural outcomes by leaving future generations abundant resources to meet their living requirements.

Likewise, business models need to consider factors beyond jobs and community infrastructure, that is, how can this business enhance relationships, create visually appealing environments and conserve ecosystem services that benefit health and well-being. These may sound like lofty goals or perhaps non-germane to the bottom line but a truly successful business generates respect, and cultivates a positive image, thus benefit greatly from community and employee loyalty and support.

Business entrepreneurs in the emerging biomass industry need to understand and respond positively to potential detractors to gain and maintain social capital. Ignoring, or defending through defaming opponents undermines credibility and threatens success of not only individual businesses but the broad biomass industry. Opposition to the use of biomass in many instances is based on previous mistakes or business behaviors which ignored basic conservation and social principles.

People concerned about biomass use tend to share some or all of the following concerns:

- Replacing croplands currently used for food and animal feed with biomass plantations and mono-culture crops
- Conversion of native forests or prairie to croplands
- Converting Conservation Reserve Program lands to biomass production
- Acceleration and expansion of forest thinning, including removal of mature, live trees for biomass
- Building roads and developing wild lands to collect biomass
- Shorting current uses/users of current uses of biomass
- Deleterious effects on soil nutrient levels, habitat, water and air quality, wildlife by removal of too much biomass
- Loss of up-cycling opportunity
- Lack of recognition of the importance of biomass to ecosystem functions including wildlife habitat.

Each of these concerns have validity and need to be proactively addressed by demonstrating through a sustainable business model that these factors have been considered and protocols developed that avoid the deleterious effects of the concerns. Sustainability principles and practices are currently being developed by IBI and USBI to assist biochar practitioners and businesses in meeting these challenges and securing a positive reputation for sustainable practices.

In today's world, a product's value is usually measured from an economic standpoint. But, as we progress, this economic value must also elevate the environmental and social value of the product or service. Due to the affects that industrialization is having on the earth, environmental groups and regulatory agencies have been formed in order to preserve the health of this planet. These groups must work together with the groups of Wall Street and main street if the human condition is going to improve particularly as populations continue to grow. Our goal is to create synergistic outcomes that maximize benefits to people, restore and enhance ecosystems and that are likewise profitable, thus can be successful over a long period. A new paradigm has been called for by many where enhanced services to the three sectors is paramount and benefit the entire economic and ecological system including human health and well-being (McDonough and Braungart 2002, Flora 2010b, Daily 2005).

1.3 Financial sustainability

Finally, the financial sustainability of a proposed business model depends on a vision that goes beyond short-term profitability. Environmental and social sustainability must be incorporated into final profitable operations. Financial sustainability requires that profit must occur without externalizing costs to the environment or to people. The triple top line should be incorporated from the beginning of the design of a project (McDonough and Braungart 2002). The designers should take advantage of the dynamics among these three points to create business opportunities and maximize values in each of these areas.

Many companies have understood the business potential inherent to sustainability (MBDC, 2010). They can create business value through the following drivers: reduced risk and liability, operating efficiencies and cost savings, synergies with stakeholders, and enhanced reputation and brand differentiation (MBDC, 2010). This vision must catalyze values to innovate continuous enhancement of productivity and process efficiency (US DOE 2010). Section 2 reviews several business models that have been developed for pyrolysis based biomass economies.

2. Frameworks for the Development of Business Models

Many different business models can be developed using pyrolysis technologies (Emrich 1985). Table 1 highlights sustainability aspects of these technologies as business models. Obviously, the development of specific technologies and thorough feasibility studies are needed.

Table 1. Sustainability aspects of pyrolysis technologies as business models.

Technology	Business Model Sustainability
Biochar production without recovery of vapors, chemicals or heat.	Not environmentally sustainable because vapors released are a pollutant. Impact in human health from emissions of pollutants and particulates. Loss of value added elements and energy reduces financial viability. Not viable in Washington State.
Biochar production with heat recovery.	Sustainability depends on development of high value biochar products and on-site or local efficient use of the heat produced. Most studies have shown that heat recovery is essential for a positive fiscal position.
Biochar production and bio-oil for power generation.	Requires high value biochar products to be economically sustainable. Well standardized bio-oils will have to be produced to be used as fuels in gas turbines or Rankine cycles. High fossil fuel price could represent an opportunity for this technology.
Biochar production and bio-oil for high value chemicals and transportation fuels.	Requires development of new technologies for bio-oil refining. Likely to result in more revenue but increase energy costs and more complex technologies.

Yoder et al. (2011) examined the economic tradeoffs of the joint production of biochar and bio-oil and noted that varying the quantity and quality of biochar and bio-oil produced could affect the potential revenue. The author proposed a methodology to identify the optimal pyrolysis temperatures for a given ratio of biochar and bio-oil prices.

2.1. Current status in biochar business development

World biochar production reached 45 million tons in 2007. Biochar production per country has been compiled by United Nations and can be found elsewhere (http://data.un.org/Data.aspx?q=Charcoal&d=EDATA&f=cmID%3aCH, retrieved 1/18/13). In 2011 IBI conducted a survey asking its members how they perceived the existing or future biochar marketplace. The summary of results is:

- 92.6% of the 212 participants of this survey considered that creating an online biochar marketplace will be useful or very useful.
- 62.9% would like to purchase products bagged for gardeners and small farms
- 55.3% would like to purchase bulk biochar for use on farms or for land reclamation and
- 49.2% also would purchase well characterized biochar for scientific research (132 participants answered this question).

Some biochar enthusiasts are currently producing biochar at varying scales or are creating the technology for biochar production. Much can be learned from these early adopters. Several listservs exist allowing for open discussion and information sharing about all aspects of biochar (http://tech.groups.yahoo.com/group/biochar-production/, retrieved 1/18/13; http://terrapreta.bioenergylists.org/buy_biochar, retrieved 1/18/13). For example, an interesting group of discussions on biochar production where members intending to produce biochar, are already producing biochar for personal use, or are commercializing their products can be found at http://tech.groups.yahoo.com/group/biochar-production/ (retrieved 1/18/13). A list of some of the companies commercializing biochar prepared by terrapreta.bioenergylists.org in 2011 (http://terrapreta.bioenergylists.org/buy_biochar, retrieved 1/18/13) is displayed in Table 2.

Table 2. A sample of companies commercializing biochar making technologies. (http://terrapreta.bioenergylists.org/buy_biochar,retrieved 1/18/13)

Company Name	Location	Website
Alterna Biocarbon	BC, Canada	http://www.alternaenergy.ca/
Aztec Wonder	MO, USA	http://www.aztecwonder.com/
Biocharm	CA, USA	http://www.biocharm.com/
Biochar Products	Oregon, USA	http://www.biocharproducts.com/
Biochar Solutions	Colorado, USA	http://www.biocharsolutions.com/
Biochar Merchants		http://biocharmerchants.com/
Blue Sky Biochar	California, USA	http://blueskybiochar.com/
Burt's Greenhouses	Ontario, Canada	http://www.burtsgh.com/
CharGROW		http://www.carbonchar.com/
Carbon Brokers International	Colorado, USA	http://www.carbonbrokersinternational.com/
Char King International	Idaho, USA	http://www.char-king.com/
Encendia Biochar	New England	http://www.encendia.com/
Grotek – Black Pearl Soil Enhancer	BC, Canada	http://www.grotek.net/en/knowledge/soilsupercharger.aspx
Genesis Biochar	California, USA	http://egenindustries.com/
Hawaii Biochar	Hawaii, USA	http://hawaiibiocharproducts.com/
New England Biochar	MA, USA	
Phoenic Energy	California, USA	http://phoenixenergy.net/biochar1
Soil Reef	Pennsylvania, USA	http://www.soilbiochar.com/
Sonoma Biochar	California, USA	http://www.sonomacompost.com/biochar.shtml
Turtleback Biochar	BC, Canada	http://turtlebackbiochar.com/
BiGchar	Australia	http://www.bigchar.com.au/bigchar.html
BlackEarth Products	Australia	http://www.blackearthproducts.com.au/
Village Coconut Charcoal	Philippines	http://villagecoconutcharcoal.com/
Carbon Gold, GroChar	UK	http://www.carbongold.com/products
Oxford Biochar	OK	http://www.oxfordbiochar.com/

Further information can be found by referencing and/or getting involved in biochar organizations such as the International Biochar Initiative, the U.S. Biochar Initiative, regional biochar initiatives or in newly formed regional or national biochar trade associations. Many biochar company websites present the results of product testing, testimonials from users, and links to scientific research or popular media articles on biochar performance. Others offer biochar consulting services and classes on biochar application (Baranick et al. 2011).

In general companies sell biochar as soil amendments in two forms: 100% pure biochar that need to be mixed with fertilizers by the consumer (example: Aztec Wonder, Blue Sky, Hawaii Biochar Product, Phoenix Energy) and biochar compost/mixes, inoculated or other engineered blends formulated to meet specific soil amendment needs (example: Biocharm, Char Grow, Soil Reef, VermiChar, Vermont Biochar, Black Earth Products) (Baranick et al. 2011). Although feedstocks and production methodologies strongly influence the characteristics and performance of the final product, some generalizations can be made about the performance and best application for the two types of commercial biochar. Table 3 summarizes some of the advantages and disadvantages of both types of the soil amendment products as studied and analyzed by Baranick et al. (2011).

Table 3. Biochar based soil amendment products (advantages and disadvantages) (adapted from Baranick et al. 2011).

Product	Advantage/disadvantages	Price Points
Model A: 100% pure biochar	(1) Less costly to produce, but sold at a lower price point (2) Geared towards the "educated" consumer (3) Can be sold in large bulks amounts – great for business to business sales (4) Delivery outside the region can be costly	(1) Average is $1 for a 40 pound box (2) Smaller quantities have higher price (up to $5/pound) but higher costs in packaging and handling (3) Larger quantities, sold by the truck or railcar load have lower price (as low as $0.6/pound) with lower handling and packing costs
Model B: Biochar Compost/Fertilizer Mixes	(1) More expensive to produce, but can be sold at higher price (2) More convenient for the "less educated" (3) Delivery to long distances is costly (4) Offers more options for expansions of product lines (5) Produces more immediate results in all soil types in first year of application	(1) Varies widely according to size and mixture and cost of ingredients besides biochar (2) Cost of packaging (3) EcoTrac sells EcoFeed for $25 for an 8 pound bag, while BioCharm is sold for $15 for a 33 pound bag before shipping

When asked about the products and services that the participants in the IBI survey would like to sell, 48.9% responded that they would like to be involved in the manufacture of biochar production equipment. 40.4% would like to be involved in engineering design services for biochar production, 31.9% would like to perform consulting (business and finance) services, 51.1% would like to do consulting services on the agronomic use of biochar, and 30.9% of the participants would like to be involved in biochar characterization and testing services. Terrapreta.bioenergylists.org compiled a comprehensive list of companies offering biochar making technologies (http://terrapreta.bioenergylists.org/company, retrieved 1/18/13) (Table 4).

Table 4. Companies commercializing biochar making technologies (From: http://terrapreta.bioenergylists.org/company,retrieved 1/18/13).

Company Name	Location	Website
ABRI-TECH Inc	Quebec, Canada	http://www.advbiorefineryinc.ca/
Adam + Partner	Garmish, Germany	http://www.biocoal.org/3.html
Advanced Gasification Technology	Italy	http://www.agtgasification.com/
Agri-Tech Producers	South Carolina, USA	http://www.agri-techproducers.com/
AGRI-THERM, Ltd	Canada	http://agri-therm.com/
Alterna Biocarbon	British Columbia, Canada	http://www.alternaenergy.ca/
Amaron Energy	Salt Lake City, Utah	http://www.amaronenergy.com/Amaron_Energy/Amaron_Energy.html
Ambient Energy, LLC	Washington, USA	http://ambientnrg.com/
Appropriate Rural Technology (ARTI)	Pune, India	http://www.arti-india.org/
Avello Bioenergy	Iowa, USA	http://www.avellobioenergy.com/
Biocarbo	Minas Gerais, Brazil	http://www.biocarbo.com/
Biochar Industries	Australia	http://biocharproject.org/
Biochar Products	Oregon, USA	http://www.biocharproducts.com/
Biochar Solutions	Colorado, USA	http://www.biocharsolutions.com/
Bioenergy LLC	St Petersburg, Russia	http://gasifiers.bioenergylists.org/gasdoc/Yudkevitch/charcoal/index.html
Biogreen-energy	France	http://www.biogreen-energy.com/
Biz Solutions	Utah, USA	http://pyrogreen.com/
Black is Green (BiG)	Australia	http://www.bigchar.com.au/
Black Earth Products	Australia	http://www.blackearthproducts.com.au/
BTG	Netherlands	http://www.btgworld.com/en/rtd/technologies/fast-pyrolysis
Carbon Brokers International	Colorado, USA	http://www.carbonbrokersinternational.com/
Carbon Char	USA	http://www.carbonchar.com/
Carbon Resources	California, USA	http://www.carbonresources.com/
Dicarbon Energy Inc	British Columbia, Canada	http://www.diacarbon.com/
Dynamotive	British Columbia, Canada	http://www.dynamotive.com/
Eco-Carbone	France	http://www.eco-carbone.com/
Ensyn	Ottawa, Canada	http://www.ensyn.com/
Eprida	Georgia, USA	http://www.eprida.com/home/index.php4
Full Circle Biochar	California, USA	http://fullcirclebiochar.com/
GEK (BEK) Gasifier,	California, USA	http://terrapreta.bioenergylists.org/company
Genesis Industries	California, USA	http://egenindustries.com/
HM3	Oregon, USA	http://www.hm3e.com/contact/index.php
ICM	Kansas, USA	http://www.icminc.com/services/gasifiers/
New Earth Renewable Energy	Washington, USA	http://www.newearth1.net/
New England Biochar	Vermont, USA	http://www.youtube.com/watch?v=RXMUmby8PpU
Oxford Biochar	Oxford, UK	http://www.oxfordbiochar.com/
Pacific Pyrolysis	Australia	http://www.pacpyro.com/
Pyrolyzer LLC	Florida, USA	http://www.pyrolyzerllc.com/
3R Environmental Techn.Group	Sweden	http://www.3ragrocarbon.com/
TSTO (Three Seconds to Oil)		http://www.mbop.org/index.htm
Waste to Energy Solutions	Florida and Alabama, USA	http://wesionline.com/index.htm

At the IBI survey 135 participants answered questions related to which equipment or service they were interested in purchasing. 77% indicated interest in purchasing biochar production equipment, 43% were interested in engineering design services for biochar production, 47% were interested in the receiving biochar characterization and testing services, 36% were interested in consulting services on the agronomic use of biochar and 14% were interested in consulting services (business and finance). Table 5 summarizes the feedstock, sustainability challenges, production technology, post-processing steps, potential co-products, biochar point of use, economic and social challenges and advantages of several potential business models. It is important to point out that Table 5 is not exhaustive. Some applications such as storm water treatment, roof runoff, wastewater applications, compost emissions that are being studied today are not reflected in this table.

Table 5. Biochar business models (http://www.biochar-international.org/commercialization, retrieved May, 3, 2012).

	Feedstock	Sustainability challenges	Production Technology	Potential co-products	Biochar point of use	Economic challenges	Social challenges	Advantages
1. Restoration Site (forest, wetland, etc)	Thinning slash, noxious weeds		Mobile pyrolysis, charring piles in situ	Biochar, bio-oil, heat for drying feedstock	Soil and watershed reclamation site	Labor intensive, need to value ecosystem restoration	Accepting the need to pay for restoring ecosystems services	Restored ecosystems store more carbon
2. Managed Forest	Thinning slash logging slash	Overcutting diminishes ecosystem services, transportation footprint	Mobile pyrolysis, hog fuel for co-gen. Feedstock for pellets or briquettes	Biochar, process heat, electricity, home heat	Commercial fertilizer, home garden	Forest thinning is labor intensive, low density slash is expensive to haul	Need to train workforce for ecological thinning	Can improve forest health, cheap fuel source, provides long term employment
3. Forest product processing waste	Sawdust, shavings, hog fuel	Overcutting diminishes ecosystem services	Co-gen pyrolysis or gasification, feedstock for pellet or briquettes	Biochar, process heat, electricity, home heat	Commercial, home garden	Supply dependent on economic growth and housing starts, resource is already fully utilized	Competition for resource	Already in widespread use
4. Biomass Plantation	Trees, grass, hemp, kudzu	Could displace native ecosystems & people, water use, monoculture problems, GM species	Co-gen pyrolysis or gasification, feedstock for pellets or briquettes	Biochar, process heat, electricity, home heat	Plantation soils, commercial fertilizer, home garden	Large capital investment & pressure to adopt unsustainable practices	Need to strengthen land tenure rights of poor people	Could be used for afforestation of degraded land
5. Urban Forestry and landscaping	Thinning, slash, logging slash, weeds, grass, clippings		Co-gen pyrolysis or gasification, feedstock for pellets or briquettes	Biochar, process heat, electricity, home heat	Commercial fertilizer, home garden	New capital investment	Nee to train workforce force for ecological thinning	Avoids disposal cost
6. Ag Waste – Industrial	Straw, cobs, orchard trimmings	Need to leave some decomposing organic matter in soil	Mobile pyrolysis, co-gen, pyrolysis or gasification, feedstock for pellets or briquettes	Biochar, process heat, electricity, home heat	Farm soils, commercial fertilizer, home garden	New capital investment		Avoids disposal cost
7. Ag Waste Subsistence	Straw, cons, orchard, trimmings, kernels, peels, hulls, pulp, offal	Need to leave some decomposing organic material in soil	Stoves, kilns feedstock for briquettes	Biochar, process heat, home heat and cooking	Farm soils	New capital investment		Avoids disposal cost
8.- Municipal Solid Waste	Trash, paper	Pollution, losing resource that could be recycles	Co-gen pyrolysis or gasification	Biochar, process heat,, electricity	Suitable for use as carbon sink only	Supply depends on economic growth, consumption		Avoids disposal cost

In a recent article (Whitfield, 2012), Whitfield a pioneer in the US commercialization of wood pellet stoves in the 1980s, discusses how knowledge from the pellet industry can help develop the biochar industry. He notes that wood pellet stoves were successfully commercialized because of two primary factors: the existence of companies looking for contracts to commercialize wood pellets, and public pressure to reduce emissions from woodstoves (which resulted in legislation in Oregon and Washington to limit wood burning).

Whitfield noted that although environmental concerns spurred the invention of wood pellet stoves, the advantages of the wood pellet stoves over other forms of heat heating was the major reason for the market success of this technology. Pellet stoves used a consistent high energy fuel that could be delivered in clean 40 pound sacks. The stoves could be thermostatically controlled, self- ignited and only required one load a day. These conditions triggered the investment of $500 million in the construction of 85 pellet mills across North-America and the commercialization of 200,000 pellet stoves (Whitfield, 2012).

The newly forming biochar industry is similar in development to the wood pellet industry of the early 1980s. Whitfield notes that while wood pellets were developed for heating use only, biochar has multiple uses across a broad range of settings. He strongly cautioned that while the multi-dimensional nature and diversity of markets for the biochar industry could eventually increase the market scope and decrease risk when competing for well-established markets (agriculture and energy), it could also blur focus at the initial stages when small but profitable specialty markets (at vineyards, nurseries, greenhouses and small organic farms) are developing. Whitfield strongly recommends focusing on and serving well these markets initially. He recommends demonstrating increased plant yields for growers and developing “designer” biochar for targeted these applications. Also critical are the development and implementation of industrial standards like the ones recently proposed by IBI (2012). Whitfield also noted that the “pyrolysis reactor” used should be easy to operate, produce good quality biochar at low cost from a wide range of feedstocks, meet current air emission standards and produce heat from the pyrolysis vapors that can be used either to dry the biomass or to satisfy a local need for heat or electricity. He noted that compared to the 1980s, marketing biochar should be easier and quicker than wood pellets. He anticipates that the biochar industry could grow well beyond the current wood pellet business in scope and scale.

Baranick et al. (2011) conducted a feasibility study as part of a Seattle University MBA Sustainable Business Practicum researching the environmental, social, and economic value of a biochar business converting slash piles from forest management activities in the Methow Valley of North Central Washington (Okanogan National Forest) into biochar to be marketed solely as a soil amendment . The client charged them to explore the possibilities of creating a truly sustainable business combining environmentally, socially and financially sound strategies (Baranick et al. 2011). The authors focused their analysis on two business models (the supply business model which produces more biochar than the potential market in the region and a business model from the demand side) and concluded that lack of consumer demand is the main hurdle in deploying their business models. Like Whitfield, Baranick’s team also recommended that their costumers implement a small operation to produce biochar that will be tested in targeted local applications and to conduct market studies with the results obtained.

Baranick et al. (2011) identified five major challenges facing the biochar industry: 1) high start up costs compared with the competing composting sector, 2) lack of consensus on biochar benefits, 3) difficulty educating potential consumers on the benefits of the product (because limited production makes it very difficult to test biochar properties at commercial scale), 4) over competition for feedstock resources, and 5) high costs associated with long distance distribution of biochar. In the opinion of the authors the major challenge facing the industry is the fact that "not all biochars are equal." Biochar characteristics and responses differ based on feedstock used, process employed, and production parameters. This represents a major hurdle to extrapolate results from one location to another. The development of general production and uses rules is critical to the success of this industry.

Baranick et al. (2011) noted that the biochar industry is in the market introduction stage and that during this phase costs tend to be high and sales volume low with poor competition and low demand. Along the recommendations of Whitfield, Baranick et al. (2011) argue that under existing conditions "demand must be created, which require educating the potential consumer base to try the product and then working to retain them as a customer." One producer in the U.S. actually gave biochar to potential customers for free. Once they were convinced that the product was effective, they were back for more and formed a loyal and solid customer base. Importantly, they spread the word among their fellow gardeners and agriculture operations. That commercial biochar business is now growing briskly. Baranick et al. (2011) recommend building small production units first and then consider the "growth stage" in which production costs will decrease together with prices to maintain competitive advantage. Realistically, competition in current biochar markets is extremely limited as there are very few producers. Until very recently, even obtaining biochar for research has been extremely difficult. More research must be done to convince end users (the market) of the benefits of biochar use but practical demonstrations are often more convincing than theoretical research.

The development of regulations for biochar will certainly accelerate its market acceptability however it will also raise costs and place a significant burden on producers already struggling to make their business economically viable. Biochar supporters recommend that first voluntary compliance with characterization and testing be encouraged, evolving to more mandatory standards as the industry and the market mature. The European Union, with a consumer public and industry much more tolerant of tighter controls, is currently moving towards development of mandatory standards. In this regard the characterization standards developed by IBI should be commended for both the methodology employed in creating the standards and in their recommendations for implementation (IBI, 2012). Some of the biochar produced could be further processed to produce activated carbon. Table 6 shows the world demand of activated carbon.

Table 6. Global demand of activated carbon (Schaeffer 2011, Global Industry Analysis 2012) (tons).

Region	2007	2012
North America	245	285
Western Europe	126	145
Asia Pacific	348	482
Other	171	238
Total demand	890	1050

In 2012 the demand for activated carbon was only 1,150 tons, mostly in the Asia Pacific region. The activated carbon market is forecast to reach 2.3 million tons in 2017 mostly due to more stringent regulations to remove mercury at coal power plants, air purification, water treatment, food and beverage processing, air purification, automotive emission canister, solvent vapor recovery and medical-pharmaceutical applications (Global Industry Analysis 2012) (http://www.researchandmarkets.com/reportinfo.asp?report_id=450634&t=e). Some of the main companies commercializing activated carbon are:

- CECA Specialty Chemicals (France) (http://www.cecachemicals.com/sites/ceca/en/business/activated_carbons/home.page),
- Calgon Carbon Corp (USA) (http://www.calgoncarbon.com/carbon_products/index.html), Chemiviron Carbon (Belgium) (http://www.chemvironcarbon.com/en),
- Clarimex SA de CV (Mexico) (http://www.clarimex.com/corporativo-i.htm),
- Haycarb Ltd (Sir Lanka) (http://www.haycarb.com/),
- Kurarat Chemical Co Ltd (Japan) (http://www.kuraraychemical.com/index.shtml), MeadWestvapo Corp (USA) (http://www.meadwestvaco.com/SpecialtyChemicals/ActivatedCarbon/index.htm),
- NORIT Americas, Inc (USA) (http://www.norit.com/),
- Osaka Gas Chemicals Co., Ltd (Japan) (http://www.ogc.co.jp/e/products/e-purification/index.html),
- Jacobi The carbon company (http://www.jacobi.net/index.php?/site),
- TIGG Corporation (USA) (http://www.tigg.com/?utm_source=bing&utm_medium=ppc&utm_campaign=activatedcarbon1), and
- General Carbon Corporation (USA) (http://www.generalcarbon.net/).

These well-established industries could be excellent markets for biochar or could serve as models for the production of engineered biochar for environmental applications.

US industrial facilities (i.e. clinker cement plants and coal fired plants) are likely to drive the need for additional activated carbon for mercury control. Another application that is likely to grow is in carbon clothing to protect the military against radiological, biological and chemical weapons. US demand is expected to grow an annual average of 13% in the long term due to new environmental standards (http://www.prweb.com/releases/activated_carbon/water_treatment/prweb8286149.htm, retrieved February 4, 2013)
. The development of engineered biochar for environmental applications is critical for the future of the industry Global Industry Analysis 2012 (http://www.researchandmarkets.com/reports/450634/activated_carbon_global_strategic_business#description, retrieved February 4, 2013).

2.2 Heat recovery and bio-oil combustion

A major weakness of most business models for biochar production is that they disregard the use of the energy produced from pyrolysis vapors. The revenue resulting from commercialization of the heat or electricity derived from pyrolysis vapors is critical for the success of biochar businesses. However, very little information is found in the literature on business models to utilize pyrolysis vapors.

Pyrolysis vapors can be condensed to produce bio-oils. Bio-oil combustion tests have been ongoing ever since the development of pyrolysis technologies. Many combustion tests at atmospheric pressure in flame tunnels and boilers have been reported in the literature at Massachusetts Institute of Technology (MIT) (Shihadeh et al. 1994), Canada Centre for Mineral and Energy Technology (CANMET) (Bank et al. 1992, Lee 1993), ENEL (Barbucci et al. 1995, Rossi et al. 1993), Colorado Oil and Gas Information System (COGIS) (Salvi et al. 1991), Red Arrow (Freel et al. 1990, Freel and Huffman 1994), Neste Oy (Gust 1994, 1995, 1996, 1997), Technical Research Centre of Finland (Oasmaa 2001), and International Flame Research Foundation (IFRF) (van de Kamp and Smart 1991, 1993).

One of the advantages of the conversion of biomass into liquid fuels is the possibility of using these fuels for highly efficient engines such gas turbines with efficiencies around 28% (Andrews et al. 1996, 1997) and diesel engines with efficiencies close to 45% (Gross 1995, Jay et al. 1995, Leech 1997, Ormrod and Webster 2000). Nevertheless, several limitations must be overcome prior to using crude bio-oils as fuels in gas turbines and diesel engines. The residence time in the combustion chamber of gas turbines is much smaller than for boilers and the ash content and alkalinity must be strictly controlled.

Currently, bio-oil is primarily used as a substitute for heavy fuels used for creating heat typically for industrial applications. Bio-oil, like bunker fuel, requires preheating or atomization prior to combustion, and therefore is limited in use. Because its heating power is less than half of that of petroleum-based fuel oil and has a much higher moisture content, twice as much bio-oil is needed to reach and maintain desired temperatures.

Bio-oil production is maximized when temperatures are higher than necessary for creating biochar (450-600° C) and can be a desirable by-product of pyrolysis. However, some producers find that the acidity of the oil and the viscosity make it problematic for equipment maintenance and use when trying to produce marketable quantities of biochar simultaneously. Several companies in Canada and the U.S. focus on bio-oil as their primary product.

As discussed in the following section, bio-oil requires energy intensive refining to move it from a bunker oil equivalent to a finer fuel usable in a broader range of engines. Energy return on energy invested is a hurdle for the commercialization of a finer grade of bio-oil.

The increased efficiency of gas turbines and diesel engines has been the main drive for bio-oil tests performed since the 1990s [Orenda Aerospace corporation (Andrews et al. 1996, 1997), Wartsila (Gross 1995, Jay et al. 1995), Ormrod Diesels (Leech 1997, Ormrod and Webster 2000), VTT energy (Jay et al. 1995, Solantausta et al. 1993, 1994), University of Rostock

(Strenziok et al. 2001), University of Kansas (Suppes et al. 1996), MIT (Shihadeh and Hochgreb 2000), Pasuali Macchine agricole (Baglioni et al. 2001), Institute Motori (Frigo et al. 1998, Bertoli et al. 2000), University of Florence (Chiaramonti et al. 2003), Universidad Politecnica de Madrid (Lopez Juste and Salva Monfort 2000)]. Reviews on the challenges of using bio-oils as fuels can be found elsewhere (Czernik and Bridgewater 2004, Chiaramonti et al. 2007). The lack of bio-oil specifications and commercial engines able to operate with these oils is the main hurdle to implementing this business model.

2.3 Bio-oil refining

Although several bio-oil refinery concepts are under study at the laboratory level (see third report: http://www.ecy.wa.gov/biblio/1207034.html, section 5.4.2) to produce fuel and chemicals from bio-oils, only the bio-oil hydrotreatment and bio-oil gasification concepts are currently being evaluated at pilot and demonstration scales (Yu and Wu 2010). The lack of technologies at the commercialization stage to produce a stabilized bio-oil compatible with the existing petroleum refineries or large bio-oil gasification plants are the main hurdle in developing a biomass economy based on pyrolysis. Several options for producing green gasoline and green diesel (drop-in fuels) via two step bio-oil hydrotreatment are shown in Figure 4. The wastewater stream shown in Figure 4B is the water produced as the result of the hydrotreatment (reaction between the oxygen and the hydrogen). Until bio-oil refineries are deployed at the commercial stage, business models based on the condensation of pyrolysis vapors will only succeed if they are able to develop one or two high-value products from bio-oil. This was the case with Ensyn which started with the production of food ingredients and specialty chemicals and is now working with Universal Oil Products (UOP) to build a bio-oil refinery based on bio-oil hydrotreatment (http://www.ensyn.com/about-ensyn/overview/).

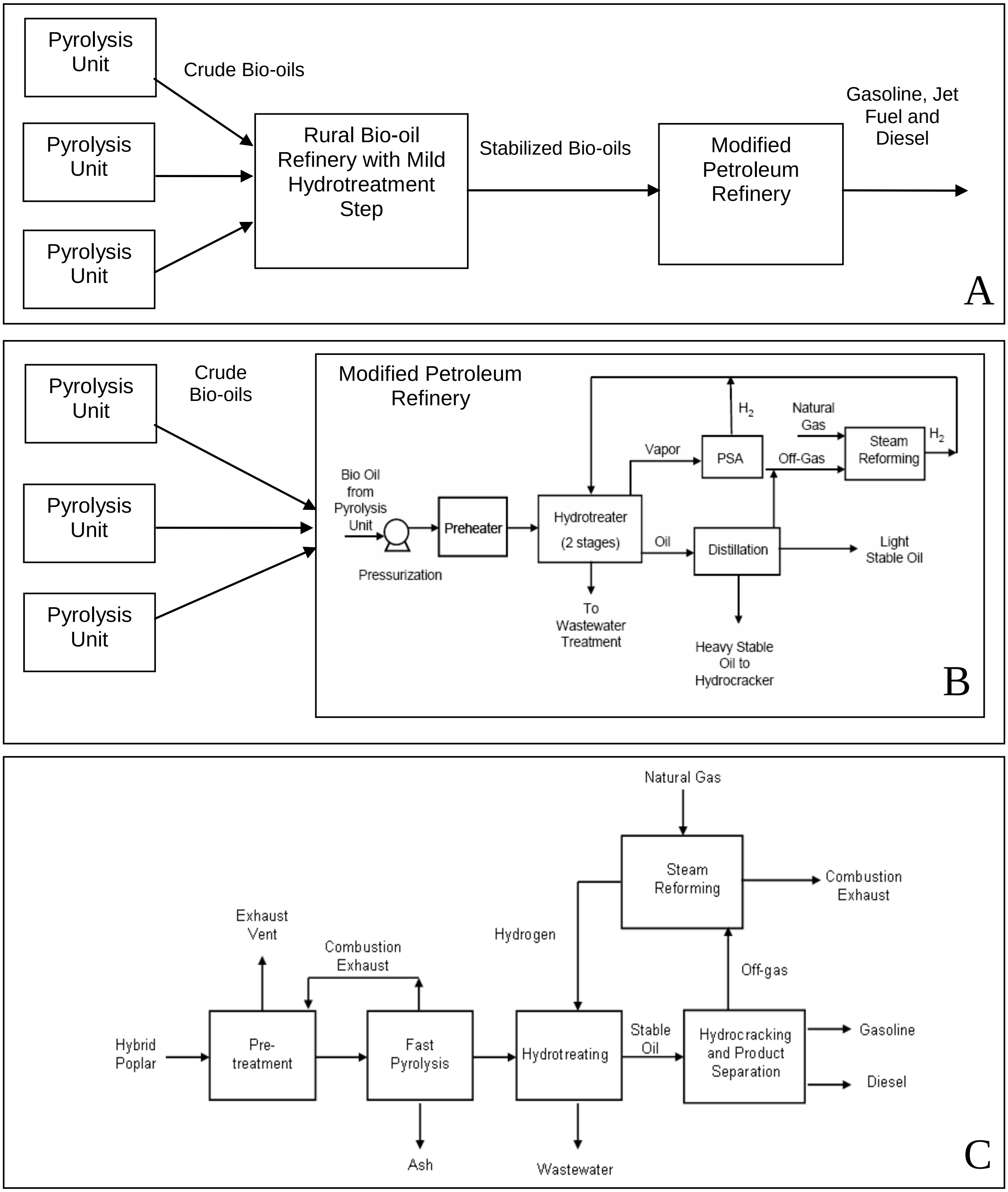

Figure 4. Schemes to use pyrolysis technologies to produce drop-in fuels. A. Distributed pyrolysis units, rural bio-oil refinery, petroleum refinery, B. Distributed pyrolysis units, centralized bio-oil refinery C. Integrated pyrolysis unit with bio-oil refinery. (Modified from Jones et al. 2009).

Bradley (2006) studied the export potential and estimated production costs in Canada, Brazil, South Africa, the Baltic and Ukraine. They compared delivery costs of pyrolysis oil at Rotterdam with the prices of competitive fossil fuels as well as potential markets in The Netherlands, Germany, Belgium, United Kingdom, Finland, Sweden and Denmark.

Prospective entrepreneurs wanting to combine biochar and bio-oil production are recommended to start on a relatively small scale addressing niche market need. Somewhere between 50 and 80 tons of wood per day would be required by a practical small enterprise (to produce 10 to 20 tons of biochar per day). Biochar can be sold to the final customers or it can be sold in bulk to a wholesaler (Simmons 1957). The success of the enterprise depends on obtaining a sufficient average price from a few different types of outlets (Simmons 1957). As a typical business development process, when small companies emerge and are successful they grow to take advantage of the size scale. This company expansion also depends on the biomass availability near the plant. Development of bio-oil, biochar, and high-value products should address local needs.

2.4. Building a business model

Business models must be developed in accordance with the type of pyrolysis unit selected. Granatstein et al. (2009) evaluated the feasibility of designing pyrolysis units to target specific applications. They classified pyrolysis units into mobile, transportable, relocatable and stationary units (Table 7).

Perhaps the main limitation of the models that have been proposed so far is that most of them consider that the pyrolysis unit will utilize waste materials. While there are many facility locations where municipal solid waste woody materials are collected (see Biomass supply chain section 4.1), agricultural or forest operations are broadly spread and biomass may not be collected even to a local point. The business model for dispersed biomass may require complex supply chains, roads, auxiliary systems and most importantly, the blessing of the communities where the units will be built. Unfortunately, all the financial studies found in the literature are based on a centralized location business model, lending a potential advantage for collected biomass. A promising alternative is the integration of pyrolysis units and/or bio-oil refineries into existing biomass processing industries (example: msw wood waste collection, and agricultural sugarcane, nut, and palm oil mills and log saw, and pulp and paper mills). These business models are likely to be more successful because the waste biomass generated by current businesses is already concentrated in a single location, the heat and/or energy produced can displace the use of external fossil fuel-based energy sources. These new units can take advantage of existing infrastructure. These factors all contribute to reduced capital and operational costs as well as higher and faster return on investment.

Some of these units using industrial wastes could later expand to process waste biomass available in the region. Furthermore, the pyrolysis component of the industry can take advantage of highly trained on-site managers, and technical and operations staff thereby reducing operational costs. The integration of pyrolysis units as part of the shift of existing biomass conversion industries into biochar production and bio-refineries is an exciting area of research with great potential.

Table 7. Features and considerations for selecting pyrolysis units (Granatstein et al. 2009).

Unit Type	**Capacity** dry tons per day (DTPD)	**Location**	**Power**	**Considerations**
Mobile	10-100	• Located at the logging deck, agricultural field or a nearby location • Mounted on a semi-truck trailer	• Electricity consumed on site is provided by the units	• Requires centralized laboratory services, maintenance, engineering and administration • Requires an external energy source to initiate pyrolysis • Heat is unused • Frequent movement increases maintenance • Distance to markets, packaging and transport of biochar
Transportable	100	• Located central to biomass supply. • Can be moved several times per year	• Supplied by a generator (similar to the mobile units but the capacity could be larger) or could have access to grid electricity	• Requires centralized laboratory services, maintenance, engineering and administration • Transported by three semi-trailer containers • Heat capture and use requires specific locations • Movement increases maintenance • Set-up and break-down time can be costly • Distance to markets, packaging and transporting of biochar
Relocatable	100-1,000	• Centralized location for biomass supply and markets • Co-location with consumer of heat desirable • Designed for easy breakdown and re-assembly at another site, if the biomass supply diminishes	• Requires access to grid electricity	• Alleviates difficulties caused by disruptions in long-term feedstock supply • On-site packaging • Distance to markets • Breakdown/reassembly cost on top of costs of feedstock transportation
Stationary	100-2,000	• Centralized location co-located with another industry	• Requires access to grid electricity	• Transporting feedstock to the facility adds cost • The environmental impact associated to the transportation of large volumes of biomass tends to be larger

3. Development and Testing of Pyrolysis Plants for Biochar Production

The pyrolysis plant is central to a biochar production business. This section addresses specific factors and methodologies to consider in designing and sizing the plant. However, this section does not cover ancillary equipment and external factors such as costs and considerations for plant siting, location or equipment for material handling, pre-processing, or biochar packaging.

Figure 5 shows an approach to develop process designs and financial analysis of a pyrolysis plant. The first step of this analysis is typically to create process flow diagrams (PFDs). With information in the literature and PFDs, it is possible to conduct mass and energy balances. Next, in order to determine the capital and operating costs, the equipment needs to be sized (these methods are not discussed in this review). Literature sources or direct providers can supply some of the capital costs. The price of the products is calculated once the capital and operating costs are determined (Spath et al. 2005).

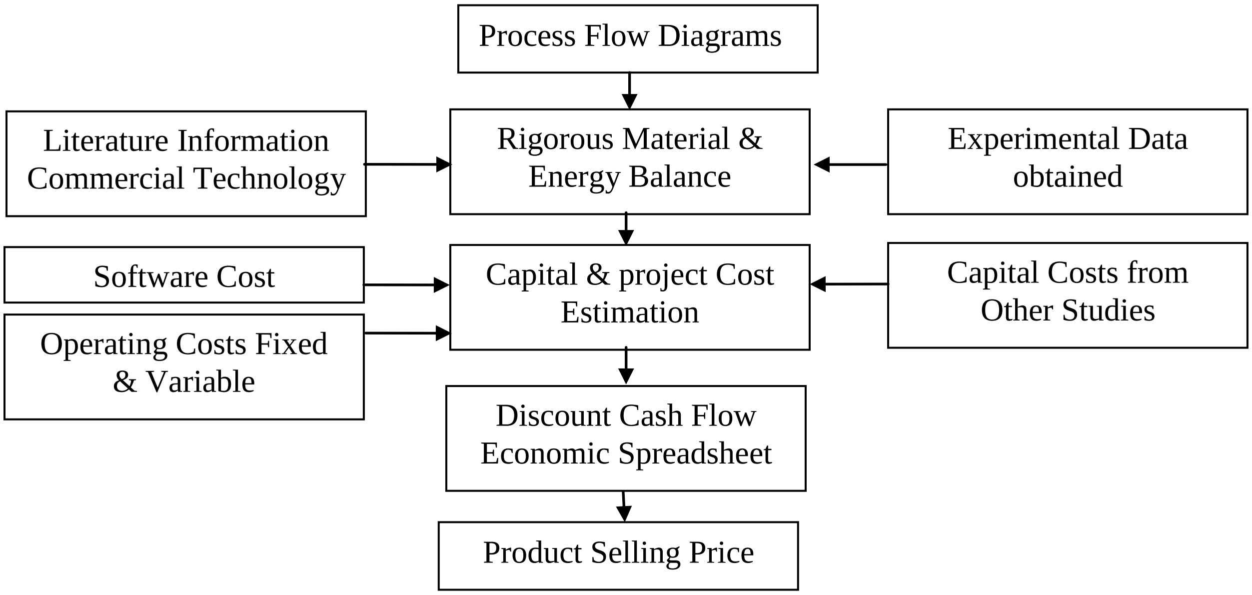

Figure 5. Process analysis approach (Spath et al. 2005).

Lynch and Joseph (2010) wrote an excellent report for IBI with guidelines for the development and testing of pyrolysis plants to produce biochar (http://www.biochar-international.org/sites/default/files/IBI-Pyrolysis-Plant-Guidelines.pdf). The report was intended to help small pyrolysis plants with development, equipment specification and process testing. Lynch and Joseph (2010) recommend those interested in the development of biochar technologies to participate in internet groups such as: http://tech.groups.yahoo.com/group/biochar-production/.

Lynch and Joseph (2010) recommend seven steps to design a pyrolysis unit:

(1) Functional specifications for the pyrolysis plant and the biochar product
(2) Process flow diagram
(3) Process instrumentation diagram
(4) HAZOP (Hazard and Operability Study)
(5) Detailed design and costing
(6) Design review
(7) Life Cycle Analysis
(8) Documentation

In this section we summarize each of these steps. See the original document for more details (http://www.biochar-international.org/sites/default/files/IBI-Pyrolysis-Plant-Guidelines.pdf).

3.1 Functional specification for pyrolysis plant

Once a business model (Section 2 Fourth report) has been identified those interested in developing and testing a pyrolysis plant should determine the functional specifications of the engineered system. The functional specification documents should describe specific behavior of the pyrolysis plant that will be designed. It should allow the reader to understand how the entire system will work (conceptually), the function of each of the unit's operational steps as well as the specifications for the final product. According to Lynch and Joseph (2010), the main components that should be sized when designing a pyrolysis plant for biochar and heat production are: pre-processing equipment (grinding, drying, chipping, sieves, screens), material handling (belt conveyors, storage bins) and feeding equipment (feed screws, lock hoppers, feed belts), dryer (see second report: http://www.ecy.wa.gov/biblio/1207033.html), pyrolysis reactor (see first report: http://www.ecy.wa.gov/biblio/1107017.html), syngas burner, gas cleaning, cooling and quenching equipment (see third report: http://www.ecy.wa.gov/biblio/1207034.html), instrumentation and electrical equipment including generators. Some of the components of the Functional Specification documentation are shown in Table 8.

Table 8. Components of the Functional Specification Document (Modified from Lynch and Joseph 2010, http://www.biochar-international.org/sites/default/files/IBI-Pyrolysis-Plant-Guidelines.pdf)

Sections	Information that should be included
Introduction	(1) Overall process general philosophy (2) Plant performance objectives (3) Product Quality Standards (see third report)
Process Description	(1) Flow diagram with a list of all the process streams
Major Components (Unit Operations)	(1) Detailed specification of the principal unit operations,
Components Supplied by other Manufacturers	(1) Material handling equipment (2) Burners (3) Instruments (4) Controls
Detailed Component Specification	(1) Identification of the subcomponents in each of the major systems (example: the kiln will have a chimney, emergency vent, char exit screw, stream injection system)
Control and Electrical System	(1) A description of the control and electrical system
Commissioning Plan	(1) Detailed description of steps to be followed during commissioning
Operating Procedures and Manuals	(1) Information that will be collected for the Operating Procedures and Manuals
Sustainability	(1) Environmental Sustainability, (2) Social Sustainability and (3) Financial Sustainability

The following provides an example of the steps leading to a Functional Specification document. In the biomass pyrolysis unit model proposed by Ringer et al. (2006) (Figure 6), the biomass size is reduced to < 1.5 mm and then dried to a moisture content of 10–50%. Key business model parameters proposed by Ringer et al. (2006) are listed in Table 9.

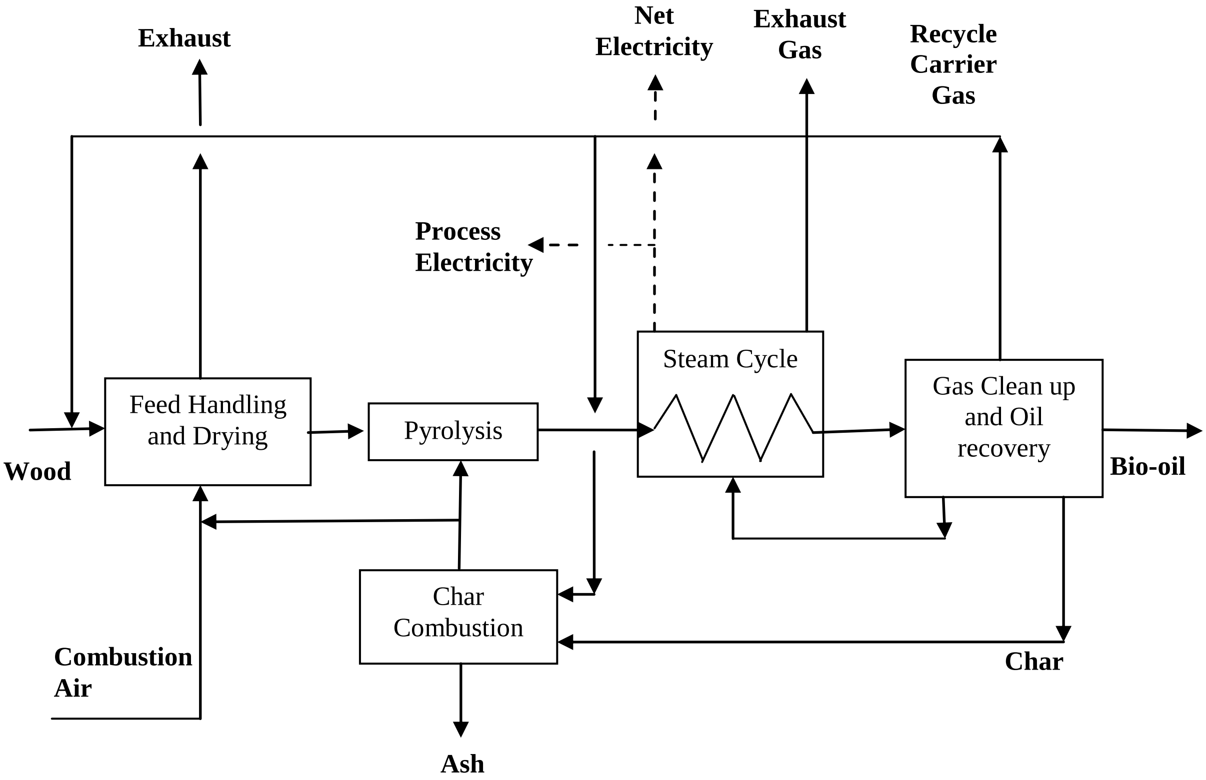

Figure 6. Biomass pyrolysis unit model proposed by Ringer et al. (2006).

Table 9. Design parameters for a particular pyrolysis scheme proposed by Ringer et al. (2006).

Parameter	**Value**
Feedstock	
Type:	Wood Chips
Moisture content:	50%
Cost:	$30/dry ton
Throughput:	550 dry tons/day
Particle size:	3–45 mm
Pyrolysis Design	
Pyrolysis type:	Bubbling Fluidized Bed
Temperature:	500 °C
Air carrier ratio:	2.75 lb air/lb pyrolysis feed
Feed moisture content:	7%
Ground particle size:	< 3 mm
Yields (wt.% Dry basis)	
Oil:	59.9
Water:	10.8
Char and ash:	16.2
Gas:	13.1

Some components that may form part of the pyrolysis unit are the following:

Washing: Washing is one of the options available to reduce the content of alkalines.

Chopping/Grinding: A typical assumption in the literature is that 50 kWh/ton of biomass is consumed during biomass grinding (http://www.biomatnet.org/secure/Fair/S538.htm). Wright et al. (2010) used the models developed by Mani et al. (2004) for hammer mills.

Drying: It is recommended to reduce the biomass moisture content to less than 7 mass % of the original biomass (Wright et al. 2010). According to (Brown 2003) biomass drying will require 50% more energy than the theoretical value (approximately: 2,442 kJ/kg of moisture evaporated).

Pyrolysis: Typical yields: Gases (10-25 mass %), Bio-oil: (55-62 mass %), Water: (4-10 mass %), Char: (15-25 mass %). Wright et al. (2010) reported values of gas and bio-oil composition that can be used for the mass balances.

Cyclones: Used for particle separation. The efficiency of cyclones will depend on particle size separated (Wright et al. 2010).

Bio-oil Condensers: There are many designs available. The fraction of oil collected in the first and second condenser and their composition will depend on the temperature used (Westerhof et al. 2007, 2011, 2012). The effect of condensation temperature on the yield of liquid fractions (bio-oil and aqueous phase) is presented in Figure 7.

Combustion of non-condensable gases and char: Consider that recycled non condensable gas and char are combusted to dry and pyrolyze the biomass (Wright et al. 2010).

Hydro-treatment section: Wright et al. (2010) conducted the mass balances in the hydrotreatment section using data provided by UOP (Marker 2005, Holmgreen et al. 2008).

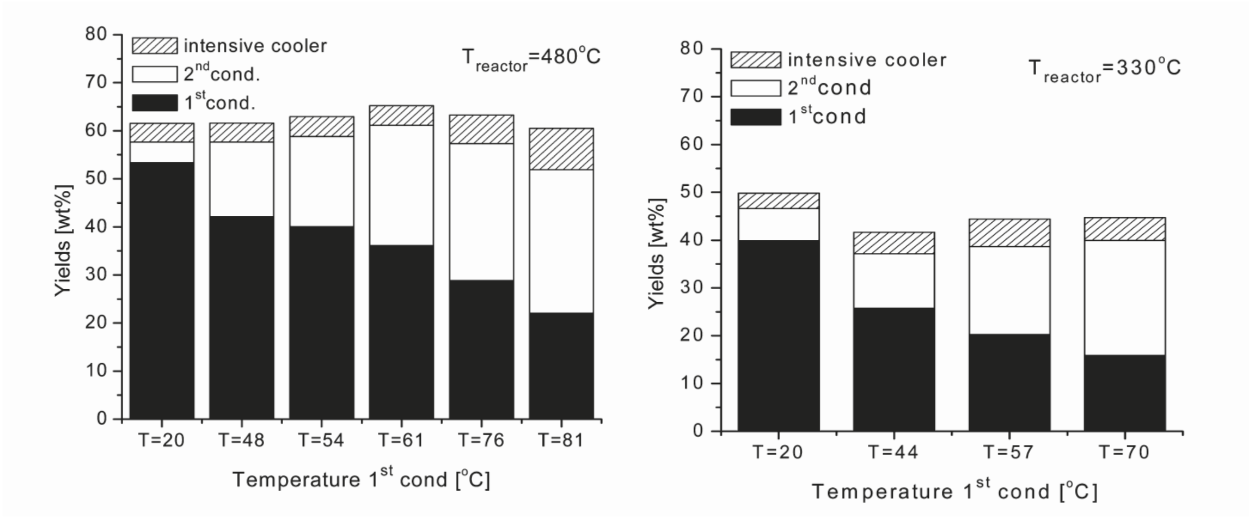

Figure 7. Changes in the yield of bio-oil as a function of condensation temperature in the first condenser. The temperature of second condenser was kept at 25 ^{o}C (Westerhof et al. 2011).

A detailed description of the key assumptions and specifications for a pyrolysis-hydrotreatment plant was published by Wright et al. (2010). The main assumptions made in the design of pyrolysis and hydrotreatment plants are presented in Table 10.

Table 10. Process design key assumptions made by Wright et al. (2010).

Section	**Section Description**	**Key assumptions**
Chopping	Size reduction to 10 mm	Incoming average particle size 10-25 mm
Drying	Biomass drying to 7% moisture	Steam drying at 200 ^{o}C. Energy required 50% more than theoretical (2,442 kJ/kg)
Grinding	Particle size reduction to 3 mm	Incoming biomass maximum size of <10 mm. Energy required: 50 kWh/ton
Pyrolysis	Biomass conversion to pyrolysis products (Fluidized bed reactor)	480 ^{o}C and 1 atm. 2.75 kg of fluidizing gas per kg of biomass. Heat provided by char combustion. Multiple 500 MT/day reactors used.
Solids Removal	Removal of entrained solid particles from vapor stream with parallel cyclones	Small particles less than 25 microns, Approximately 90% particle removal
Bio-oil Recovery	Collection of condensing vapors	Rapid condensation to about 50 ^{o}C. 95% collection of aerosols.
Storage	Storage of bio-oil and char	4 weeks storage capacity
Combustion	Provides process heat and steam generation	120% excess air combustion, 1,100 ^{o}C gas temperature, 200 ^{oC} steam generation
Hydroprocessing	Upgrading of bio-oil to naphtha range and diesel-range product fractions	Hydrogen production from oil by aqueous phase reforming P > 1,000 psia and T > 300 ^{o}C

3.2. Process flow diagram and mass and energy balances

Once the design objectives have been clearly specified and documented, the engineers have to conduct mass and energy balances of the system that will be built (Lynch and Joseph 2010). The readers are recommended to follow the procedures described in several excellent chemical engineering text books (Himmelblau and Riggs 2004, Felder and Rousseau 2005, Sinnott 2007).

Figure 6 (previous section) showed a diagram of a pyrolysis unit (Ringer et al. 2006). The in and out streams should be numbered and information on the flow rate and the intensive properties (Temperature- T, Pressure-P, composition) of each known stream should be added. Examples of mass and energy balances and information needed to conduct these balances in pyrolysis plants can be found elsewhere (Lynch and Joseph 2010, Ringer et al. 2006, Daugaard and Brown 2003, Xu et al. 2011, Roberts et al. 2010, Sadaka et al. 2002, Garcia-Perez et al. 2008, Boateng et al. 2008, Rath et al. 2003, Catoire et al. 2008, Domalski et al. 1986, Zhang 2004, Wright et al. 2010).

Detailed mass and energy balances of the pyrolysis and hydrotreatment step can be found in appendix B of the Wright et al. (2010) report and in the report published by Jones et al. (2009). The mass and energy balances conducted by Jones et al. (2009) used CHEMCAD models and Microsoft Excel spreadsheets.

The results of the mass and energy balances can then be represented in many forms. Figure 8 shows a Sankey diagram representing the results of the energy balances for a pyrolysis plant processing corn stover (Roberts et al. 2010).

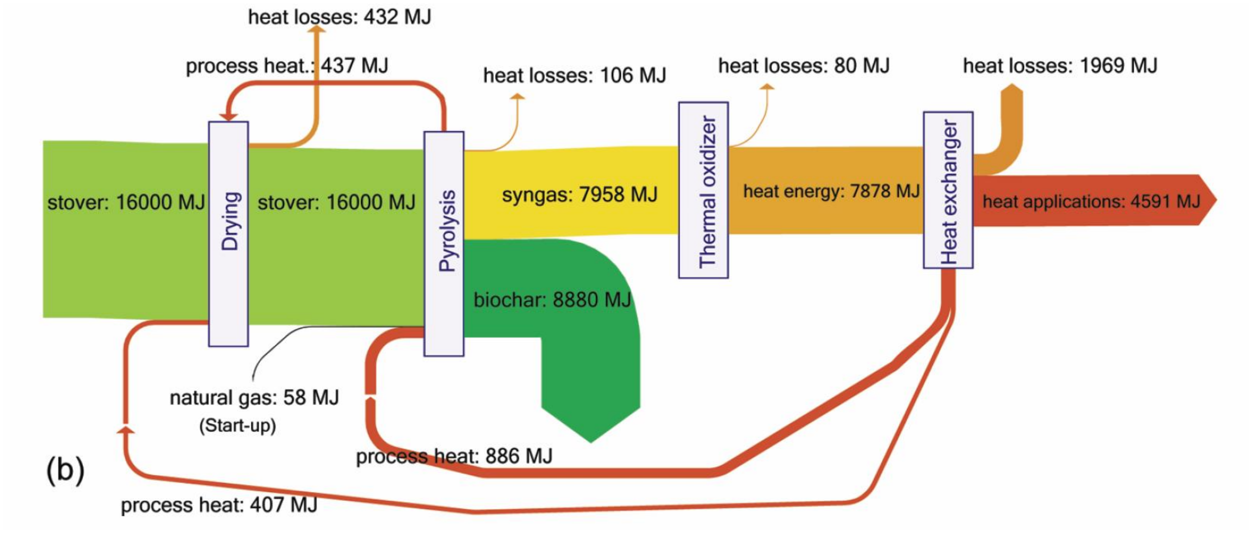

Figure 8. Sankey diagram representation of the results of energy balances of a pyrolysis plant processing corn stover (Roberts et al. 2010).

3.3. Process and instrumentation diagram (PID)

Lynch and Joseph (2010) show a detailed process and instrumentation diagram (PID). The diagram should show that there is enough monitoring and control to ensure that the plant is operating properly and meeting emission and safety standards (http://www.biochar-international.org/sites/default/files/IBI-Pyrolysis-Plant-Guidelines.pdf).

3.4. Hazard and operability study methodology (HAZOP)

The first and the third reports in the series of this report cover many of the potential hazards in carbonization processes (http://www.ecy.wa.gov/ biblio/1107017.html, http://www.ecy.wa.gov /biblio/1207034.html). According to Lynch and Joseph (2010) the HAZOP should include the following risks for operator and the public: 1) fire and explosion, 2) particle and gaseous emissions, 3) gas leakage (particularly CO), and 4) noise pollution. The system should have pressure relief systems to prevent explosions. Furthermore, pyrolysis system designers should make sure that equipment meets and preferably exceeds all gaseous and particulate emission standards as well as noise and odor beyond the site boundary (see third report: http://www.ecy.wa.gov/biblio/1207034.html). The project should comply with all air, water, and soil quality directives. Likewise, designers need to ensure that feedstock comes from a sustainable source and that the use of all feedstocks that will be processed does not have any negative environmental impact and that the system is able to produce biochar that is tested and suitable for application in soils.

3.5 Detailed design and costing

A detailed design implies the selection of equipments, pipes, pumps, fans. It should be conducted by specialized credited engineers (Lynch and Joseph 2010). At this stage designers should also make sure that construction materials have been appropriately selected to withstand operational temperature, pressures and the materials used. Information for cost estimation can be found in section 4 of this report.

3.6 Design review

The review of designs and cost estimates should be conducted by independent experts (Lynch and Joseph 2010).

3.7 Life cycle analysis

Very few life cycle analyses on biomass pyrolysis are reported in the literature (Hsu 2011). Hsu (2011) quantified the green house gas (GHG) emissions and net energy value (NEV) for pyrolysis-derived green gasoline and green diesel produced via hydrotreatment of crude bio-oils. The Energy Independence and Security Act (EISA) of 2007 set advanced biofuels GHG emissions and NEV requirements compared with petroleum derived fuels in 2005 (http://www.gpo.gov/fdsys/pkg/BILLS-110hr6enr/pdf/BILLS-110hr6enr.pdf). The method followed was the same used by Hsu et al. (2011) in a previous study for ethanol. While SimaPro c.7.2 was the main life cycle assessment modeling software used, Econoinvent v. 2.1 was the source for life cycle inventories for secondary materials and energy of these unit processes. The impact of GHG emissions was calculated using the 100 year global warming potential for the gases. GHG emissions for the pyrolysis fuels reference was 0.142 kg CO2 equiv. per km (53% lower than conventional gasoline). The NEV calculated was 1.12 MJ/km gasoline and 0.93 MJ/km of diesel. These values are higher than the NEV for gasoline of -1.2 MJ per km in 2005 (Hsu 2011). Electricity use accounts for 27% of the net GHG emissions, and fossil-based hydrogen accounts for 6% of the GHG emissions. The GHG emissions can be lowered if electricity and hydrogen are produced from biomass instead of from fossil sources (Hsu 2011).

3.8 Documentation

The documentation should be produced for: The Commissioning Manual, Operation and Maintenance Manual, and the HAZOP (Lynch and Joseph 2010). In the documentation it is desirable to indicate what level of training is required to operate the plant, how many shifts will be required and how staff will be trained and certified to operate these units.

4. Financial Analyses

A number of technoeconomic analyses on biomass pyrolysis have been published (Rogers and Brammer 2009, 2012; Bridgewater et al. 2002, Peacock et al. 2006, Farag et al. 2002, Ringer et al. 2006, Solantausta and Huetair 2000, Badger et al. 2011, Wright et al. 2010, Jones et al. 2009). Pyrolysis of biomass is still an emergent technology. System investment costs are not easy to estimate (Kuppens et al. 2010).There is not enough information to do financial analyses with the frame of reference of the application of the triple top line concept from the design. In this section, data available in the literature is shown mainly for feedstock cost, and capital and operating costs. A detailed explanation of assumptions made for pyrolysis technoeconomic studies can be found in Appendix D at Wright et al. 2010. Please be cautioned that the information provided corresponds to currently available equipment costs (typically first generation designs) and that opportunities exist to develop new solutions that will drive down these costs. Some authors (Wright et al. 2010) used the RAND Corporation analysis, which take into account risks associated with estimating costs of building a pioneer plant.

4.1 Biomass supply chain

The biomass supply chain must be analyzed in order to estimate the cost of biomass at the gate of the pyrolysis unit. Negotiating the price of the biomass prior to construction of the plant is highly recommended. Contracts are typically based on a five year minimum with the option for longer contracts.

Urban wood waste, forest and agricultural residues can be integrated into a sustainable business model, thereby avoiding development of monoculture plantations to sustain the biomass/biochar industry (Flora 2012). Facilities should be designed to co-process organic resources generated in local communities, farms and forests to reduce costs associated with industrial scale production and/or collection of biomass and to minimize the carbon footprint associated with transportation of feedstocks and products. In the case of urban wood waste one is able to take advantage of the fact that they are already associated in a collection system. Systems should be designed to significantly reduce greenhouse gas emissions associated with the production of biofuel. Bio-fuel recovery and carbon sequestration pyrolysis technologies should be carbon neutral or negative (Flora 2012).

The Department of Ecology Waste 2 Resources (W2R) program has tracked organic materials in the solid waste stream in Washington since 1992 using facility reports, recycling surveys, and waste characterization studies. Facilities report the quantity, type, and county of origin of organic waste materials that are collected for uses such as recycling, composting, other types of waste diversion, incineration, and landfill disposal. W2R determines the makeup of the disposed wastes by completing waste composition studies. This information can be used to estimate the available feedstocks for pyrolysis applications.

Annual Solid Waste Reports and Recycling Survey: Washington’s solid waste rules require annual reporting from solid waste facilities with permits or conditional exemptions. In addition to the required reports, voluntary recycling surveys are sent to non-regulated facilities that handle recyclable or reusable material. The W2R program receives annual reports and surveys from 29 types of regulated and non-regulated facilities, including landfills, incinerators, piles, and compost and recycling facilities. Table 11 lists the facility types reporting on annual solid waste reports and recycling surveys.

Table 11. Types and quantities of solid waste facilities in Washington.

Facility Type	Number of Facilities	Facility Type	Number of Facilities
Anaerobic Digester	6	Limited MRW	21
Ash monofill	1	Limited Purpose Landfill	24
Baling and compaction	1	Material Recovery Facility	73
Beneficial Use	1	MRW Collection Event	120
Biosolid - Unpermitted	1	MRW Fixed	35
Biosolids	452	MRW Used Oil Collection Facility	37
Compost Facility	66	MSW Landfill	60
Drop Box	68	Pile	94
Energy Recovery Facility	4	Recycling Facility	316
Historic Landfill	569	Recycling Survey (non-regulated)	438
Inert Waste Landfill	45	Surface Impoundment	0
Inert/Demo (304)	4	Tank	0
Intermediate Solid Waste Handling Facility	13	Tire Storage	12
		Transfer Station	104
Land Application	29	Woodwaste Landfill (304)	9

Solid waste facilities report quantities of incoming wastes in approximately 200 material categories, including 16 wood and wood fiber categories and 20 other organic material categories. Wood and wood fibers are reported by the following facility types: limited purpose landfills, piles, and compost and recycling facilities (regulated and non-regulated). Facilities reported four types of organic woody materials in Washington in 2010. Their reported uses are summarized in Table 12. Table 13 lists the number of facilities for each county that reported collecting organic woody material for composting, recycling, or diversion in 2010. See Appendix A for definitions of terms and explanation of facility types.

Table 12. Woody materials going to solid waste facilities in Washington in 2010.

Woody Materials Reported in Annual Solid Waste Reports and Recycling Surveys (2010)	Applications Reported			
	Solid Waste	Burning for Energy	Recycle	Compost
Landclearing Debris		X	X	X
Sawdust/shavings				X
Wood Waste	X	X	X	X
Yard Debris	X	X	X	X

Table 13. Number of facilities by county reporting organic woody materials for composting, recycling, or diversion in 2010.

County of Origin[1]	Landclearing Debris		Other Wood Waste	Sawdust or Shavings	Wood Waste		Yard Debris		
	Compost or Recycle	Burn for Energy	Compost	Compost	Compost or Recycle	Burn for Energy	Compost or Recycle	Mixed with Food, Compost	Burn for Energy
Adams							1 S		
Asotin						1 S	1 M		
Benton					1 S	1 M, 2 S	1 L, 1 M		
Chelan	1 S		1 S, 1 M		6 S	1 S	2 M, 4 S		
Clallam	1 L			1 S	1 M, 1 S	1 L	1 M		
Clark	1 L, 1 M				1 L, 3 S	2 L, 1 M, 5 S	1 L, 2 M, 2 S		2 L
Cowlitz					1 M	1 L, 2 M, 1 S	1 L, 2 M, 1 S		
Douglas					1 S		1 S		
Franklin			2 S		1 L	1 M	1 M, 2 S		
Garfield							1 S		
Grant					3 S	1 M, 2 S	2 M, 2 S		
Grays Harbor	1 S		1 S		1 M, 2 S	1 M, 3 S	1 S		
Island	1 M, 1 S			1 S	1 M, 2 S	3 S	1 M, 4 S		
Jefferson	1 S				2 S	1 S	3 M, 2 S		
King	6 L, 1 M, 3 S	1 M, 2 S	1 L, 2 S	1 S	2 L, 1 M, 16 S	7 L, 3 M, 3 S	4 L, 4 M, 8 S	5 L	
Kitsap	1 L, 1 M, 2 S	1 S	1 M	1 S	1 M, 7 S	2 M, 2 S	1 L, 5 M, 5 S		1 S
Kittitas	1 S				1 S	2 S	2 M, 1 S		
Klickitat			1 S						
Lewis	1 S	1 S			1 M, 3 S	1 L, 2 S	3 S		1 S
Lincoln							1 S		
Mason	1 S	1 L, 2 M	1 M, 1 S		1 L, 1 S	2 L, 1 M, 5 S	1 S		1 L, 2 S
Pacific					1 S	2 S			
Pierce	2 L, 2 M, 7 S	1 M, 2 S	1 M		2 L, 1 M, 14 S	2 L, 4 M, 3 S	6 L, 4 M, 8 S		
San Juan					1 S	1 S			
Skagit	1 S				1 L, 1 S	1 L, 2 S	1 M, 2 S	1 L	
Skamania		1 M				1 L			1 M
Snohomish	2 L, 3 M, 4 S	1 L, 1 S	1 M, 1 S		2 L, 2 M, 10 S	2 L, 2 M, 8 S	5 L, 3 M, 2 S	1 L, 1 S	
Spokane		1 M	1 S	1 L	2 M, 3 S	2 L, 3 M, 4 S	3 L, 3 S	4 L	1 L, 1 S
Thurston	2 M, 5 S	1 L	1 S		1 L, 1 M, 6 S	1 L, 6 S	1 M, 2 S	2 L, 1 M	
Wahkiakum					1 S	1 S			
Walla Walla			1 M, 1 S		2 S	1 S	2 M, 1 S		
Whatcom	1 S		1 S		1 M, 2 S	2 S	3 M, 2 S	2 M	1 S
Whitman			1 S		1 M, 1 S	1 M, 1 S	3 S		1 M
Yakima			1 M		2 S	1 L, 1 S	1 L, 1 M		
Key: S = small (< 1,000 tons of material); M = medium (1,000 -5,000 tons of material); L = large (> 5,000 tons of material).									

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[1] Columbia, Ferry, Okanogan, Pend Oreille, and Stevens counties are not represented in this table because they had no woody materials reported by solid waste facilities.

See the *Organic Materials Recycled, Diverted, and Disposed Indicator* (http://www.ecy.wa.gov/beyondwaste/bwprogOrganics.html) of the *Beyond Waste Progress Report* (http://www.ecy.wa.gov/beyondwaste/bwprog_front.html) for trend information and a complete list of organic materials reported by solid waste facilities since 1992. For a discussion of all solid waste types, facility reports and trends, see the *Solid Waste in Washington State, 20th Annual Status Report* (Ecology, 2011) https://fortress.wa.gov/ecy/publications/publications/1107039.pdf

Characterization of Disposed Wastes: Since annual reports from municipal solid waste (MSW) landfills and incinerators do not provide details on the content of mixed wastes going to MSW landfills and incinerators, the W2R program conducts periodic waste characterization studies. These studies provide a statistical estimate of the makeup of the waste going to landfills and mixed MSW incinerators. The latest of these studies is the *2009 Washington Statewide Waste Characterization Study* (Ecology and Cascadia Consulting Group, 2010) (https://fortress.wa.gov/ecy/publications/publications/1007023.pdf). This information supplements the annual reports and surveys from solid waste facilities and provides a more complete picture of the quantity and types of waste materials that are generated in the state. Table 14 shows the estimated percent of organic woody materials disposed in MSW.

Table 14. Percent of organic woody material in MSW.

Organic Woody Material Disposed in MSW	Estimated Percent of MSW (%)	90% Confidence Interval (+/-)
Compostable Paper	5.6	0.4
Green Waste	5.3	0.9
Lumber and Pallets	7.9	1.2
Natural Wood	0.3	0.2
Remainder/Composite Wood	1.5	0.3
Total Organic Woody Material Disposed in MSW	20.6	

Organic Woody Materials Available as Feedstocks for Pyrolysis Applications in Washington: Adding information from annual solid waste reports, the recycling survey, and waste characterization studies, the W2R provides annual estimates of the composition of the solid waste stream in Washington. In 2010, organic woody materials made up 21.4% (3.30 million tons) of all solid waste generated in Washington, of which 71.3% (2.35 million tons) was recovered and 28.7% (0.95 million tons) was disposed in landfills. Other organic materials made up 9.3% (1.43 million tons) of solid waste generated. See Figures 9 and 10.

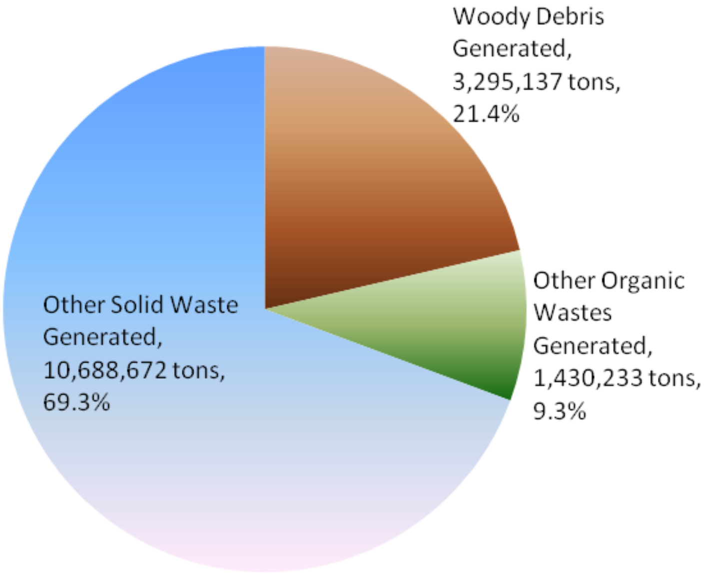

Figure 8. Solid waste generated in Washington in 2010.

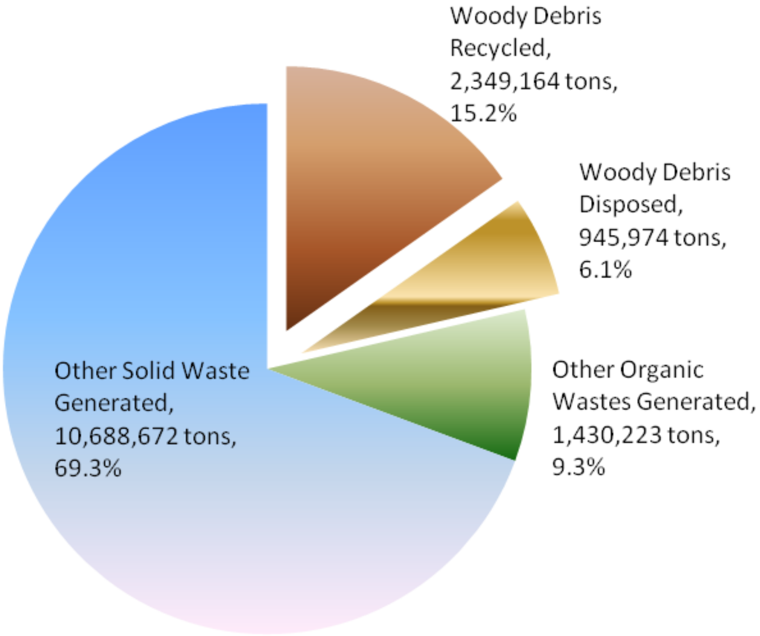

Figure 9. Organic woody material recovered and disposed in 2010.

Wood, woody debris, and wood fibers that were recovered from the waste stream or disposed in Washington can be summarized in six basic categories, totaling 3.30 million tons in 2010 (see Table 15). Wood makes up 49.5% of the total collected at 1.63 million tons. Yard debris (some mixed with food) accounts for another 33.8%, or 1.12 million tons. Other woody or wood fiber categories (land clearing debris, compostable paper, and sawdust) make up the remaining 16.7%.

Table 15. Organic woody material recovered and disposed in Washington in 2010 (tons)[2]

Organic Woody Material	**Recycled/Diverted - Facility Types**				**Disposed - Facility Types**			**Total**
	Compost	**Other Reuse & Recycling**	**Energy Recovery**	**Total Recycled**	**MSW Landfills**	**Limited Purpose Landfills**	**Total Disposed**	
Compostable Paper				-	254,703		254,703	254,703
Landclearing Debris	44,090	106,197	130,766	281,053			-	281,053
Sawdust	14,318			14,318			-	14,318
Wood	32,641	300,178	847,115	1,179,934	441,183	8,822	450,005	1,629,939
Yard Debris	376,895	122,019	50,452	549,366	241,059	207	241,265	790,631
Yard Debris/Food Scraps[3]	324,493			324,493			-	324,493
Total Organic Woody Materials	792,437	528,394	1,028,333	2,349,164	936,945	9,029	945,974	3,295,138

The amount of organic woody material in the solid waste stream has increased over the last ten years, from 2 million tons in 2001 to 3.3 million tons in 2010. The amount of organic woody material composted, recycled, and diverted from disposal more than doubled during that time, from 1.14 million tons in 2001 to 2.35 million tons in 2010. The amount of organic woody material disposed in landfills and incinerators increased from 0.87 million tons in 2001 to 0.95 million tons in 2010. See Figure 11.

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[2] Data compiled by Washington Department of Ecology, Waste 2 Resources, from solid waste facilities' annual reports. MSW landfill data is estimated using the 2009 Washington Statewide Waste Characterization Study.

[3] US EPA study, *"Best Management Practices in Food Waste Programs"*, *Freeman & Skumatz,* (http://www4.uwm.edu/shwec/publications/cabinet/composting/EPA_FoodWasteReport_EI_Region5_v11_final.pdf) shows that the average amount of organics collected from mixed yard and food waste programs per participating household is 25-30 pounds per household per week; the food waste component is only 7-9 pounds (about 29 percent of the total collected). If paper products are included in collection programs they can make up at least 50 percent of the materials by weight.

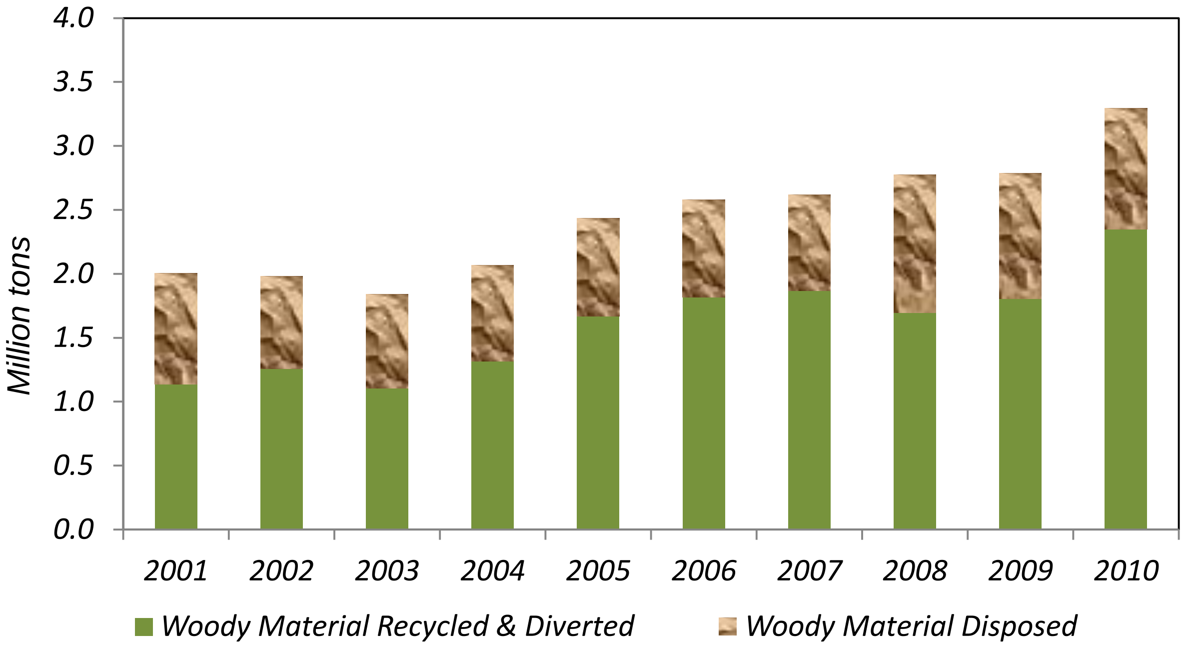

Figure 10. Organic woody material recycled, diverted, and disposed in Washington: 2001 – 2010.

Feedstock cost is highly dependent in the existence of competitive uses for the material that will be processed. Woody waste has monetary value due to the energy content as hog fuel at minimum. The tipping fees associated with the processing of municipal solid waste fractions are difficult to estimate. The most common methodology used to dispose MSW is in landfills. For the past five years the average tipping fee of MSW in landfills in the State of Washington was $56/ton (Washington State Department of Ecology, 2012). Figure 12 shows the evolution of tipping fees in the state for the last four years. Although, the average fees have remained almost constant in this period of time the standard deviation (variability on the price paid) has varied substantially.

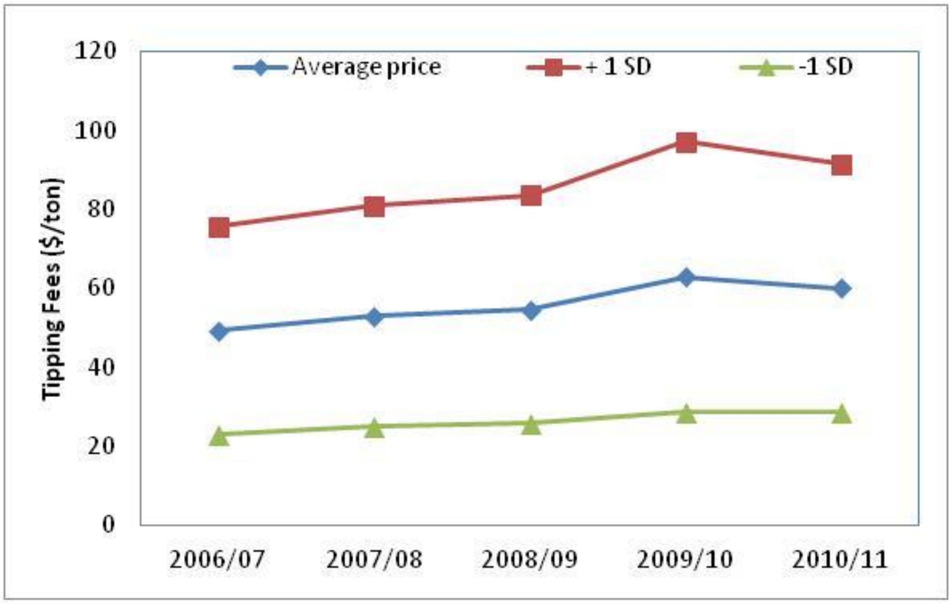

Figure 11. Tipping fees of MSW in landfills in Washington State showing the range plus or minus one standard deviation. (Source: Adapted from Washington State Department of Ecology (2012) using 14 landfills with information from the last five years).

The market price of hog fuel in Washington State in 2000 ranged from $6 to $22 per bone dry ton (http://www.clark.wa.gov/recycle/documents/9 Energy Recovery Incineration.pdf). Different considerations for the biomass cost (from the point of view of people that are going to build a pyrolysis plant) are given in the next chapter of this report.

The price that must be paid for biomass, standing or lying on the land is referred to as the *feedstock value*. The price range for different agriculture and forest feedstocks (i.e., corn stover, cereal grain straw, sorghum stover, switchgrass, prairie grass, logging residues, forest thinnings, etc.) has historically varied from less than $10/dry ton to $50/dry ton (Perlack and Hess 2006). Most studies reported in the literature convey the “price” of raw materials in the absence of any significant increase in demand and with limited consideration for opportunity cost. The deployment of a biomass industry could dramatically changes the equation for feedstock supply prices, creating demand that did not exist prior to the creation of the industry and consequently higher prices. It is typical to pay $10 per ton of straw on the field in a windrow. The value of delivered straw bales in the Idaho dairy market in 2004 was between $32 and $42 per ton (Grant et al. 2006). Market values of $50 to $83 per ton of forest biomass delivered can also be considered typical because forest supply chains are less developed (Wright et al. 2010). Table 16 shows the costs associated with biomass transportation logistics.

Table 16. Logistic costs of dry herbaceous feedstock (i.e. field dried corn stover) ($/dry ton) (2007 $) (US DOE 2010).

	2007	2009	2012	2017
Harvest and Collection	$20.35	$13.30	$12.15	$12.15
Storage and Queuing	$7.25	$7.25	$2.45	$2.45
Preprocessing	$12.40	$14.15	$11.50	$11.50
Transportation and Handling	$13.70	$11.45	$7.90	$7.90
Total Feedstock Logistics, $/dry ton	**$53.70**	**$46.15**	**$35.00**	**$35.00**

The US Department of Energy (2010) reports costs associated with harvest and logistics for woody biomass as well as the price paid to the grower (Table 17).

Table 17. Dry woody biomass feedstock logistics projection (US DOE 2010).

Year	Harvest and Logistics	Grower Payment	Total Delivered Cost to Processing Plant
	$ dry US ton	$ dry US ton	$ dry US/ton
2007	51.85	15.70	67.55
2008	47.80	15.70	63.50
2009	42.50	15.70	58.20
2010	38.50	15.70	54.20
2011	36.10	15.70	51.80
2012	35.00	15.70	50.70
2017	35.00	26.20	61.20

Rogers and Brammer (2009) published an analysis of transportation costs for energy crops (short rotation coppice willow and miscanthus) converted in a network of pyrolysis plants. Transportation costs between the field and the pyrolysis units were calculated using fixed and variable cost for freight haulage. The authors found that the number of round trips per day a truck could make was the key parameter controlling transportation costs.

4.2 Biomass preprocessing

The goals of biomass pre-processing are: 1) size reduction, 2) biomass drying below 10 mass%, 3) providing buffer storage space for periods of no operation, 4) providing storage space for period between deliveries, and 5) unloading trucks in acceptable times (Rogers and Brammer 2012).

4.2.1 Capital costs

Preprocessing equipment may include a chipper, grinder, dryer or a hammer mill depending on the feedstock and pyrolysis process used (Badger et al. 2011). The US Environmental Protection Agency (2007) funded a report containing information on the costs associated with the different steps of converting biomass resources into power. Table 18 shows capital costs associated with each piece of equipment for biomass processing plants capable of processing 100, 450 and 680 tons/day. Using these reported costs, an estimate of the capital cost of a biomass preparation process can be calculated and broken down into three parts: 1) receiving system (truck tipper, conveyor, and radial stacker), 2) processing system (reclaim feeder, conveyor, metal separator, dryer, screener and grinder), and 3) buffer storage (storage bin for 24 hours) (US EPA 2007).

The estimates considered that small facilities (100 tons/day) primarily would handle feedstock manually. For large conversion systems (450 and 680 tons/day) a fully automated preparation yard is cost effective because, although it is more capital intensive, it requires less labor. For fast pyrolysis, the data provided by The US Department of Agriculture, the US Department of Energy and NREL (Antares Group 2003) (Table 18) should be complemented with drying and fine grinding costs. Costs reported by Badger et al. (2011) are summarized in Table 19. Others have reported on the capital cost of biomass preprocessing units (Naimi et al. 2006, Ringer et al. 2006, Spath et al. 2005).

Table 18. Biomass fuel preparation capital costs (Antares Group 2003, US EPA 2007).

Component	**Ton / Day Fuel (as received)**		
	100	**450**	**680**
Receiving System			
Truck tipper	$230,000	$230,000	$230,000
Conveyor to wood pile		$40,000	$45,000
Radial stacker, adder		$190,000	$205,000
Front end loader, adder	$100,000		
Receiving Equipment Subtotal	**$330,000**	**$460,000**	**$480,000**
Processing System			
Reclaim feeder		$230,000	$230,000
Conveyor		$149,000	$160,000
Metal Separator	$40,000	$40,000	$40,000
Screener	$150,000	$220,000	$250,000
Grinder	$250,000	$400,000	$600,000
Processing Equipment Subtotal	**$440,000**	**$1,039,000**	**$1,280,000**
Buffer storage	**$60,000**	**$98,000**	**$135,000**
Fuel metering	$252,000	$313,000	$364,000
Controls	$115,000	$166,000	$196,000
Equipment Subtotal	**$1,197,000**	**$2,076,000**	**$2,455,000**
Equipment installation	$500,000	$1,093,000	$1,220,000
Civil/structural work	$370,000	$787,000	$877,000
Electrical work	$170,000	$275,000	$305,000
Direct Cost Subtotal	**$2,237,000**	**$4,231,000**	**$4,857,000**
Engineering (10% of direct cost)	$223,700	$423,100	$485,700
Contingency (8% of direct cost)	$178,960	$338,480	$388,560
Indirect Costs Subtotal	$402,660	$761,580	$874,260
Total Prep-Yard Cost	**$2,639,660**	**$4,992,580**	**$5,731,260**
Prep-Yard Unit Cost ($/ton/day)	$26,397	$11,046	$8,453

Table 19. Capital cost summary including the cost of transportation trucks and driers (Badger 2002).

	46 t/day	230 t/day	460 t/day	818 t/day	2047 t/day
Truck, small dump, 12 m^3	$40,000				
Large dump trailer only, 24.5 m^3	$27,000				
Self unloading trailer van only, 81 m^3	$40,000				
Standard trailer van only, 80 m^3	$24,000	$24,000	$24,000	$24,000	$24,000
Scales, mechanical		$40,000	$40,000	$40,000	$40,000
Scales electronic		$110,000	$110,000	$110,000	$110,000
Bar code scanner/computer system					$10,000
Whole truck dumper w/hopper					$604,000
Truck trailer only dumper w/hopper		$234,000	$234,000	$234,000	
Scaling dick screen	$19,100	$19,100	$24,750	$30,900	$30,900
Hammer mill (hammer hog)	$49,050	$49,050	$50,025	$59,625	$59,625
Enclosed metal bin w/loader	$2,041,000	$4,320,000			
Metal silo, conical bottom w/ inloader	$1,276,000				
Concrete silo	$855,000	$2,532,000			
Hopper, live-bottom, 9 mdrg chain conv	$26,153	$35,850	$35,850	$42,300	$42,300
Conveyor belted (33.5 m length)	$51,000	$51,000	$51,000	$53,250	$53,250
Metal bldg w/concrete pad 1-side open	$62,000	$244,000			
Open pile w/concrete pad	28,338	$41,719	$121,124	$5,958	$5,958
Front end loader, rubber tired, w/9 m3 bucket		$250,000	$250,000	$250,000	$250,000
Magnet bar	$3,975	$4,800	$4,800	$4,800	$7,600
Magnet self cleaning bar	$7,800	$7,800	$8,400	$11,950	$17,100
Magnet pulley head	$2,645	$2,645	$4,685	$5,995	
Non-ferrous metal detector	$6,4785	$6,475	$6,475	$9,965	$9,965
Dryer, rotary	$250,000	$521,000	$887,200	$1,362,200	$3,300,300

Capital costs of similar installations for other capacities can be calculated using the *six-tenths factor rule.* This rule states that if unit *b* with one capacity has a cost that is known, then a similar unit *a* with X times the capacity of the first unit will cost $X^{0.6}$ times the cost of the initial unit (Peters et al. 2003):

$$\text{Cost of equipment } a = (\text{cost of equipment } b)\, X^{0.6} \qquad (1)$$

For less than 10 years, common indices result in fairly accurate estimates.

$$\text{Present cost} = \text{original cost} \bullet (\text{Index value at present/ index value of original cost}) \qquad (2)$$

Cost indices are published regularly. Several different types of indices include estimations for equipment costs construction, labor, materials or other various specialized fields. Some of the more common indices include: the Engineering News-Record Construction Index, the Nelson-Farrar Refinery Construction Index, and the Marshall and Swift Equipment Cost Index.

4.2.2 Operating costs

Operating costs essentially include energy and labor. Although, labor, in standard economic assessment, is considered a cost, it is a societal benefit susceptible to being reduced with the help of governmental programs. However in this report, labor is going to be associated as an operation cost according to the revised literature. Labor costs associated with the operation of a 100, 452 and 678 ton/day unit were estimated by the Antares Group (2003) (Table 20). The *Monthly Labor Review*, published by the U.S. Bureau of Labor Statistics can be used to estimate labor and benefit costs. Spath et al. (2005) provides information on salaries for employees of thermochemical plants.

Table 20. Preprocessing labor requirements (Antares Group 2003).

Employee Position	**Tons/day Fuel (as received)**		
	100	**450**	**680**
Delivery Coordinator	1	1	1
Assistant Coordinator		1	1
Employee Supervisor	1		
Front End Loader Operator	2		
Operators	1	2	2
Total Employees	**5**	**4**	**4**

According to final product specification and pyrolysis reactor characteristics, it is necessary to reduce the feedstock size. The yield of bio-oil product is directly related to the particle size used (Shen et al. 2009, Westerhof et al. 2012). Biomass size reduction consumes large quantities of power (Naimi et al. 2006, Ringer et al. 2006). Energy requirements for biomass grinding can be estimated from research by Mani et al. (2004). Depending on the material and the grinding mechanisms (shear, impact or attrition), the energy consumed by the grinder may vary (10-50 kW/ton) (Naimi et al. 2006, Wright et al. 2010). Farag et al. (2002) estimate grinding costs to be as much as $11/ton. Chipping branches and stumps to 2 inch wood chips costs approximately $4/ton. Grinding 2 inch wood chips to about 0.04 inches is $1.8-6/ton (Himmel et al. 1985, Farag et al. 2002).

For MSW and typical biomass, the moisture content is above 40%. In order to optimize the pyrolysis reaction it is necessary to dry the feedstock below 15%. Therefore, the cost of drying is also very important, especially for wet feedstock. About 50% more energy is required for biomass drying than the theoretical minimum of 2.4 MJ per kg of evaporated moisture. Using a steam rotary dryer, Wright et al. (2010) suggest that the drying energy required is 5.0 MJ per kg of evaporated water. Wood chips are often dried during the warmer months by letting the piles sit for four to six weeks in order to reduce the cost of drying. Due to snow and low temperatures that occur during the winter months, outdoor drying does not work well and the piles must be periodically rotated to prevent fermenting (Farag et al. 2002).

4.3 Pyrolysis units (pyrolysis reactor + condensation system)

4.3.1 Capital costs

The literature for pyrolysis units estimates different capital investment costs (Brammer et al. 2005, Bridgwater et al. 2002, Siemons 2002). The most accurate way to determine process equipment costs is with firm bids from suppliers. Quick estimates can often be supplied by the fabricators and will be close to the bid price. Past purchase orders are another way to determine costs (Peters et al. 2003). Table 21 lists prices for different pyrolysis units depending on their production capacity (Miles 2009). Figures 13-19 show pyrolysis reactors by price groups.

Table 21. Cost of different carbonization units for biochar production (Miles 2009).

Capital Cost (USD)	Production TPY Biomass	Example Kilns	Batch time or Capacity
<1,000	30 lb/batch	New England Biochar "Shotgun" Andrew Heggie	100 lb (2-4 hr) 6,000 (8 hr)
1,000-10,000	10-600 tpy	Adam Retort (NE Biochar)	3 t (4-6 hr)
100,000-1,000,000	1000 pph 2000 tpy	Biochar Systems Carbon Diversions Pronatura	250 pph 500 pph
1,000,000-10,000,000	20,000 tpy	Alterna, Best Energies Bioenergy LLC, Carbon Diversions, 3RAgrocarbon (Terra Humana) Dynamotive, advanced Biorefinery, Renewable Oil, EPRIDA, Pyrogen	2-10 tph 2-5 tph

Figure 12. Carbonization units < $1,000 (Miles 2009).

Figure 13. Pyrolysis reactors costing less than $10,000 (Miles 2009).

Figure 14. Carbonization system costing under $500,000 (Miles 2009).

Figure 15. Pyrolysis reactors under $1,000,000 (Miles 2009).

Figure 16. Pyrolysis reactor under $10,000,000 (Miles 2009).

Figure 18 shows the scheme of the technology commercialized by BEST. This technology is able to process 2.9 dry tons/h and is able to shred, dry carbonize, cool, screen, grind, bag and ship the biochar. The plant can produce 6,600 tons per year of biochar. The capital cost of this unit is $3.5 million (Miles 2010).

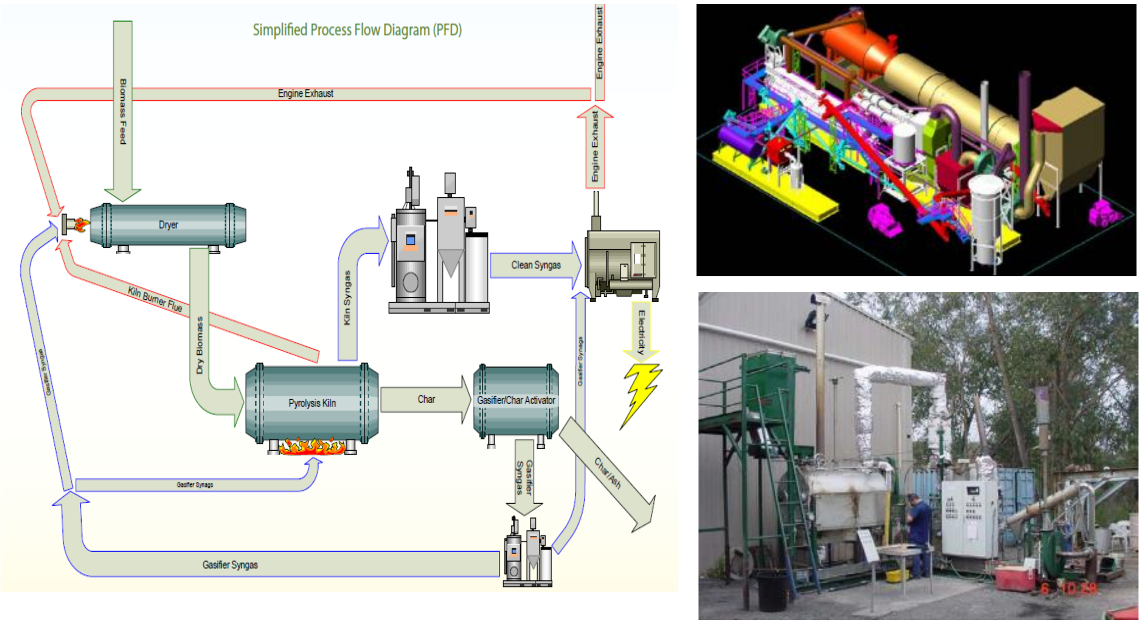

Figure 17. BEST Energies System (Miles 2009).

Capital investment costs of a pyrolysis unit can be calculated using several formulas (Kuppens et al. 2010, Siemons 2002, Bridgwater et al. 2002). Capital investment cost can be estimated using the equation developed by Bridgwater et al. (2002) if the hourly mass flow rate in tons per hour (ϕ, ton/ h) of dried and ground wood fed into the reactor is known. A feeding system, the pyrolysis reactor, a liquid recovery system, and a storage unit for the pyrolysis oil as well as buildings and construction and commissioning costs are all included in the investment costs of the equations presented in this section (Kuppens et al. 2010):

$$I_{pyrolysis} = 4.0804 \bullet 10^4 \bullet (\phi \bullet 10^3)^{0.6194} + 1.19 \bullet 10^5 \bullet (0.7\ \phi)^{0.4045} \tag{3}$$

Where: I = Investment cost (EUR)
ϕ = hourly mass flow rate
$4.0804 \bullet 10^4$ represents the feedstock and materials handling system cost
$(\phi \bullet 10^3)^{0.6194}$ represents the pyrolysis reactor cost
$1.19 \bullet 10^5$ represents the bio-oil product recovery system, and
$(0.7\ \phi)^{0.4045}$ represents the cost of bio-oil storage

All the equations listed in this section should be used with care because they are only valid for the construction materials, the year, the capacity and the technologies used by the authors that obtained these empirical equations.

Using the equation proposed by Siemons (2002), the capital investment cost ($I_{pyrolysis}$ EUR) can be calculated if the reactor's thermal capacity (C) in MW is known (equation 4). The pyrolysis reactor, an electricity generator for on-site electricity consumption, equipment and the installation and commissioning for a feedstock drier are all included in the costs that will be obtained with this equation.

$$I_{pyrolysis} = 6.91453 \bullet 10^2 \bullet C\ 0.76 \tag{4}$$

This equation takes into account different types of pyrolysis reactors. The cost data of other technologies such as the rotating cone of BTG or Pyrovac's vacuum pyrolysis have been taken into account, with the exception of fluidized bed systems, which explains the deviation of this estimate compared to other estimates (Siemons 2002, Kuppens et al. 2010).

The following equation represents another formula based on an analysis of a typical fluidized bed system (Brammer et al. 2005). This formula depends on the moisture content of the feedstock (μ), which may require a higher consumption of heat, and the mass input flow (m) in kg s^{-1} (Kuppens et al. 2010).

$$I_{pyrolysis} = 4.744 \bullet 106 \bullet (m + 0.0921)0.504 + 1.074 \bullet 10^6 \bullet m \bullet (1+ \mu) + 824 \tag{5}$$

Regression analysis on 13 data points were used to develop the equation that follows (Islam and Ani 2000, Ringer et al. 2006, Siemons 2005, Van de Velden and Baeyens 2006, Van de Velden et al. 2008, Venderbosch et al. 2006). This represents a linear regression with the capital investment cost as the dependent and hourly mass flow of the biomass *(ϕ)* as the independent variable (Kuppens et al. 2010).

$$I_{pyrolysis} = (1.906 + 0.598 \bullet \phi) \bullet 10^6 \qquad (6)$$

Farag et al. (2002), Badger et al. (2011), Jones and Anderson (2011), Cole Hill Associates (2004) and Ringer et al. (2006) estimated the capital plant cost of different sized pyrolysis units that include feed preparation, planning, and construction (Table 22). The cost of land and site preparation is not included in these estimates (Farag et al. 2002).

Table 22. Dynamotive bio-oil plant capital cost including site planning, preparation, feedstock and combustion costs (Cole Hill Associates 2004, Jones and Anderson 2011, Farag et al. 2002).

Capacity (ton/day)	Capital Cost ($ million)
6 ton/day (BEC) (Jones and Anderson 2011)	0.1 – 0.2
20-25 ton/day (BECG) (Jones and Anderson 2011)	1.0 – 1.5
25 ton/day (Dynamotive) (Cole Hill Ass. 2004)	2.6
45 ton/day (Cole Hill Ass. 2004)	2.5
100 ton/day (Dynamotive) (Farag et al. 2002)	6.6
100 ton/day (Dynamotive) (Cole Hill Ass 2004)	5.6
100 ton/day (ROI) (Badger et al. 2011)	6.0
200 ton/day (Dynamotive) (Farag et al. 2002)	8.8
200 ton/day (Dynamotive) (Cole Hill Ass. 2004)	8.2
400 ton/day (Dynamotive) (Farag et al. 2002)	14.3
400 ton/day (Dynamotive) (Cole Hill Ass. 2004)	12.6
550 ton/day (Ringer et al. 2006) (includes 35% contingency)	28.4

A detailed cost breakdown of the installed equipment for feedstock preparation, pyrolysis, quench system with steam, and power production for a 550 t/day unit estimated by Ringer et al. (2006) is shown in Table 23.

Table 23. Installed equipment costs for 550 ton/day pyrolysis units (Ringer et al. 2006, Wright et al. 2008).

Plant Area	Installed Equipment Cost ($ Million)	%
Feedstock Handling and Drying	$5.57	19.61
Pyrolysis	$3.92	13.80
Quench	$1.94	6.83
Heat recovery	$1.14	4.01
Product Recovery and Storage	$0.80	2.81
Recycle	$1.38	4.86
Steam and Power Production	$3.16	11.12
Utilities	$3.13	11.02
Equipment Contingency – 35%	$7.37	25.94
Total Installed Equipment Cost	$28.41	100

The total capital investment cost for a 550 ton/day pyrolysis plant as estimated by Ringer et al. (2006) is shown in Table 24. The total equipment cost is used to estimate other costs.

Table 24. Capital investment cost for a 550 ton/day unit (Ringer et al. 2006).

Component	Basis	Cost
Total Equipment Cost Warehouse Site Development	Calculated by equations 1.5% of equipment costs 9% of ISBL	$28,410,567 $426,159 $826,448
Total Installed Cost (TIC)	**Sum of Above**	**$29,663,173**
Indirect Costs Filed Expenses Home Office & Construction Fee Project Contingency	 20% of TIC 25% of TIC 3% TIC	 $5,932,635 $7,415,793 $889,895
Total Capital Investment (TCI)	**Sum of Above**	**$43,901,497**
Other Costs (Startup)	10% of TCI	$4,390,150
Total Project Investment	**Sum of Above**	**$48,291,646**

A detailed estimation of the cost of equipments needed for a pyrolysis and hydrotreatment unit can be found in Appendix A of the Wright et al. (2010) report.

4.3.2 Operating costs

Mass and energy balances are needed to determine variable costs (Ringer et al. 2006). The cost of electricity could represent approximately 17% of the annual operating cost (at $0.05-0.08 per kWh) (Wright et al. 2010). Utility costs proposed by Farag et al. (2002) associated with a 100, 200 and a 400 ton/day pyrolysis unit are shown in Table 25.

Table 25. Dynamotive plant utility costs (Farag et al. 2002).

Wet Wood Plant Size	100 ton/day	200 ton/day	400 ton/day
Electricity used per operating hour	550 kWh/h	962 kWh/h	1788 kWh/hr
Yearly operating hours	7920 hrs/year		
Electricity @ $0.065/kWh (per year)	$283,140	$495,238	$920,462
Nitrogen* (per year)	$80,000	$160,000	$320,000
Miscellaneous chemicals (per year)	$120,000	$240,000	$480,000
Natural as needed (MJ/year)	13,068,000	26,136,000	52,272,000
Natural Gas** @ ($0.00672/MS) (per year)	$88,214	$176,428	$352,856

*Nitrogen used as a fluidized bed

** A 2001 Dynamotive claim was used to calculate the amount of natural gas used in the process. This claim stated that .0 MJ of energy from an external fuel source out of a total 2.5 MJ is needed per kg of bio-oil produced.

Assuming an average one way haul distance to the bio-oil refinery, pyrolysis oil transportation costs can be estimated on a cost per gallon basis (Badger et al. 2011). Transportation cost for bio-oil estimate by Farag et al. (2002) is $0.05/gal of liquid oil. The estimated bio-oil transportation costs for various industrial capacities are seen in Table 26.

Table 26. Estimated transportation costs (Farag et al. 2002).

Wet Wood Plant Size	100 ton/day	200 ton/day	400 ton/day
Bio-oil Produced (gallons/day)	8,790.9	17,581	35,163
Cost for Transportation ($/year)	145,049	290,099	580,197

Several expenses are associated with high temperature grease, gasket material, coupling, component replacement, and other required standard maintenance. Most of these expenses occur on an annual basis. Approximately 2.5% of the cost of the pyrolysis module is a fair estimate for maintenance costs (Badger et al. 2011). Various labor cost estimates are reported in the literature (Badger et al. 2011, Farag et al. 2002, Ringer et al. 2006). Labor and wages estimated for 100 and 550 ton/day units is shown in Table 27.

Table 27. Break down of labor and wages for 100 and 550 ton/day units.

	ROI (100 t/day) (Badger et al. 2011)		**Dynamotive (100t/day)** (Farag et al. 2002)		**Fluidized bed (550 t/day)** (Ringer et al. 2006)	
Labor	Number required	Annual Salary $/year	Number required	Annual Salary $/year	Number required	Annual Salary $/year
Plant manager	1	55,000	1	80,000	1	121,600
Supervisor			1	60,000		
Plant engineer					1	79,000
Maintenance supervisor					1	72,940
Assistant plant manager/bookkeeper	1	35,000				
Shift supervisor					4	45,000
Maintenance tech					5	34,400
Plant operators (console, floating)	10	30,000	6	25,000-35,000	20	30,400
Accountant, bookkeeper & purchasing			1	45,000		
Lab manager/Chemist					1	60,780
Administrative assistants					2	24,300
Total	**12**	**390,000**	**9**	**220,000**	**35**	**1,342,920**

For an analysis of a 100 t/day Dynamotive plant Cole Hill Associates (2004) assumed that the pyrolysis plant will be in operation 24 hours a day, seven days a week with 8 hour shifts was made by . A 20% labor overhead rate is commonly assumed.

The nascent pyrolysis industry must work with insurance companies in order to identify safe working practices. Insurance costs estimated by Badger et al. (2011) for a 100 t/day pyrolysis unit are shown in Table 28.

Table 28. Annual average general and administrative fixed insurance expenses based on 100 dry tons per day (DTPD) (Badger et al. 2011).

Type of Insurance	**100 DTPD**
Property insurance	$42,113
Liability insurance	$39,539
Laboratory analysis	$19,150
Miscellaneous	$6,277

Farag et al. (2002) estimated yearly maintenance cost to be 10% of the capital cost of the plant (Table 29). Badger et al. (2011) estimated maintenance cost for a 100 t/day mobile pyrolysis unit to be $91,551/year, which is much lower than that estimated by Farag (2002) of $660,000/year.

Table 29. Estimated (yearly) maintenance costs for wet wood pyrolysis plants (Farag et al. 2002).

Wet Wood Plant Size	100 ton/day	200 ton/day	400 ton/day
Maintenance Cost	$660,000	$880,000	$1,4300,000

Figure 19 shows the distribution of the operational costs for 100, 200 and 400 t/day pyrolysis units obtained by Farag et al. (2002). Maintenance, feedstock, and labor are the most important costs. Capital and operating costs as estimated by Farag et al. (2002) and Badger et al. (2011) are listed in Tables 30 and 31, respectively.

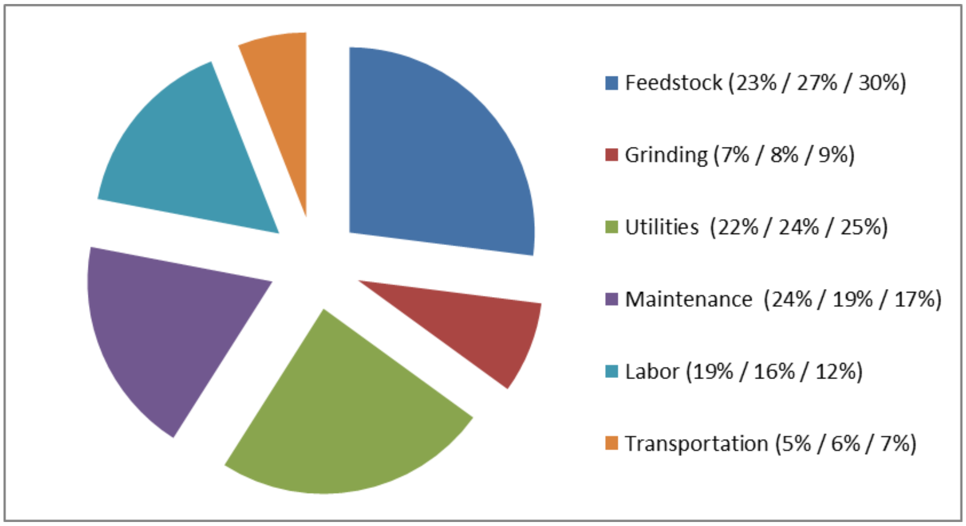

Figure 18. Operational cost pie chart for 100, 200 and 400 ton/day plants respectively (Farag et al. 2002).

Table 30. Total capital and operating costs (Farag et al. 2002).

Wet Wood Plant Size	**100 ton/day**	**200 ton/day**	**400 ton/day**
Feedstock cost	$654,772	$1,309,544	$2,619,089
Grinding cost	$181,881	$363,762	$727,525
Electricity for process	$283,140	$495,238	$920,462
Nitrogen	$80,000	$160,000	$320,000
Miscellaneous chemicals	$120,000	$240,000	$480,000
Natural gas	$88,214	$176,428	$352,856
Labor	$487,500	$649,984	$812,468
Maintenance	$660,000	$880,000	$1,430,000
Additional non-production labor	$44,196	$88,393	$176,786
Utilities (non-production) + potable water	$19,643	$39,286	$78,571
Potable water, heat, exchanger water, sewage	$10,000	$20,000	$40,000
Supplies & services	$62,857	$125,714	$251,429
Transportation	$145,049	$290,099	$580,197
Total Annual Operating Cost	**$2,837,252**	**$4,838,488**	**$8,789,383**
Gallons produced	2,900,986	5,801,972	11,603,945
Dollars per gallon without capital cost payment plan	$0.98 / gal	$0.83/gal	$0.76/gal
Capital cost	$6,600,000	$8,800,000	$14,300,000
Annual loan payment (equal amounts, 10 year payback period at 8%)	$648,441	$5,751,036	$10,272,339
Total annual operating cost with loan payment	$3,521,693	$5,751,036	$10,272,339
Dollars per gallon with capital cost payment plant	**$1.21 /gal**	**$0.99/gal**	**$0.89/gal**

Table 31. Breakdown of ROI operating and capital costs (US $/year), 80% online (Badger et al. 2011).

	100 DTPD (Pine wood chips)
Variable Costs $ (US dollars)	
Feedstock costs ($ 25.00/green ton)	$1,460,000
Electrical utilities	$104,869
Thermal utilities	$0
Maintenance	$91,551
Trucking costs (pyrolysis oil)	$76,692
Subtotal variable costs	$1,733,112
Fixed costs	
Wages & benefits & travel	$565,200
Property insurance	$42,113
Liability insurance	$39,539
Laboratory fees	$19,150
Subtotal fixed costs	$666,002
Total annual operating costs (fixed + variable)	$2,399,114
ROI system capital costs*	$6,030,816
Annual loan payment 100% borrowed (9% interest, 10 year term)	$916,749
Annual gallons produced (80% online), 60% yield	3,504,000
Total annual operating costs with loan payments	$3,315,863
Cost per gallon of oil	**$0.94**

* Equipment included in capital costs are the plant modules, a dryer, a hammer mill, and a feedstock metering bin, along with all associated conveyors and site preparation and permits.

4.4 Bio-oil production costs

Technoeconomic analyses have been performed for the production of pyrolysis oil for more than a decade (Brammer et al. 2006, Cottam and Bridgwater 1994, Gregoire 1992, Gregoire and Bain 1994, Islam et al. 2000, Farag et al. 2002, Ringer et al. 2006, Solantausta et al. 1992, Wright et al. 2010). As shown in Table 32, the overall estimated cost of crude bio-oil is $0.41-$3.61 per gallon.

Table 32. Bio-oil production costs (Ringer et al. 2006).

Study	Capacity (t/day)	Feedstock	Bio-oil cost ($/gal)
Cottom and Bridgwater (1994)	1,000	Wood	0.41
Arthur (1991)	1000	Wood	0.41
Arthur (1991)	250	Wood	0.46
Gregorire and Bain (1994)	1,000	Wood	0.50
Gregoire (1992)	250	Wood	0.50
Solantausta et al. (1992)	1000	Wood, peat and straw	0.59 – 2.46
Radlein and Bouchard (2009) (Dynamotive)	200	Wheat straw	0.59
Badger et al. (2011)	100	Pine wood chips	0.94
Farag (2002) (Dynamotive)	100, 200, 400	Low-grade wood chips	1.21, 0.99, 0.89
Ismam and Ani (2000)	2.4 - 24	Rice husks	1.73-0.83
Polagye et al. (2007)	10, 100, 500, 1,816	Forest thinning	2.70, 1.32, 0.96, 0.85
Granatstein et al. (2009)	10, 100, 500, 1816	Forest thinning	3.61, 1.44, 1.18, 1.03

Comparing costs is difficult due to the wide variety of key assumptions found in the literature regarding plant capacity, biomass cost, reactor technology and many other variables (Wright et al. 2010). Wright et al. (2010) show bio-oil production costs as a function the capacity of a pyrolysis unit. They confirmed that the commercialization of crude bio-oil at $0.86/gallon may be viable if petroleum prices are close to $100/barrel. Although large scale plant systems have not yet achieved commercial status, they tend to generate lower production costs due to economies of scale. Small stand-alone units are likely to be less viable than larger units co-located with existing industries and that use waste materials. Capital equipment needs can be significantly reduced by sharing existing wood handling facilities. Savings could be made by co-sharing labor.

Pootakham and Kumar (2010) compared bio-oil transportation costs by pipeline vs. truck and found that for the conditions studied energy input in transport of bio-oil by pipeline was higher than by truck.

4.5 Bio-oil refineries

The economic viability of two bio-oil refinery strategies based on bio-oil hydrotreatment is reported by Jones et al. (2009) and Wright et al. (2010). Wu et al. (2010) discuss the economics of bio-oil gasification followed by a Fischer Tropsch synthesis step. However, the production of high value products is not considered in any of these analyses.

4.5.1 Bio-oil hydrotreatment refinery

Jones et al. (2009) and Wright et al. (2010) published reports on the financial analysis of producing green gasoline and green diesel from bio-oil. Wright et al. (2010) examined fast pyrolysis of corn stover to bio-oil with subsequent upgrading of the bio-oil to naphtha and diesel range fuels via hydrotreatment. Jones et al. (2009) studied hybrid poplar as the feedstock. Wright et al. (2010) studied two different 2000 dry ton per day scenarios. The first scenario generates hydrogen on-site for fuel upgrading by separating a fraction of the bio-oil. The second scenario relies on merchant hydrogen. Liquid fuel production rates of 134 and 220 million liters per year for the hydrogen production and purchase scenarios respectively were the results obtained from the modeling effort. These plants have a capital cost of $287 and $200 million. The hydrogen purchase scenario employs 2,040 kg/h of hydrogen to up-grade 60,000 kg/h of bio-oil (Wright et al. 2010). With the hydrogen purchase option, corn stover at a product value (hydrocarbon) of $3.09/gallon with an on-site hydrogen production for $2.11/gallon can be used to produce a petroleum fraction in the naphtha distillation range and in the diesel distillation range (Wright et al. 2010). These values correspond to crude bio-oil production costs of $0.83/gallon. This technology is still relatively immature despite the fact that these results suggest that pyrolysis derived biofuels are competitive with other alternative fuels (Wright et al. 2010).

Jones et al. (2009) analyzed a design case with fast pyrolysis of woody biomass. Hybrid poplar as the feedstock was assumed to operate with a feed rate of 2,000 tons per day. A supply of hydrogen produced from natural gas via steam reforming is required to hydrotreat the bio-oil in order to reduce the oxygen content. The total project capital investment was calculated to be $303 million for a stand-alone plant design. Almost a third of the cost is tied to fast pyrolysis, nearly a third to hydrotreatment, and nearly a third to hydrogenation components of the plant, with the remainder for utilities and hydrocracking (Table 33) (Jones et al. 2009).

Table 33. Total project capital investment cost for a stand-alone fast pyrolysis plant using wood biomass (Jones et al. 2009).

	Cost in million 2007 dollars	Contribution (%)
Fast pyrolysis	92	30
Hydrotreating	81	27
Hydrocracking and separations	29	10
Hydrogen generation	86	28
Utilities, etc	15	5
Total Cost	303	100

A cost of $2.04 per gallon was calculated based on catalyst cost assumptions, 2007 energy prices, and this project’s capital investment cost with additional heat and material balance. This does not include any cost downstream from the refinery. It represents the production of renewable gasoline and diesel fuel from woody biomass at the plant gate. The assumed feedstock cost of $50.70 per dry ton of hybrid poplar (at the gate) is the largest single component of the cost of production. This cost could be significantly reduced if reclaimed fiber from urban wastes or waste materials from agricultural and forest operations is used.

Table 34 shows the contribution of direct and indirect costs to the production of green gasoline. Obviously, feedstocks are an important component of the overall production costs. Next is the cost of natural gas to produce hydrogen. Catalysts and chemicals are additional important costs.

Table 34. Average annual costs of a stand-alone pyrolysis oil production and refining plant with a capacity of 2,000 tons/day. The operating contributions as well as the main capital for production are shown (Jones et al. 2009).

	2007 dollars per gallon	**Contribution %**
Feedstock (at $50.70 per dry ton)	$0.48	23
Natural gas (at $7.78 per square foot)	$0.32	16
Catalysts and chemicals	$0.15	7
Waste disposal	$0.01	Negligible
Utilities (cooling water, electricity, steam)	$0.17	8
Fixed costs (labor, operating supplies, etc.)	$0.22	11
Capital depreciation	$0.20	11
Average income tax	$0.13	7
Average return on investment	$0.36	18
Production cost, per gallon gasoline equivalent	**$2.04**	**100**

Co-location with an existing refinery could lower costs (Jones et al. 2009). The production cost is most sensitive to the assumed return on investment (ROI), with plant size (tons per day) close behind as shown by financial and market sensitivities. The research shows that catalyst costs, followed by delivered feedstock price are most sensitive to modeled production costs (Jones et al. 2009). Jones et al. (2009) concluded that up-grading pyrolysis oil to hydrocarbon fuels could be an economically attractive source of renewable fuels due to petroleum industry infrastructure ready products and the cost of production at $2 per gallon (in 2007 dollars).

Wright et al. (2010) conducted sensibility analysis with favorable, base case and unfavorable costs shown in Table 35. Table 36 shows the results obtained by Wright et al. (2010) on the capital cost and product value of a gallon of gasoline equivalent for the scenarios studied.

Table 35. Parameters used in the sensibility analysis (Wright et al. 2010).

Sensibility Analysis	**Favorable**	**Base Case**	**Unfavorable**
Biomass Cost ($/ton)	$50	$75	$100
Bio-oil Yield (wt/wt feed)	0.7	0.63	0.5
Fuel Gas Credit Value ($/MMBTU)	$10	$5	$2.5
Char value ($/ton)	$30	$20	$10
Capital Cost (millions $)	$173	$247	$321
Catalyst Cost (millions $)	$0.88	$1.77	$3,53
Fuel Yield (wt/wt feed)	0.3	0.25	0.2
Hydrogen Purchase Scenarios			
Capital Cost (millions $)	$120	$172	$223
Fuel Yield (wt/wt feed)	0.47	0.42	0.37
Hydrogen Price ($/GGE)	$1	$1.5	$2

Table 36. Capital cost and product value for the scenarios studied (Wright et al. 2010).

	n^{th} Plant	Optimistic	Base Case	Pessimistic
Capital Cost (millions $)	$200	$307.9	$584.9	$793.2
Product Value ($/Gallons of Gasoline Equivalent)	$2.11	$2.54	$3.41	$4.07

4.5.2 Bio-oil gasification/Fischer-Tropsch (F-T) refinery

Similar to commercial coal to liquid (CTL) and gas to liquid (GTL) plants of SASOL and SHELL which correspond to at least 10% of the capacity of a modern refinery, a reasonable biomass-to-liquids (BTL) plant capacity is more than one million tons of biosynfuel (Henrich et al. 2009). Henrich et al. (2009) used costs of existing plants to estimates costs. Biosynfuel is about twice as expensive as untaxed motor fuel derived from crude oil (Henrich 2007, Henrich et al. 2009). Considerable savings can be achieved by locating a plant within an existing industrial complex like an oil refinery or a chemical complex (Henrich et al. 2009). Rail access is particularly important since electrified rail transport is an efficient, cheap and clean way to transport material. Henrich et al. 2009 used specific costs for large gas to liquid plants reported by Boerrigter (2006) in their cost estimates of a gasification bio-refinery. Biosynfuel can be obtained for about 1.04 Euros per kg or 0.8 Euros per liter (Henrich et al. (2009). In central Europe, about half of the manufacturing costs are from delivering the biomass.

Wright et al. (2008) evaluated the production of bio-oil for subsequent production of Fischer Tropsch liquids (FTLs). A centralized gasification plant can use biomass to produce FTLs from $1.56 per gallon of gasoline which is equivalent to 550 million gasoline gallon equivalent (GGE) per year in an optimally sized plant (Wright et al. 2008). Three distributed processing systems were investigated based on the scale of biomass processing capacity including: 1) on farm pyrolyzers with a 5.4 ton per day capacity, 2) small cooperative pyrolyzers with a 55 tpd capacity, and 3) large cooperative pyrolyzers with a 550 tpd capacity. Costs as low as $1.43 for total fuel capacities of 2,500 million GGE were achieved when a very large centralized bio-oil processing plant that accepts bio-oil for catalytic up-grading to transportation fuels was combined with distributed processing. A $4 billion total capital investment (distributed pyrolyzers and centralized bio-oil processing plant) is projected for this optimally sized distributed processing system, compared to $1.6 billion for a centralized biomass processing facility (Wright et al. 2008).

Wu et al. (2010) studied the technoeconomic viability of a bioenergy supply chain based on bioslurry from mallee biomass in Western Australia. Distributed pyrolyzers within the biomass production area were utilized by the bioslurry supply chain to deliver the bioslurry fuels to a central bio-energy plant once it converted the harvested green biomass into slurry fuels. The overall economic feasibility of such a supply chain depends on the trade-off between the reduction in biomass transport cost and the increase in cost due to the introduction of distributed pyrolyzers (bioslurry preparation included) and bioslurry transport. A bioslurry-based supply chain is only competitive at a large scale (e.g. > 1,500 tons per day) when a dedicated bio-energy plant is situated within the biomass production area. Small bio-energy plants (e.g. < 500 dry tons per day) favor a conventional biomass supply chain. However, a significant advantage offered by a bioslurry-based supply chain includes lower delivery cost of fuels at the plant gate when the central bio-refinery plant is distant from the area of biomass production (Wu et al. 2010).

5. Technology Improvements and Development of New Products

The economic analyses described in the previous sections should not be reduced to simple cost estimates, but should be used to identify areas for improvement in an iterative and permanent process to increase total quality and reduce costs. First generation technologies are unlikely to result in huge profits. It is through continued research and development efforts to reduce costs and increase total process quality that these technologies will mature and gradually became competitive and sustainable. Lynch and Joseph (2010) wrote a detailed methodology for testing, data collection and safe operation of a pyrolysis plant. Once the plant is in operation, focus should be maintained on further improving the design (reduce cost or increase total quality or reduce costs). Figure 20 shows a general strategy for process improvements proposed by Moen and Nolan (Edosomwan 1996) . This strategy, along with others available in the literature, should guide research and development actions driving the gradual evolution of pyrolysis units and bio-oil refineries to build new, better performing units. The Moen and Nolan strategy is an eleven-step process that makes use of the plan-do-check-act Shewhart scheme to improve processes. The strategy begins with the selection of the area that will be improved followed by a continuous improvement cycle (Edosomwan 1996).

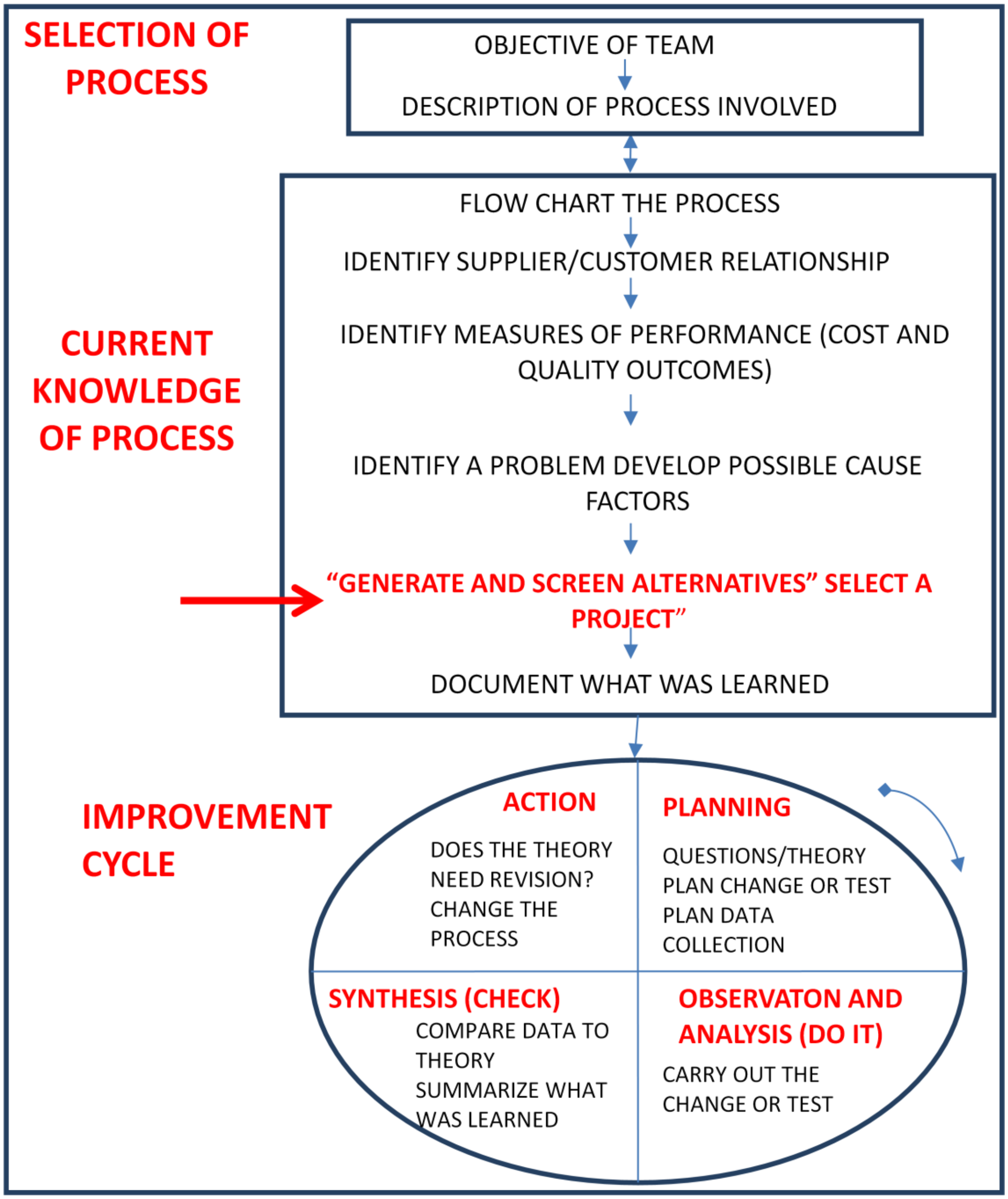

Figure 19. Moen and Nolan strategy for process improvements (Edosomwan 1996).

In addition to improving pyrolysis units and bio-oil refineries (processes), research and development is also necessary to develop new products from bio-oil and biochar. As explained in the third report the development of high-value products from these fractions is critical to ensure the economic viability of these technologies. Especially critical for the success of pyrolysis technologies is the development of engineered biochar for environmental applications. Figure 21 shows a general strategy proposed by Boath (2006) to guide the development of new products which can be applied to develop new products from bio-oil and biochar.

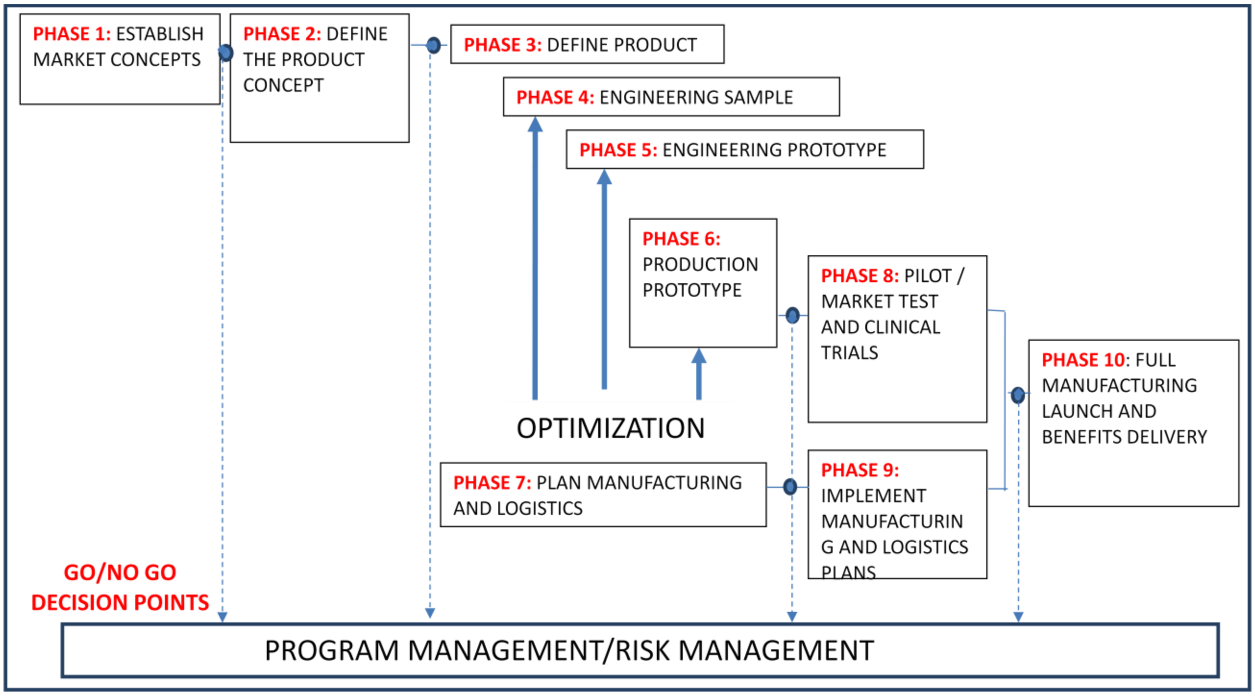

Figure 20. General strategy for product development (Juran and Godfrey 2000, Boath 2006).

For pyrolysis designers, the economic analysis described in this report should not be considered an end goal. Rather, it is a critical step to evaluate economic sustainability and a means to identify design weaknesses that require continued further attention. The viability of this industry will depend on continuous research and development efforts.

6. Conclusion

Most of the business models described in the literature are based on waste biomass resources generated from agricultural and forest operations. Very little information is available on pyrolysis business models using separated fractions from Municipal Solid Wastes. Another business model with great potential is the use of waste materials generated by existing biomass processing industries (pulp and paper, sugar cane, palm oil mills) as feedstocks for the pyrolysis process. A sustainable pyrolysis business model design must incorporate triple top line analysis.

Depending on components of a chosen business model (e.g. co-location, low feedstock prices, use of waste materials), bio-oil production costs could be competitive (< $0.83/gal) with current petroleum prices (> $100/ barrel). However, with low petroleum prices, it is very difficult to develop a viable bio-oil industry for the production of transportation fuels. After the cost of biomass, the cost of methane to produce hydrogen is the second most important component in the production of biofuels, according to the financial analysis of bio-oil hydrotreatment refineries. Development of technologies to produce high-value bio-oil products is vital to the financial viability of this industry.

The economic analyses should not be reduced to simple cost estimates. The cost structure obtained is a powerful tool to identify areas susceptible to improvements. First generation technologies are unlikely to result in huge profits, but through continued research and development efforts to reduce costs and increase their total quality these technologies will mature and gradually became competitive and sustainable.

Washington has the entrepreneurial wisdom, technical and research strength, and agency capacity for developing a biochar industry utilizing local biomass resources. A coordinated effort of interested stakeholders is needed to drive industry development. Stakeholders include: biochar reactor technology developers/manufacturers, environmental and agronomic applications businesses, distributors, government agencies, NGOs, and researchers (Fuchs et al. 2012). All will be required to support biochar commercialization. While a trade association would be best for this effort, no such entity currently exists.

The biochar industry could grow based on the example of the wood pellet industry which began in the 1980s in response to the need for clean burning solid fuel devices as an alternative to fuel oil for heating homes and small businesses (Fuchs et al. 2012). Nationally, the wood pellet industry now has numerous appliance manufacturers, hundreds of distributors and employs many hundreds of installers, not to mention over 80 wood pellet mills nearing a half billion dollars of capital investment. All of this began in Washington and the Pacific Northwest. Biochar industry development will occur globally. With pyrolysis business ventures and biochar applications expanding across the nation, why should leaders in the Pacific Northwest conduct a coordinated effort to develop this industry? Regionally, we are at the right time and right place with the technical capability to lead this global industry. Our capability to lead the biochar market sector development comes from the following strengths:

1. Entrepreneurial capability to develop the production technology and field uses in environmental, agricultural and industrial applications.
2. Pacific Rim location for marketing technology capability and intellectual property.
3. Resource base in our woody refuse and our forest resources to create sustainable carbon negative solutions and provide technology and capacity for a regional bio-economy.
4. Regional strength in our research centers' scientists, engineers and extension specialists to conduct the laboratory and field work to support new applications and develop new markets for stable, highly porous and adsorptive carbon for expanded environmental ecological and soils uses.
5. Non-governmental Organization leadership with the regional carbon strategy through the Northwest Biocarbon Initiative, (Climate Solutions), and activities of International Biochar Initiative (IBI) and US Biochar Initiative (USBI) have expanded rapidly.

Ideally, a trade association or other group would form to support the industry development. However, we are at early stages in this industry (Fuchs et al. 2012). Therefore, the leadership of a team is needed to bring biochar to the market place to provide the numerous environmental services identified above. Therefore, we recommend forming a support group with the following functions:

- Organizing an industry development effort.
- Establishing a trade group and industry practice areas to help organize specific committees. Committees could include: building robust and expanding markets, industry marketing for biochar producers, educational needs, consultants and applications, feedstock biomass resources, environmental, agronomic and forestry applications, functionalizing biochar for specific characteristics and niche markets, regulatory and permitting for production facilities.
- Identifying funding needs and secure funding sources.
- Conducting a needs and opportunities assessment, writing and or coordinating grant applications with industry partners, agencies, universities and NGOs as necessary to support the developing industry.
- Creating connections among industry technology leaders and developers with regional and international research leaders and potential investors.
- Developing markets for biochar uses for numerous applications.

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