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

Part 2: Literature Review of the Biomass Supply Chain and Preprocessing Technologies

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From Field to Pyrolysis Reactor

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

Part 2: Literature Review of the Biomass Supply Chain and Preprocessing Technologies

From Field to Pyrolysis Reactor

by

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Funding for this study is provided by the Washington State Department of Ecology (Ecology) with the intention to address the growing demand for information on the design of advanced pyrolysis units and systems to collect, transport and pre-treat feedstocks. The authors wish to thank Mark Fuchs from the Waste 2 Resources Program (Ecology), and David Sjoding from the WSU Energy program for their continuous support and encouragement. This is the second of a series of reports exploring the use of biomass pyrolysis to sequester carbon and to produce fuels and chemicals.

This report is the second in a series of four reports available on the Department of Ecology's website at: http://www.ecy.wa.gov/programs/swfa/organics/recovery.html. 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, bio-char 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 through Waste to Fuel Technology funds administered by Ecology are also available at: http://www.ecy.wa.gov/programs/swfa/organics/recovery.html. 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 like bio-fuels and other valuable products, in addition to recovering stable carbon and nutrients, promotes economic vitality and aides in the protection of the environment. This creates robust markets and sustainable jobs in multiple sectors of the economy and facilitates closed-loop material management where a by-product from one process becomes feedstock for another with no or minimal waste generated.

Disclaimer

The objective of this review is to describe existing technologies to create clean, non-polluting pyrolysis units for the production of energy, fuels and valuable by-products. The Department of Ecology and Washington State University provide this publication to help the public understand and take advantage of existing technologies to handle and pre-treat biomass resources that will be converted via fast or slow pyrolysis into liquid transportation fuels, bio-chemicals and biochar. Another 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 does not intend to exclude any technology or company offering similar services which, due to time and space limitations, was not cited in this report.

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Executive Summary

The production of bio-oil (condensable pyrolytic liquid) and biochar via fast or slow pyrolysis is gaining attention due to the potential to develop advanced bio-fuels (transportation fuels derived from lignocellulosic materials) (Amonette 2010, Elliott 2010, and Garcia-Perez 2010). Using rural or centralized refineries, bio-oil produced from pyrolysis units distributed throughout the state can be refined to produce gasoline, diesel and jet fuel. With hydrotreatment of the resulting bio-oil, roughly 120 gallons of transportation bio-fuels (hydrocarbons produced from bio-oils) can be produced by the pyrolysis of one ton of dry biomass (Elliott 2010). At this rate, thirty four percent of the original biomass can be converted into green gasoline and green diesel, resulting from a 61 percent thermal process efficiency while carbon recovery to fuel is 55 percent (Elliott 2010). The bio-oil production potential using woody biomass residues generated in Washington State is around 4.4 million tons (around 1,057 million gallons) (Garcia-Perez and Smith 2011). Refining of these raw bio-oils could result in the production of around 2 million tons (around 724 million gallons) of transportation fuels like gasoline, diesel and jet fuel.

Interest in biochar as a soil amendment for carbon sequestration is also increasing (Lehmann and Joseph 2009). On a global scale biochar as a soil amendment could reduce current emissions of carbon dioxide (CO_2), methane and nitrous oxide by a maximum of 1.8 Pg CO_2 C ($Pg=10^{15}$ g) equivalent per year (12 percent of the current anthropogenic CO_2-C emissions) and by a total net of 130 Pg CO_2-C over the course of a century (Woolf et al., 2010). Biochar could also enhance soil conservation (Amonette 2010, Wolf et al., 2010). The total potential for bio-char production from biomass residues in Washington exceeds 2 million tons annually (Garcia-Perez and Smith 2011).

A coordinated effort between industry, research universities, laboratories and state agencies is needed to build the markets and industry required to collect, transport, and convert the large volumes of organic waste to fuels and biochar.

A thorough understanding of existing alternatives for biomass harvesting, preprocessing, pyrolyzing, and collecting products is presented in this report. This is instructive for deploying pyrolysis technology that accounts for the wide range of available feedstocks and processing options in Washington State. This report summarizes the most relevant technologies for pretreating biomass prior to pyrolysis: harvesting, collecting, transporting, grinding, separating and drying of biomass produced from forest, agricultural, and municipal waste.

Preface

This preface has been added to explain the technical and social value of the series of reviews entitled “Methods for Producing Biochar and Advanced Bio-fuels in Washington State”. Similarly, this preface advises the readers on how to read these series of documents, which were published in the order they were written and not necessarily in the order in which they should be read.

The biomass inventory of Washington State (Frear et al., 2005) created a lot of interest in the business community to explore ways to take advantage of the underutilized resources available in the region. The utilization of our biomass resources and the need to address complex environmental and economic problems are the main drivers for the renewed interest on using fast or slow pyrolysis to produce bio-char and drop-in fuels in the state.

The authors are often contacted by carbonization companies interested in moving their overseas operations to our state and need guidance to choose technologies appropriate for the feedstocks available, as well as about existing environmental and safety regulations. Many pyrolysis companies have failed in the past because they were unaware of the complexity of the new biomass economy that is under development, as well as by the lack of some of the technologies and components needed for the system they wanted to build. Unfortunately the number, and the nature, of the questions received by the authors from the policy makers and the business community is so diverse, and the information available so disperse that the authors were not able to provide well documented advice in a timely manner. This review is an attempt to put together a single document outlining the technologies and alternatives that need to be integrated to deploy models of a biomass economy based on pyrolysis.

Some readers may find that this review resembles a text book and that the language in certain areas is very descriptive. The lack of an up-dated text book on biomass pyrolysis that provides a good frame for more detailed discussions and the existence of many potential business models are the primary reasons for choosing this general descriptive language. The authors also recognize that experts may find reading particular sections of this report of limited value especially if they are within his/her core area of expertise. It is our hope that these experts will find the other sections informative and that after reading all the reports they will have a system view and will be able to choose appropriate technology systems to convert a targeted waste feedstock into fuels, energy and biochar. For those readers interested in identifying the appropriate set of technologies for a given business model for a particular waste feedstock we recommend reading the reports in the following order:

1.- Introduction (Section 1 First Report)
2.- Evolution of Pyrolysis Technologies (Section 2 First Report)
3.- From the Field to the Gate: Collection, Preprocessing and Transportation of Biomass (Section 2 Second Report)
4.- From the Gate to Pyrolysis Unit: Biomass Storage and Pre-Processing (Section 3 Second Report)
5.- Criteria to Select Pyrolysis Reactors (Section 3 First Report)
6.- Kilns (Section 4 First Report)
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8.- Converters for Processing Wood Logs (Section 6 First Report)
9.- Converters for Processing Wood Chips (Section 7 First Report)
10.- Fast Pyrolysis Reactors (Section 8 First Report)
11.- Product Recovery (Section 2 Third Report)
12.- Product Quality (Bio-oil Characterization) (Section 3 Third Report)
13.- Product Quality (Bio-char Characterization) (Section 4 Third Report)
14.- Products from Bio-oil and Bio-char (Section 5 Third Report)
15.- Vehicle Gasifiers using Bio-char as Fuels (Section 9 First Report)
16.- Regulatory issues of Current Pyrolysis Technologies (Section 6 Third Report)
17.- Business Models (Section 1 Fourth Report)
18.- Financial Analyses (Section 2 Fourth Report)

Background

Energy demand is expected to grow by more than 68 percent by 2025 while global oil production begins to decline. Domestic oil production is already in decline and current petroleum imports supply more than 55 percent of U.S. energy needs (EIA 2008). The current population of Washington consumes nearly twice the world's average consumption per capita of 31.7 barrels per 1000 people per day. In Washington, 178,000 barrels per day (44 percent of the daily usage) are consumed in the form of gasoline, 85,000 barrels per day (21 percent) of diesel fuel and 56,000 barrels per day (14 percent) of jet fuel. All of the oil consumed in Washington is imported (Mason et al., 2009).

Although Washington is the leading producer of hydroelectric power in the U.S., and renewable sources such as sun and wind energy can satisfy the growing need for sustainable electric power, in-state production options for liquid transportation fuels are limited to biofuels (Mason et al., 2009). An obvious starting point for sustainable biofuel production is to utilize the state's solid organic wastes (Yoder et al., 2008, Mason et al., 2009).

According to the Washington State biomass inventory funded by the Department of Ecology, about 16.4 million tons of underutilized organic waste is produced every year (Frear et al., 2005, Liao et al., 2007). This organic waste consists of 5.5 million tons of forest residues concentrated in the western and northern regions of the state and 2.4 million tons of agricultural waste concentrated in the eastern region of the state (Figure 1). Washington also produces 0.4 million t/year of land clearing debris; 0.4 million tons of non-wood yard residues; and 0.8 million t/year of wood residues in municipal solid wastes.

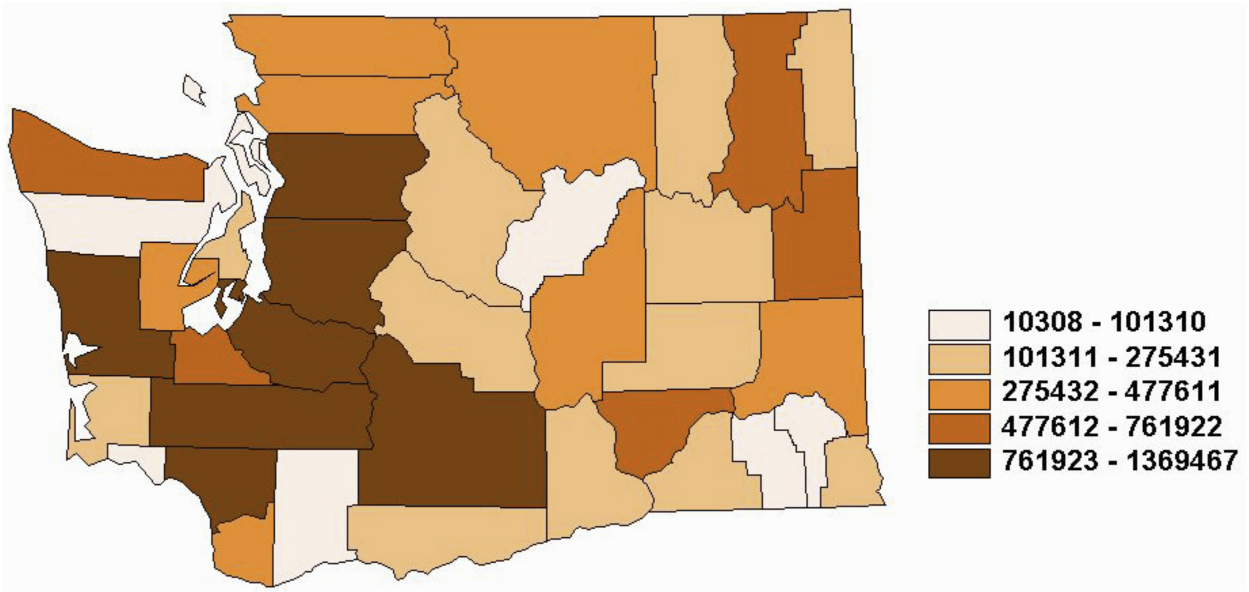

Figure 1. Location of available organic waste (tons per day) generated in Washington (Frear et al., 2005).

The production of bio-oil and biochar via fast or slow pyrolysis is gaining attention due to the potential to develop advanced bio-fuels (Amonette 2010, Elliott 2010, and Garcia-Perez 2010). Using rural or centralized refineries, bio-oil produced from pyrolysis units distributed throughout the state can be refined to produce gasoline, diesel and jet fuel. With hydrotreatment of the resulting oils, roughly 120 gallons of transportation fuels can be produced by the pyrolysis of one ton of dry biomass (Elliott 2010). At this rate, Thirty four percent of the original dry biomass can be converted into hydrocarbon. This result corresponds to a thermal process efficiency of 61 percent and 55 percent carbon efficiency (Elliott 2010). Using fast pyrolysis followed by a mild hydrotreatment to process “waste” biomass resources it is possible to produce 11.4 percent of the current oil consumed in the state (Garcia-Perez 2010) also near the current aviation fuels consumption in the state. The first bio-oil refinery demonstration unit is being built in Kapolei, Hawaii by a number of companies (Tesoro, Ensyn and UOP, LLC) as well as Pacific Northwest National Laboratories (PNNL). The technology looks promising and a scale up is anticipated (Elliott 2010).

Interest in biochar as a soil amendment for carbon sequestration is also increasing (Lehmann and Joseph 2009). On a global scale biochar as a soil amendment could reduce current emissions of carbon dioxide (CO_2), methane and nitrous oxide by a maximum of 1.8 Pg ($P = 10^{15}$) CO_2 C equivalent per year (12 percent of the current anthropogenic CO_2-C emissions) and by a total net of 130 Pg CO_2-C over the course of a century (Woolf et al., 2010). Biochar could also enhance soil conservation (Amonette 2010, Wolf et al., 2010). The total potential for bio-char production, from biomass residues in Washington exceeds 2 million tons annually (Garcia-Perez and Smith 2011).

Millions of tons of biomass from forest residues, agricultural biomass, and municipal solid waste must be collected regularly in order to reach significant production of bio-fuels in this state (Mason et al., 2009). A coordinated effort among industry, research universities, laboratories and agencies is necessary to assemble the technologies (many of which exist), required to convert these volumes of organic waste and to establish a supply chain.

A thorough understanding of existing alternatives for biomass harvesting, preprocessing, pyrolyzing, and collecting products is instructive for deploying pyrolysis technology that accounts for the wide range of available materials and processing options in Washington State. This report summarizes the most relevant technologies for pretreating biomass prior to pyrolysis: harvesting, collecting, transporting, grinding, separating and drying of biomass produced from forest, agricultural, and municipal waste. (Garcia-Perez et al., (2010), (http://www.ecy.wa.gov/pubs/1107017.pdf) describe existing alternatives for pyrolysis reactors as well as for downstream processing).

1. Introduction

The primary objective of the supply chain and preprocessing scheme is to produce biomass fuel at the lowest possible cost that meets the requirements of the pyrolysis unit with regard to fuel quality from different biomass feedstock (Garcia-Perez et al., 2011). This is the first step in bio-fuel production so it should be thoroughly studied (Miles 2011). The biomass supply chain is comprised of a series of sequential steps that includes growing, harvesting, grinding, densifying, drying, storing, transporting, handling, product recovery and bio-oil refining (Figure 2). The main parameters of biomass that influence yield and composition of pyrolysis oil and fuel quality are moisture content, ash content, and particle size (Bridgewater and Peacocke 2000, Kersten 2005, Meier 1999, Mohan et al., 2006, Murwanashyaka et al., 2001, Shen et al., 2009). Chemical characteristics and desired yields of biomass fuels are largely influenced during the growing and harvesting phase. Physical characteristics of biomass are controlled in the preprocessing phase (van Loo and Koppejan 2008). Fuel handling, storage, feeding and the pyrolysis process itself determine the final fuel quality (van Loo and Koppejan 2008).

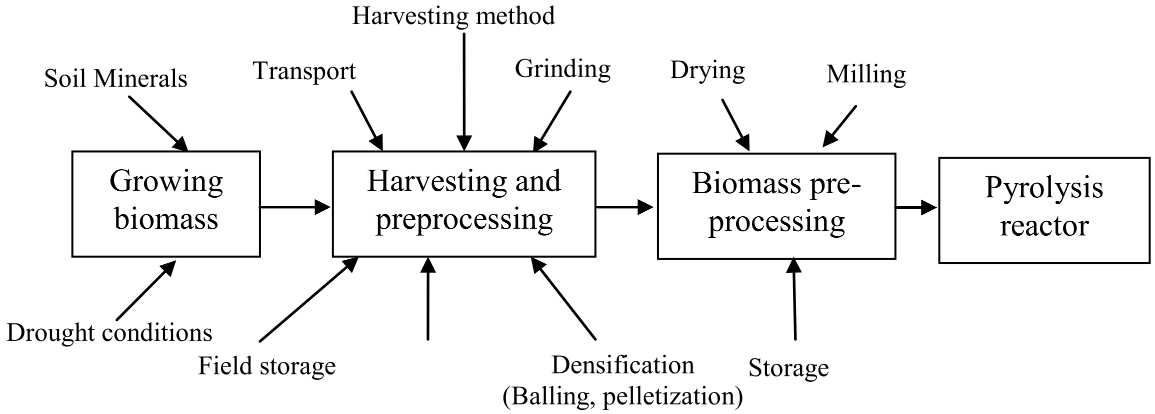

Figure 2. Factors in the supply chain that influence quality of solid biomass (Modified from: van Loo and Koppejan 2008).

Lacking any specific report that addresses requirements for biomass harvesting, collecting, drying and grinding of the feedstock, we rely on information provided by other thermochemical conversion technologies (gasification and combustion) as references to understand supply and preprocessing chains for pyrolysis units (Atchison and Hettenhaus 2003, Barbosa-Cortez et al., 2008, Badger 2002, Brown 2003, Cummer 2002, Kummar and Sokhansanj 2007, Sokhansanj et al., 2006, Uslu et al., 2008, van Loo 2008, Wynsma et al., 2007). This report focuses on the supply chain for: 1) municipal solid waste (e.g. clean construction and demolition wood, fiberboard, yard trimmings, and land clearing debris), 2) forestry residues (e.g. branches, treetops, whole trees from early thinning and pruning) 3) agricultural residues (e.g. straw) and 4) energy crops. Innovations are needed at each stage of the biomass supply chain in order to develop a biomass economy in Washington. During the supply chain and pre-processing it is possible to control the quality of the feedstock. Many problems encountered during biomass conversion can be reduced or eliminated if the quality of the fuel is controlled. In the case of biomass combustion poor fuel quality causes 95 % of operational and maintenance problems (Miles 2011).

2. From Field to Gate: Collection, Preprocessing and Transportation of Biomass

Preprocessing operations associated with collection, transport, storage, handling and preparation of *municipal wood waste, agricultural residues*, *forest residues*, must occur before biomass reaches the pyrolysis plant. This section considers those operations so that an evaluation of technology options and trade-offs can be made (Hess et al., 2006). Supplying biomass in a timely manner so as to minimize storage and handling at the plant is important to developing a competitive biomass industry.

The main goals for a biomass supply chain are to: 1) supply biomass with a specified range of characteristics to standardize equipment, and set limits for maintenance, and personnel support; 2) establish clear quality standards for received biomass; 3) standardize energy density to reduce the transportation, handling, and storage costs; and 4) optimize biomass quality by decreasing impurities, lowering moisture content, and reducing particle size (van Loo and Koppejan 2008).[1] These actions can be performed outside or inside the pyrolysis plant, and depending on the material and the local conditions the production steps and the sequence can vary (van Loo and Koppejan 2008).

One of the main challenges of processing feedstock is developing a steady supply of biomass. In a study carried out by the Idaho National Lab, Hess et al., (2006) propose a supply chain for 2,000 metric t/day (1 metric t = 1.099 US t) of ground wheat and barley straw to a centralized processing plant in which the collection, storage, and transportation of the biomass is conducted at both 16 hours per day and 6 days per week. The authors presented a detailed methodology to calculate supply costs. It was not possible to find any study on supply chain for the conditions of Washington State. A technical study by Campbell et al., (2008) on the development of biomass fuel plans for a biomass power plant can be referenced to create biomass fuel plans for pyrolysis units.

2.1. Municipal Solid Waste

Of the 4.98 million tons municipal solid waste (MSW) generated in Washington in 2009 (Washington State Department of Ecology 2010a), 2.24 million tons (45%) were recycled (Washington State Department of Ecology 2010b). Organic materials followed by constructions materials, paper packaging and products, and wood debris represent the main waste sources accounting for more than 68% of the total MSW generated in Washington (Figure 3). A significant portion of the state's MSW represents potential feedstocks for pyrolysis, such as, wood debris, yard waste, paper, and some components in the construction materials stream (natural wood, insulation, drywall, etc) (Table 1). The use of pyrolysis and gasification to process MSW is an ongoing area of research and has been implemented with varying degrees of success in different locations. In 2005, more than 100 pyrolysis/gasification units processed MSW fractions around the world (Williams, 2005).

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[1] For further information on decreasing impurities, lowering moisture content, and reducing particle size see Garcia-Perez M., T. Lewis, C. E. Kruger, 2010.

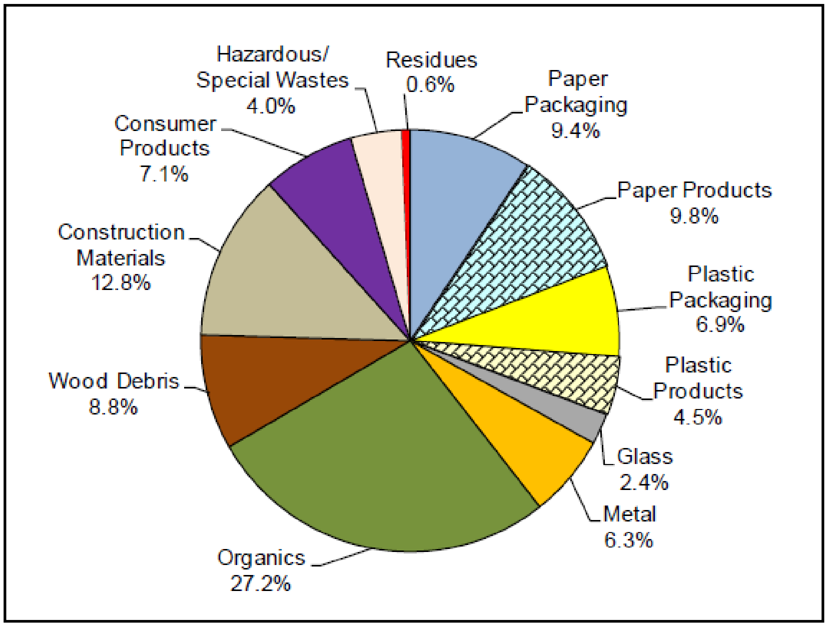


Figure 3. Overall statewide disposed waste stream composition by material class in 2009 (Washington State Department of Ecology, 2010a: http://www.ecy.wa.gov/pubs/1007023.pdf).

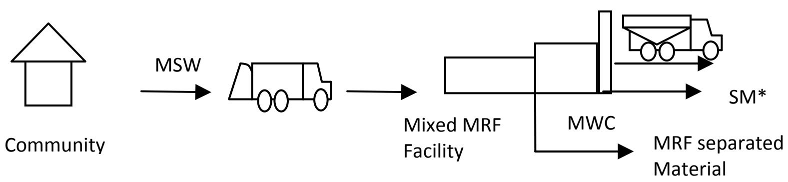
2.1.1. Collection and Separation Strategies

Separation of recyclables from MSW is critical for the implementation of more complex strategies to obtain higher value products from organic waste management systems (Williams, 2005). Three main separation strategies for MSW are: (1) source separation by the generator or the collector; (2) collection and separation of commingled recyclables at a centralized recycling facility; and (3) collection of mixed MSW with transportation to a centralized processing facility (Spencer, 1994). Traditional waste management schemes for the final disposition of MSW can be classified generally as: *recycling*, *landfill*, *composting* and *combustion*. The strategy used depends on population size, land availability, and municipal priorities (Kreith, 1994). Nine of the most common waste management schemes used in the United States are shown in Figure 4 (Kreith, 1994). Each of the strategies used for MSW separation are described in the sections that follow as background consideration for pyrolysis facility design and operation. For pyrolysis, it is desirable to separate the yard waste and other lignocellulosic materials at the source in order to reduce contamination. While mixed trash is transported from the community by a single truck to a processing facility in strategies 1 and 2 (Figure 4), strategies 3 and 4 involve source separation of yard waste and recyclable materials. These fractions are transported in two or more trucks to the final processing facility. In the first strategy, MSW is separated in a material recovery facility, recyclables are commercialized, and non-recyclables are incinerated at a municipal waste combustion facility. The second strategy produces refuse-derived fuel which is combusted and a non-combustible material that is land filled with ash generated in the combustion step. The separation of yard waste in the third strategy and recyclable fractions in the fourth strategy allow development of higher value applications (compost and recycled materials).

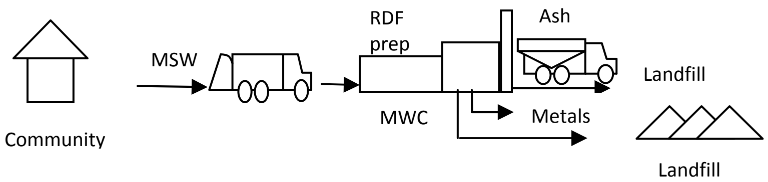
Table 1. Overall statewide disposed waste stream detailed composition, 2009 (Source: Washington State Department of Ecology, 2010a: http://www.ecy.wa.gov/pubs/1007023.pdf).

Material	Est. Percent	Est. Tons	Material	Est. Percent	Est. Tons
Paper Packaging	**9.4%**	**469,574**	**Paper Products**	**9.8%**	**490,049**
Newspaper Packaging	0.2%	12,088	Newspaper	1.4%	70,594
Cardboard/Kraft Paper Packaging	3.7%	185,311	Cardboard/Kraft Paper Products	0.1%	3,894
Other Groundwood Paper Packaging	0.1%	7,344	Magazines	0.9%	46,149
Mixed/Low Grade Paper Packaging	2.6%	130,662	High-Grade Paper Products	1.0%	49,667
Compostable Paper Packaging	1.2%	58,191	Other Groundwood Paper Products	0.3%	13,874
R/C Paper Packaging	1.5%	75,979	Mixed Low Grade Paper Products	1.6%	81,068
			Compostable Paper Products	4.1%	201,801
Plastic Packaging	**6.9%**	**345,235**	Paper Processing Sludge	0.0%	0
#1 PETE Plastic Bottles	0.7%	33,344	R/C Paper Products	0.5%	23,003
#1 PETE Plastic Non-bottles	0.3%	14,563			
#2 HDPE Plastic Natural Bottles	0.3%	12,547	**Plastic Products**	**4.5%**	**222,910**
#2 HDPE Plastic Colored Bottles	0.3%	17,017	#1 PETE Plastic Products	0.0%	172
#2 HDPE Plastic Jars & Tubs	0.4%	20,020	#2 HDPE Plastic Products	0.0%	1,883
#3 PVC Plastic Packaging	0.0%	710	#3 PVC Plastic Products	0.0%	1,109
#4 LDPE Plastic Packaging	0.0%	329	#4 LDPE Plastic Products	0.0%	116
#5 PP Plastic Packaging	0.3%	16,732	#5 PP Plastic Products	0.1%	3,574
#6 PS Plastic Packaging	0.5%	22,579	#6 PS Plastic Products	0.1%	6,068
#7 Other Plastic Packaging	0.5%	26,282	#7 Other Plastic Products	1.3%	63,916
PLA Packaging	0.0%	312	PLA Products	0.0%	53
Plastic Merchandise Bags	0.5%	24,139	Plastic Garbage Bags	1.3%	64,784
Non-industrial Packaging Film Plastic	2.0%	101,092	Plastic Film Products	0.3%	13,465
Industrial Packaging Film Plastic	0.4%	21,911	R/C Plastic Products	1.4%	67,771
R/C Plastic Packaging	0.7%	33,657			
			Consumer Products	**7.1%**	**355,387**
Glass	**2.4%**	**117,970**	Televisions – CRT	0.6%	29,012
Clear Glass Containers	0.9%	42,353	Televisions – LCD	0.0%	0
Green Glass Containers	0.2%	8,592	VCR's, DVD's, DVR's	0.0%	1,646
Brown Glass Containers	0.4%	17,490	Computer Monitors – CRT	0.0%	1,476
Plate Glass	0.1%	5,082	Computer Monitors – LCD	0.0%	322
Stoneware/Kitchen Ceramics/Glassware	0.2%	8,893	Computers	0.0%	1,292
R/C Glass	0.7%	35,560	Computer Peripherals	0.1%	3,674
			Audio Equipment	0.1%	4,109
Metal	**6.3%**	**315,715**	Gaming Equipment	0.0%	742
Aluminum Beverage Cans	0.5%	23,031	Other Consumer Electronics	0.6%	30,031
Aluminum Foil/Containers	0.1%	5,426	Textiles – Organic	1.8%	87,471
Other Aluminum	0.1%	5,166	Textiles – Synthetic	1.0%	48,869
Other Nonferrous	0.1%	5,854	Shoes, Purses, Belts	0.4%	17,931
Food Cans - Tinned	0.7%	35,772	Tires & Rubber	0.3%	15,216
Food Cans - Coated	0.1%	5,054	Furniture	2.0%	97,620
White Goods	0.1%	7,365	Mattresses	0.1%	5,660
Other Ferrous Metal	2.9%	145,220	R/C Consumer Products	0.2%	10,317
R/C Metals	1.7%	82,826			
			Hazardous/Special Wastes	**4.0%**	**198,588**
Organics	**27.2%**	**1,356,253**	Pesticides/Herbicides	0.0%	253
Food - Vegetative	13.1%	654,458	Mercury Vapor Lighting	0.0%	0
Food - Non-vegetative	5.2%	258,823	Compact Fluorescent Lights	0.0%	184
Leaves & Grass	4.1%	203,909	Fluorescent Tubes	0.0%	64
Prunings	0.5%	26,941	Asbestos	0.0%	0
Animal Manure	3.2%	159,888	Latex Paint	0.1%	6,213
Animal Carcasses	0.3%	12,598	Solvent-based Glues	0.2%	7,990
Crop Residues	0.0%	0	Latex-based Glues	0.0%	242
Fruit Waste	0.1%	7,395	Oil-based Paint & Solvent	0.0%	2,086
R/C Organics	0.6%	32,241	Caustic Cleaners	0.0%	800
			Dry-cell Batteries	0.0%	1,465
Wood Debris	**8.8%**	**438,174**	Wet-cell Batteries	0.0%	207
Treated Wood	1.1%	56,145	Gasoline/Kerosene	0.0%	1,317
Painted Wood	1.9%	96,883	Motor Oil	0.0%	513
Dimensional Lumber	1.0%	51,929	Antifreeze	0.0%	3
Engineered Wood	1.1%	54,324	Other Vehicle Fluids	0.0%	77
Pallets & Crates	1.7%	86,705	Oil Filters	0.0%	1,545
Other Untreated Wood	0.5%	26,916	Explosives	0.0%	24
Wood By-Products	0.3%	12,574	Medical Wastes	0.5%	25,067
R/C Wood Wastes	1.1%	52,698	Pharmaceuticals/Vitamins	0.0%	1,343
			Disposable Diapers	2.8%	140,020
Construction Materials	**12.8%**	**637,619**	Other Cleaners & Soaps	0.1%	6,150
Natural Wood	0.1%	5,147	Other Hazardous	0.0%	1,549
Insulation	0.4%	22,379	Other Non-hazardous	0.0%	1,473
Asphalt Paving	0.2%	9,676			
Concrete	0.2%	10,917	**Residues**	**0.6%**	**31,022**
Drywall	2.6%	131,475	Ash	0.2%	7,889
Carpet	2.9%	145,282	Dust	0.1%	4,060
Carpet Padding	0.7%	33,211	Fines	0.3%	15,590
Soil, Rocks, Sand	1.2%	58,009	Sludge/Special Industrial	0.1%	3,483
Asphalt Roofing	1.2%	62,215			
Plastic Flooring	0.2%	10,054			
Ceramics & Brick	1.4%	69,617	**Totals**	**100.0%**	**4,978,496**
R/C Construction Materials	1.6%	79,639	**Sample Count**	**530**	

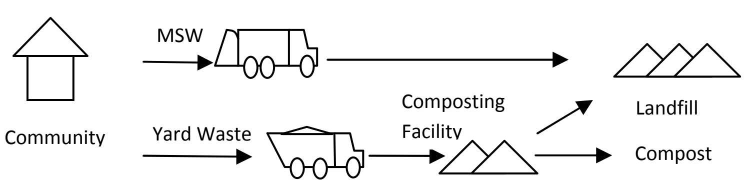
Strategy 1: MSW to Mixed MRF Facility and Mass Burn



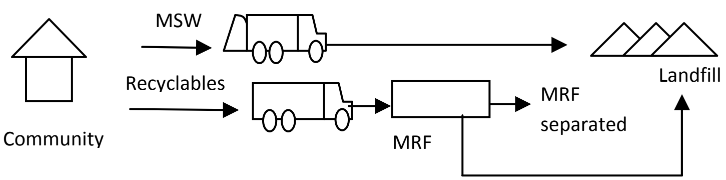
Strategy 2: MSW to RDF Combustion



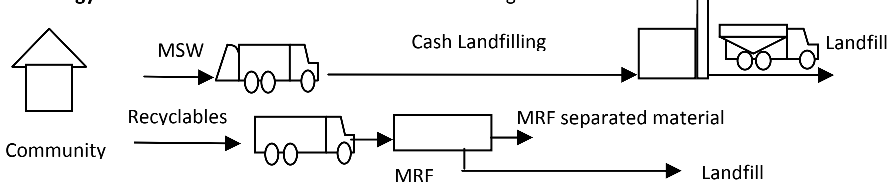
Strategy 3: Yard Waste Composting and Land filing



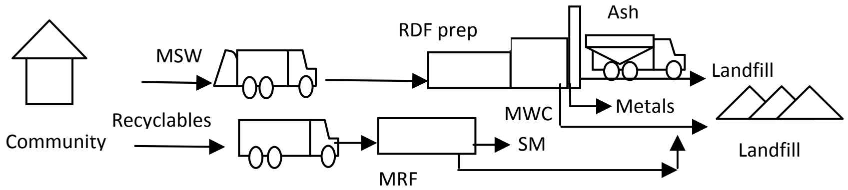
Strategy 4: Curbside Recycling and Landfilling



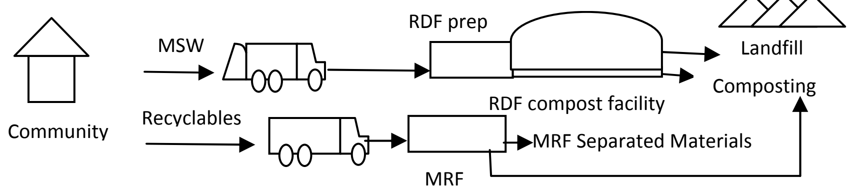
Strategy 5: Curbside MRF Mass Burn and Cash Landfilling



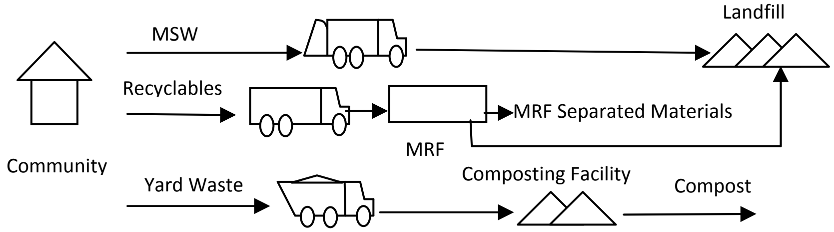
Strategy 6: Curbside Recycling RDF Combustion and Cash Landfilling



Strategy 7: Curbside Recycling RDF Composting and Landfilling



Strategy 8: Curbside Recycling, Yard Waste Composting and Landfilling



Strategy 9: Curbside Recycling, Yard Waste Composting, Mass Burning and Ash Landfilling

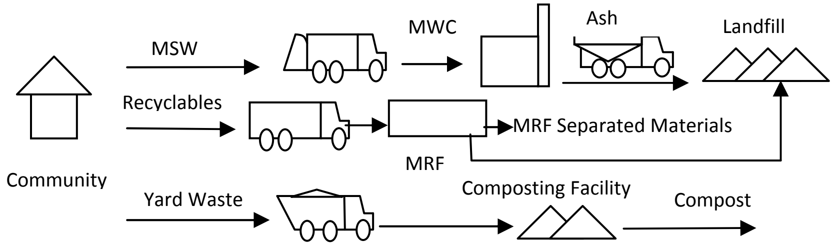


Figure 4. Common waste management schemes used in the United States. ***MRF:*** **Material Recovery Facility;** ***MWC:*** **Municipal Waste Combustion;** ***RDF:*** **Refuse Derived Fuel;** ***SM:*** **Separate Materials (Kreith, 1994).**

The fifth and sixth strategies in Figure 4 also involve the separation of the recyclables from the MSW, which is critical for more complex strategies to obtain higher value products. Strategies 8 and 9 involve source separation and separate transportation of yard waste, recyclables and the rest of the MSW (Kreith, 1994). For using a pyrolysis reactor, it is desirable to separate at the source the wastes obtained or to produce refuse derived fuel from the MSW fraction. Figures 5, 6 and 7 show examples of different collection vehicles involved in the nine strategies explained above.

Strategies 8 and 9 are the most promising for the integration of Pyrolysis to the processing of municipal solid wastes. The separation of yard wastes at the source is critical to obtain a clean stream that can be pyrolysed or composted. However, the potential of MRF separated materials as feedstock for pyrolysis has been poorly studied. The scientific community should study more thoroughly MSW supply chains to identify separated fractions with potential to be used as feedstock for pyrolysis processes.

Source Separation: With source separation, recyclable fractions are separated by the generator or at the curbside by the collector. Specially designed multi-compartment vehicles store and transport the separated fractions to a consolidation site for further processing (Spencer 1994). Single stream and dual stream are the most common types of source separation (Lopez and Kemper 2008). In the single stream customers put all recyclables (paper and commingled containers) in a single container. In the dual stream source separated customers place recyclables in at least two containers. Materials are collected in collection trucks with compartments for the various materials. Some sorting is still necessary after unloading to clean and further segregate materials.

Commingled Collection: In the case of commingled collection the generators only separate recyclable materials from non-recyclables Recyclables are transported to material recovery facilities (MRF) where they are separated by recyclable component: paper, glass, metal, plastic, etc.

Mixed Municipal Solid Waste Collection: In the case of the mixed municipal solid waste collection, generators do not separate waste at all. A single collection vehicle (Figure 5) picks up the mixed waste which is transported either to a landfill, an incinerator, or a material recovery facility where separation of recyclable fractions takes place.

2.1.2. Transportation and Waste Management Schemes

Tansportation of Municipal Solid Waste is linked to the waste management scheme selected. Specific trunks have been designed to transport MSW to the final processing unit. When there is not separation waste separation at the source, trunks with single compartment are used (Figure 5). In the case where the generators separate waste, compartmentalized recycling trucks (Figure 6) are the best option. For Yard waste, trunks as the one shown in Figure 7 are used. The transportation of the separate Yard waste, allows having a clean feedstock (Figure 8) ready to be used for composting or pyrolysing.

Figure 5. Truck for mixed MSW (source: http://www.flickr.com/photos/joekuby/317477168/)

Figure 6. Compartmentalized recycling truck (Source: Treehuger web site: http://www.treehugger.com/files /2008/11/celebrate-zero-waste-day.php).

Figure 7. Yard waste truck (Source: Montgomery website: http://www.montgomerycountymd.gov /apps/news/blog/solidwasteBlog.asp?blogID=2&Cat=Transfer%20Station).

Figure 8. Yard Wastes (clean feedstock) (Courtesy of WA Department of Ecology)

The densification of land clearing debris is a strategy that is being studied to allow longer transportation distances. Forest Concepts of Auburn, WA (http://www.forestconcepts.com/) has developed a system to bale and transport land clearing debris to a centralized facility to be chipped or to be pelletized (Figure 9). This densified biomass can be used to produce bio-oils or biochar. The authors were not able to find any study on the use of yard wastes as feedstock for pyrolysis.

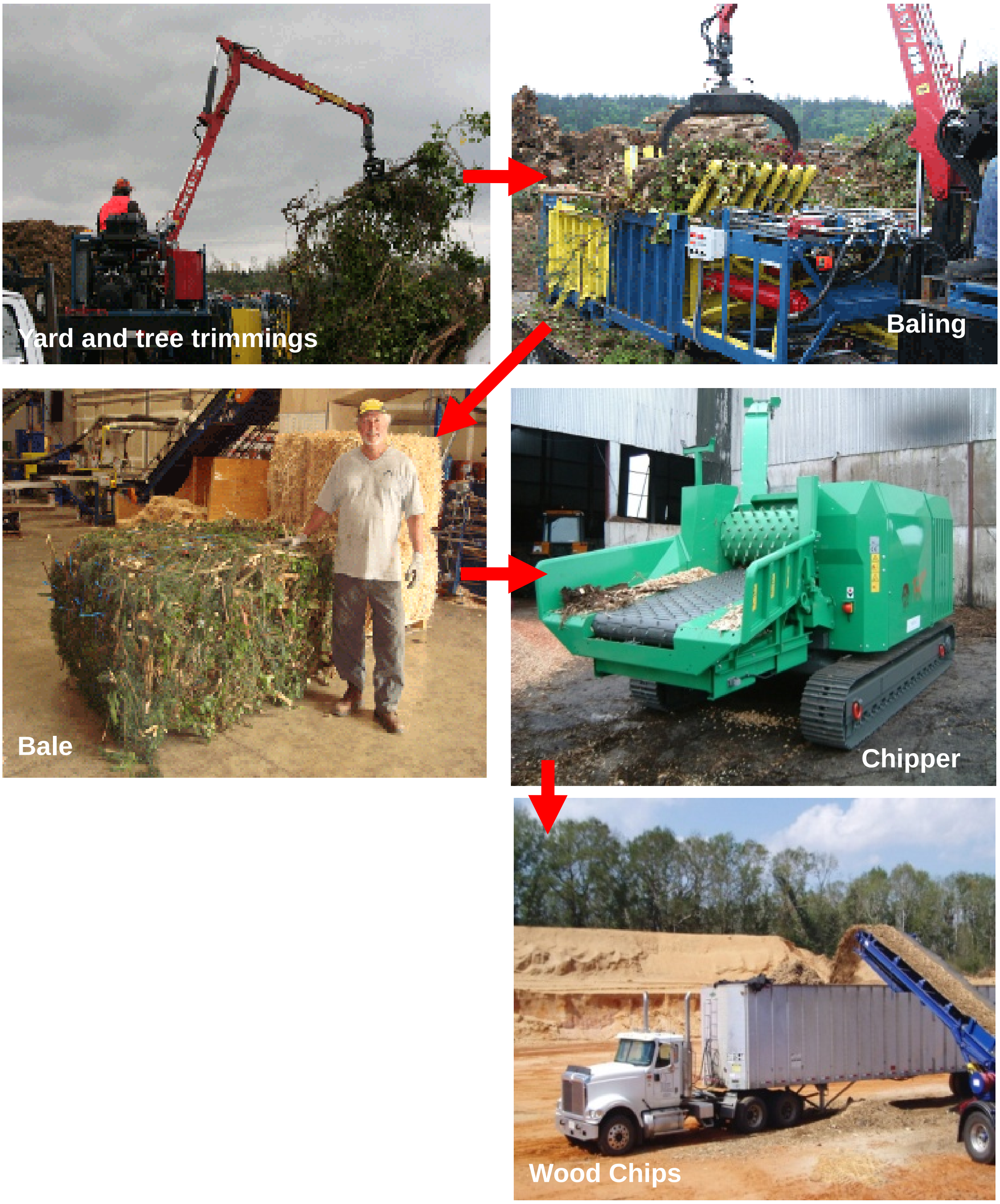


Figure 9. Supply chain for using yard and tree trimmings to produce chips (http://www.forestconcepts.com/).

2.1.3. Material Recovery Facilities

Some schemes used to handle municipal solid wastes use material recovery facilities (MRFs) (See Figure 4). The material recovery facilities are solid waste management facilities that collect, compact, repackage, sort, and process materials for the purpose of recycling using manual and/or mechanical methods. It is possible to incorporate pyrolysis as an optional waste to fuel or energy recovery and recycling technology at MRFs. Generally there are two types of MRFs: 1) in *clean, or source separated, MRFs,* recyclable materials (such as paper and commingled containers) are separated by the consumer prior to collection. Finished products from the paper stream (newspaper, mixed paper, and some corrugated) can be suitable feedstocks for pyrolysis. Products from the commingled container stream include: ferrous metals, aluminum, glass, PET, and HDPE (Lopez and Kemper 2008); 2) in *dirty, or non-source, separated MRFs,* materials are delivered as mixed MSW. Products are similar to those from clean MRFs but separation is not as effective (Lopez and Kemper 2008). Figure 10 shows comingled municipal solid wastes that are typically processed by some material recovery facilities. These materials are also sometimes landfilled.

Figure 10. Poorly separated Wastes (Courtesy of WA Department of Ecology)

Commingled recyclables are received in the tipping floor where front loaders typically move the material onto the conveyors. At the MRF, MSW fractions (paper, plastics, aluminum, glass, and ferrous materials) are separated taking advantage of the physical and chemical characteristics of each of the fractions in sequential separation steps (Dubanowitz 2000). Most MRFs commercialize separated fractions in the form of bales (Figures 11 and 12) which typically are loaded with forklifts onto tractor trailers for shipment to a reprocessing facility. Residues left after the recyclable fraction is removed are landfilled, combusted, or composted (Dubanowitz 2000). The pyrolysis of Recycled paper, cardboard and plastic bales to produce drop in fuels and bio-char is an area that has been poorly studied.

Figure 11. Baled recyclable materials a) Recycled paper (http://www.bficanada.com/English /USServices/Locations/JerseyCityRecycling/default.aspx) b) Plastic containers and metal cans (http://recycle.georgetown.org/recycling-how-does-it-work/).

Figure 12. Baled cardboard (http://www.everydayrecycling.com/fiber.html)

A material recovery facility (MRF) recovers ferrous metals, high-density polyethylene (HDPE), polyethylene terephthalate (PET) plastics, aluminum, and different kind of papers and cardboards. This kind of facility can recover approximately 15% of the total MSW in usable materials; the other 85% can be used to produce refuse derived fuel (RDF) (Williams 2005).

Co-mingled separation has been worked out largely for recycling plastics, metals, glass, paper and cardboard, but does not provide a good separation for food and green waste contaminated with containers.

2.1.4. Composting Facilities

As shown in Figure 4 composting is one of the technologies forming part of solid waste management strategy that can be used to process mixed MSW or separately collected leaves, yard wastes and food wastes (Kreith 1994). Theoretically composting could be used to process up to 36 percent of the MSW (Figure 3, Washington State Department of Ecology, 2010a). Composting can also be used to recycle food waste, soiled papers, and clean woody waste from land clearing yard.

In Washington, typically compost is for source separated food and yard waste. A possible diagram of composting process is shown in Figure 13. Before the composting step some size reduction and possibly some adjustment of the carbon to nitrogen ratio are needed.

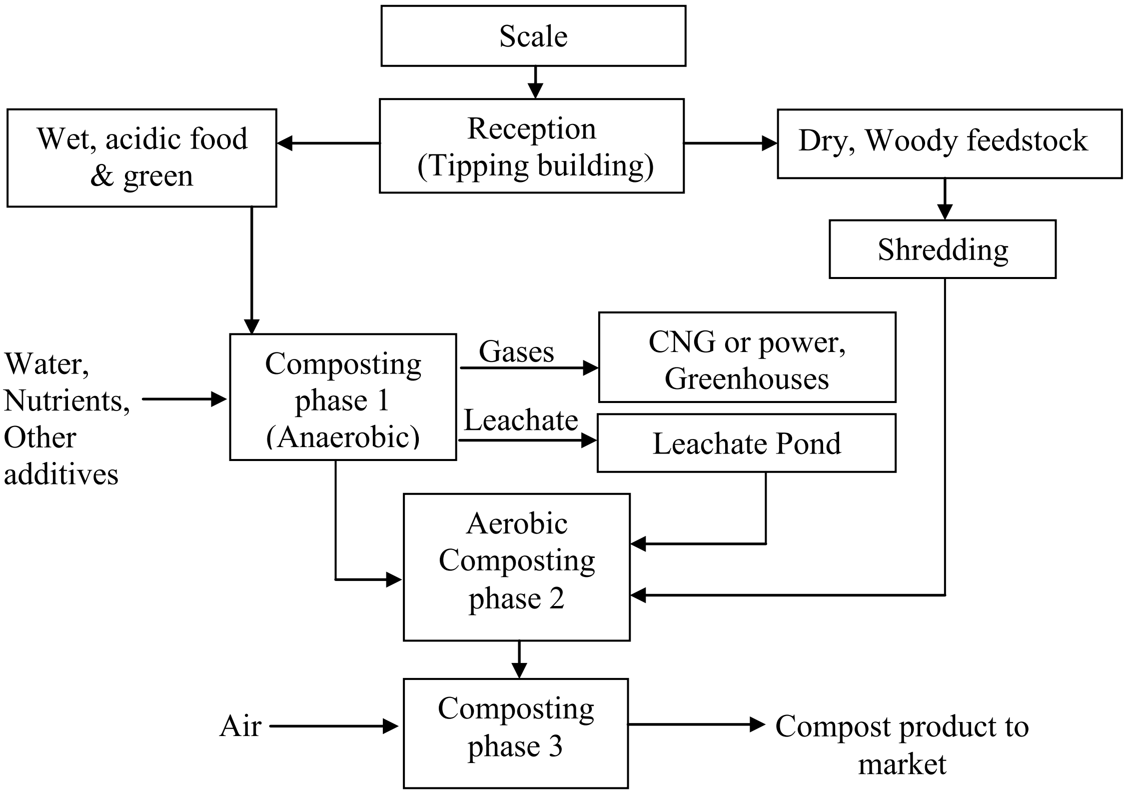


Figure 13. Scheme of a generic composting facility

Composting proceeds in three steps: (1) lag period (exponential growth) (2) active phase and (3) maturation phase. Compost systems in Washington State are Windrow composting and aerated Static Pile (ASP). In windrow composting the mixture of raw material is placed in narrow piles aerated and turned regularly. These systems aerate primarily by natural or passive air movement. The aerated Static Pile (ASP) typically uses a blower to supply the air to the piles. An aeration pipe on the bottom of the pile is connected to a blower that either pulls or pushes air through the pile (http://www.fao.org/docrep/007/y5104e/y5104e07.htm#TopOfPage). An important fraction of the woody material that is currently composted could be used for pyrolysis.

2.2. Urban Wood Waste

The term “urban wood waste” has not specifically been defined by industry groups or regulatory agencies. However, “*wood waste present in municipal and commercial solid waste*” is widely used as a collective reference for construction and demolition wastes (C&D), wooden pallets, packaging materials, furniture and appliances, cabinets, yard and tree trimmings, land clearing residues, and other forms of waste that consist primarily of wood (Badger 2002). Thermal utilization of urban waste wood offers a low-cost biomass fuel which is advantageous for large-scale biomass combustion plants (van Loo and Koppejan 2008). Some of the urban wood waste collected is relatively clean (see Figure 14 and 15). Other sources are poorly separated and sometimes are contaminated with plastics and other waste fractions (see Figure 16). “The cleanness” of the waste depends on both, the separation at the source and the transportation system.

Figure 14. Well separated Urban Wood Wastes (Courtesy of WA Department of Ecology)

Figure 15. Well separated wooden pallets and cardboard (Courtesy of WA Department of Ecology)

Figure 16. Poorly separated urban wood waste (Courtesy of WA Department of Ecology)

Wooden pallets make up a considerable portion of urban waste wood. Only about 20 percent of pallets are recycled. Pallets may contain preservatives or water repellants in addition to the nails and strapping from pallet repairs, and they may be contaminated with chemicals from spills while in service. Nevertheless, most pallets are free of non-wood materials, with the exception of nails (Badger 2002). The supply chain for wooden pallets is illustrated in Figure 17.

A processing plant that produces wood waste sized between 10 and 100 mm (3/8 - 4 in) and mostly free of ferrous and non-ferrous metals contains four main steps (van Loo and Koppejan 2008): 1) A low speed shredder containing a 100 mm (4 in) screen basket; 2) a magnetic roller and an overband magnet to remove iron pieces; 3) a 10 mm (3/8 in) mesh to screen the waste wood; and 4) a system to separate out non-ferrous metals. A centralized wood waste pre-treatment plant used to upgrade large amounts of various kinds of waste wood can achieve a productivity rate of up to 100 tons per hour, producing pellets as the final product (van Loo and Koppejan 2008).

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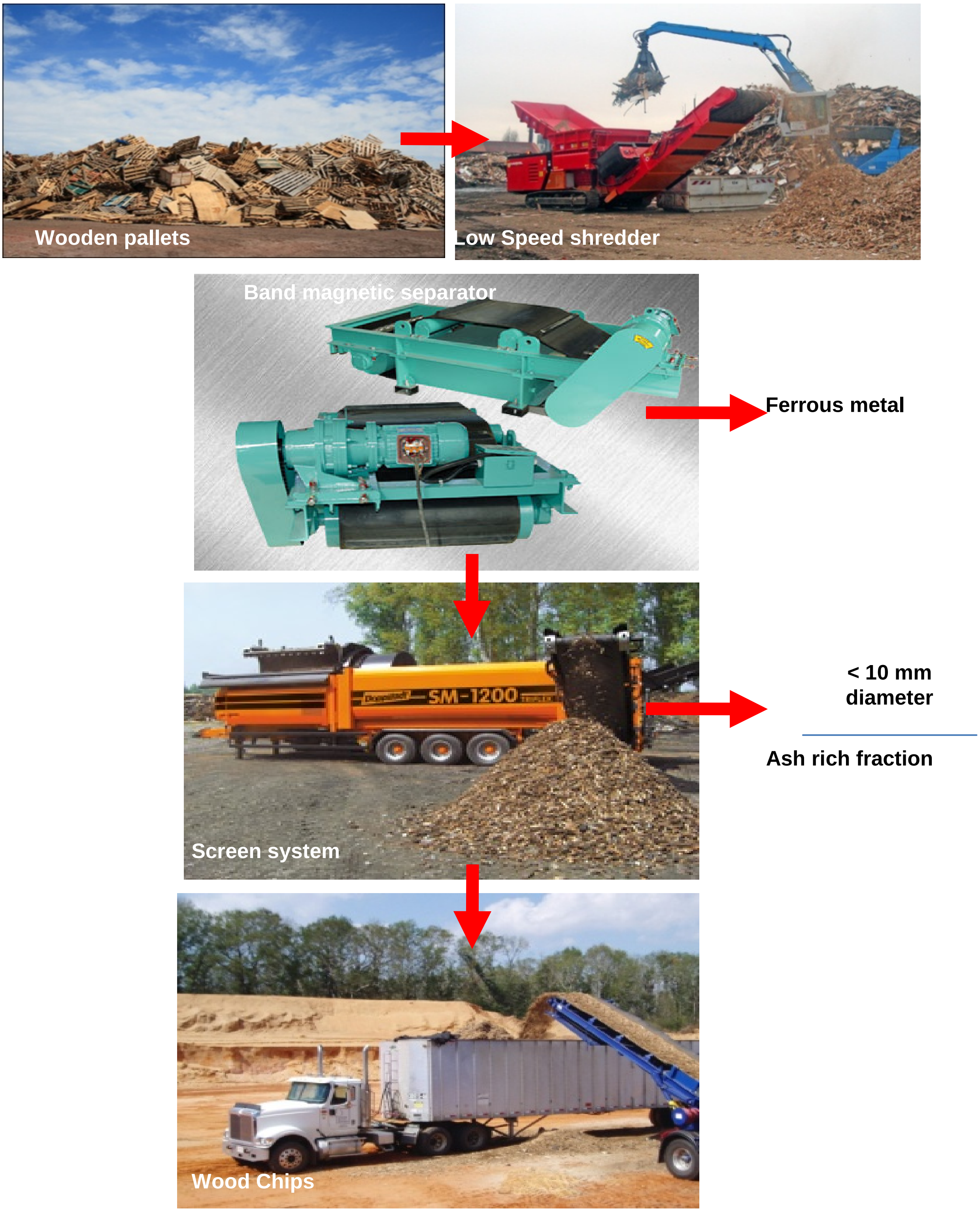

Figure 17. Wooden pallet supply chain for Washington State (Badger 2002).

Waste wood is an extremely heterogeneous fuel due to its different sources. For example, construction and demolition debris may contain anywhere from 15 to 85 percent wood by weight (Badger 2002). Classification standards for wood wastes are being developed in Europe by the European Committee for Standardization (CEN TC 343, "Solid Recovered Fuels") (van Loo and Koppejan 2008).

Waste wood can vary significantly in chemical composition and content of impurities depending on local constraints (van Loo and Koppejan 2008). Concentrations of impurities and crucial ash forming elements generally increase with decreasing fuel particle size with wood waste (van Loo and Koppejan 2008). Therefore, most of these elements can be effectively removed from the fuel by discharging undersized fuel particles. A waste wood processing plant with a facility dedicated to separating undersized particles and which also has units for separating ferrous and non-ferrous metal can significantly reduce these concentrations (van Loo and Koppejan 2008).

OMNI Enterprises has developed dry bricks as fuels from cardboard and pallets (Miles 2011). These dense bricks have shown to be excellent fuels combusting with low emissions. There are very few pyrolysis studies devoted to understand the behavior of urban wood wastes during pyrolysis.

2.3. Forest Residues

Considering the type of green, yard trimming resources, and the fact that a pyrolysis biomass facility may be built to process feedstocks from municipal, forest and agricultural resources we include a brief review of forest harvesting and collection methods. Harvest, collection and processing of forest residues are discussed briefly in this section. The Woody Biomass Utilization Desk Guide by Wynsma et al., (2007) describes technologies for harvesting woody biomass and provides information on how to offset the costs of fuel reduction and ecosystem restoration while developing a viable biomass industry. Wynsma et al., (2007) provide an excellent review with suggestions for local managers on how to locate and collaborate with biomass businesses. In many areas of the state the pyrolysis units that will be installed are likely to process forest wastes together with municipal solid wastes. This will provide for increased capacity of the processing units and to take advantages of the economies of scale.

2.3.1. Harvest and Collection

Integrated whole tree harvesting and chipping systems are typically employed when biomass fuels are to be produced from thinning and include felling, extraction (removal and transportation of timber or residues typically end cuts, tops and limbs), processing (including removing the limbs and bucking) and chipping the residues. Using a closely coupled operation reduces supply costs significantly and provides a homogeneous product (van Loo and Koppejan 2008). A supply chain for forest thinning suitable for Washington is shown in Figure 18. Some of the technologies used for forest residues can be applicable or adaptable to handling and processing solid wastes, especially yard waste. Bundling, storing and chipping are well suited for yard waste handling also.

Figure 18. Supply chain for forest thinning (Sources: http://www.deere.com/en_US/cfd/forestry/deereforestry/media/images/landing/stories/909j-feller-buncher-2-lg.jpg; http://www.johndeere.com/en_US/cfd /forestry/ deere _forestry /info center/feature_stories/pf_harvesting-energy.html; http://www.unb.ca/standint/nbcc/machine/other/Peart_Jennith.htm; http://en.wikipedia.org/wiki/File:Europe _Chippers _1.jpg)

It is important to point out that in addition to the method shown in Figure 18, it is also possible to chip the biomass at the source. Several pieces of machinery (manual, semi-mechanical, or fully mechanical) customary to the conventional logging industry are used to harvest forest thinnings including a *feller buncher,* which can cut and stack up to 200 trees per hour(Forest Encyclopedia Network 2009)) (Figure 19); *a harvester slingshot*; a *forwarder*; or a *skidder* (Barbosa-Cortez et al., 2008; Kumar and Sokhansanj 2007). A forwarder can be used with small logs to reduce soil impacts of skidding (Forest Research, 2001).

Figure 19. Feller buncher with grappling device and disk (source: http://www.deere.com/en_US/cfd/forestry/deere_forestry/track_fellerbunchers/deere_fellerbuncher_selection.html).

Limbs and bark contain high amount of extractives many of which are waxes. These residues are good feedstocks for pyrolysis but the resulting oils are rich in waxy materials responsible for clogging problems during condensation if not properly handled (Brown 2003, Oasmaa et al., 2003a and b). A variety of equipment options including chain saws, harvesters, stroke delimbers, or a flail which mechanically removes limbs and bark (Figure 20) at the stump or landing, where a grinder can produce chips suitable for further processing into chemicals or fibers (Brown 2003). Grinders can also produce suitable particles for pyrolysis.

Figure 20. Delimbing and debarking using a flail (Source: http://www.ansonvillefire.com/site_ flash/320cMed.jpg).

Baling residues (Figures 21) reduces air space that creates a considerably higher payload and reduces transportation costs by 10 to 50 percent compared to unchipped materials, (van Loo and Koppejan 2008). A single baler can produce 20 – 60,000 bundles per year. Bundles are also less susceptible to biological degradation than slash, making covering during short-term storage and transportation unnecessary. However, under some circumstances a 2-step process may be more expensive than to chip and haul in one operation.

Figure 21. Wood bundler baling forest residues (Source:); and slash bundles at roadside (Source: http://www.deere.com/en_US/cfd/forestry/deere_forestry/media/flash/photogallery/energy_wood_harvestor/1490d/index.html and http://www.unb.ca/standint/nbcc/machine/ other/Peart_Jennith.htm).

2.3.2. Processing Forest Residues

Chipping is the primary method for processing forest residues for fuel production and can be completed at the logging site with a mobile chipper or at a mill (van Loo and Koppejan 2008). Chipping requires 1-3 percent of the wood fuel energy content and allows for wood fuel to be produced economically using low quality wood such as rough, partly rotten, and salvageable trees, logging residues, limbs and bark, and excess growth. Chips are blown from the chipper into a trailer to separate leaves and debris from the fuel (Badger 2002).

Chippers can produce three different types of chips: 1) *whole-tree chips* produced primarily from unmerchantable timber by feeding the entire tree (trunks, limbs and branches) into the chipper; 2) *round-wood chips* made from tree trunks after the branches and limbs have been removed; and 3) *clean chips* made from debarked tree trunks. Clean chips are usually sold for pulp markets and typically have an ash content of less than 0.05 percent (Badger 2002). Whole-tree and round-wood chips typically have higher ash content, by about 1.0 percent which may include soil particles (Badger 2002).

2.3.3. Industrial Mill Residues

Industrial mill residues that result from processing forest products are a significant feedstock for pyrolysis units (Badger 2002). *Primary mill residues* (green mill residues – moisture content >20%, ash content varies based on the feedstock and ranges from 3-4%) are produced from pulp and veneer plants as well as lumber mills and include chip rejects, sawdust, slabs, “hogged” bark stripped from logs, and end-cuts remaining after green wood has been milled. Primary mill residues may include dirt and stones (Badger 2002).

Secondary mill residues (dry mill residues) are byproducts of wood product industries that utilize kiln-dried material to manufacture consumer and industrial goods and are characterized primarily by cleanliness, minimal bark content, relatively low moisture content (<10%), fairly high energy value, an ash content <0.5% (Badger 2002), and include sawdust, trimmings, shavings, flour, sander dust, end-cuts, chip rejects, flawed dimension lumber, and other byproducts. Disadvantages of these residues include the need for dry storage and the potential need for special handling to manage processing emissions for residues that have surface coatings such as paint, varnish, plastic-based laminates, or residues containing glues and adhesives (Badger 2002).

2.4. Agricultural Residues

A pyrolysis biomass facility may be built to process feedstocks from several sources including municipal, forest and agricultural resources. We extend our brief review to agricultural harvesting and collection methods. This section reviews supply chains for agricultural biomass such as straw, whole crops and grasses. Technologies used for gathering and removing agricultural biomass from the field for densification and transportation vary depending on the state of the biomass in the field, the moisture content, and the end use. Several preprocessing options for herbaceous materials are shown in Figure 22.

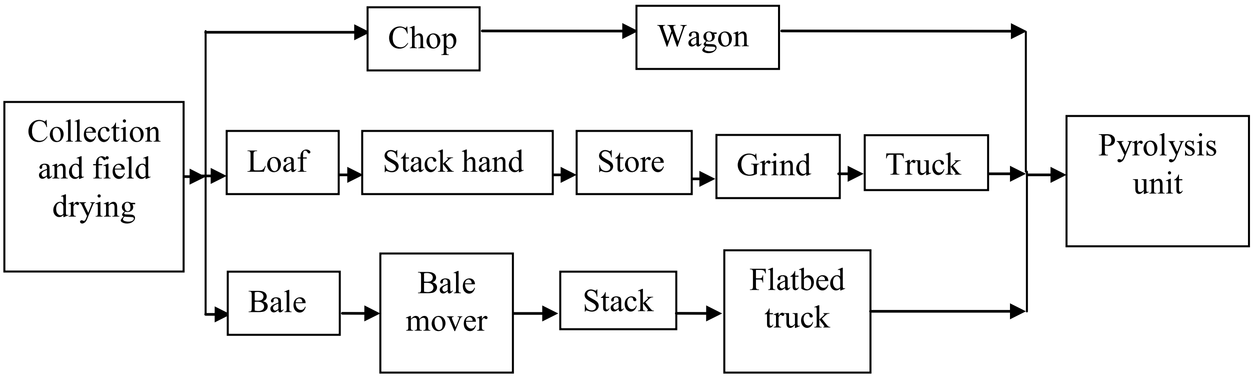

Figure 22. Collection and transportation of biomass to a pyrolysis unit is presented in a generic flow diagram (Kumar and Sokhansanj 2007).

Typically, herbaceous materials are a bulky by-product of the main crop (wheat, blue grass seed and barley), and may require additional steps to densify the material prior to transport. In some cases, additional steps for drying are applicable before transportation. Applicable densification strategies and transportation options depend on the bulk density of the biomass which is different for each material. For example, different forms of biomass result in varying densities (Table 2).

Table 2. Bulk volume and density of selected biomass sources delivered (Adapted from: McKendry 2002, Sokhansanj et al., 2009, Sokhansanj et al., 2006).

Biomass	**Bulk Volume (m^3/t)**	**Bulk Density (kg/m^3)**	**Bulk Density (lb/ft^3)**
Wood*			
Hardwood chips	4.4	230	14.3
Softwood chips	5.2–5.6	180–190	11.2–11.8
Pellets	1.6–1.8	560–630	34.9–39.2
Sawdust	6.2	120	7.5
Planer shavings	10.3	100	6.2
Straw*			
Loose	24.7–49.5	20–40	1.2–2.5
Chopped	12.0-49.5	20–80	1.2–5.0
Baled	4.9–9.0	110–200	6.8–13.7
Moduled	0.8–10.3	100–125	6.2–7.8
Harmmermilled	9.9–49.5	20–110	1.2–6.8
Cubed	1.5–3.1	320–670	19.9–41.7
Pelleted	1.4–1.8	560–710	34.9–44.2
Switchgrass			
Chopped (20–40 mm long) (25/32– 1 9/16 in)	12.5–16.7	60–80	3.7–5.0
Ground particles (1.5 mm loose fill) (1/16 in)	8.3	120	7.5
Baled (Round or large squares)	5.6–7.1	140–180	8.7–11.2
Ground particles (1.5 mm pack fill with tapping**) (1/16 in)	5.0	200	13.7
Briquettes (32 mm diameter x 25 mm thick) (2 ¼ in x 1 in)	2.9	350	21.8
Cubes (33 mm x 33 mm cross section) (1 5/16 in x 1 5/16 in)	2.5	400	24.9
Pellets (6.23 mm diameter) (1/4 in)	1.4–2.0	500–700	31.1–43.6

* Dry, ash-free tons

** Biomass is spread into the container while tapping the container – achieving <25% increased density

Chopped biomass can be ground to an average size of 1 mm which has a density in the truck box of approximately 200 kg/m^3 (12.5 lb/ft^3) a density that is suitable for a short haul (< 160 km or < 99 miles). For longer hauls and long-term storage, a bulk density of 300-700 kg/m^3 (18 - 44 lb/ft^3) typically obtained through pelletization (Sokhansanj et al., 2006, Sokhansanj et al., 2009) is preferred.

The value of agricultural biomass is based on several factors. For example, in 2004, straw in Idaho was $32-42/t. These values include: the raw straw (laying in the field) at $3.8-5.75/t, a baling charge of $15.2-17.2/t, $4-5.5/t to remove bales from the field and stack by the road, and a transportation charge of $10-12/t for up to 70 miles (Hess et al., 2006). Prices for straw in the region have increased significantly in recent years as the feed markets have tightened. Concerns about the environmental consequences of straw removal and adequate valuation of the raw straw were raised by Huggins and Kruger (2012) who reported nutrient fertilizer values in the straw of more than $13/t and potential "in field" agronomic value associated with water conservation of crop residues. They further report that within field considerations for residue removal are extremely important in Eastern Washington, as residue removal usually results in negative impacts on soil quality and soil organic matter. Many of these concerns can be addressed by returning bio-chars to the field.

Grain straw, corn stover, and other similar crop residues are harvested, dried and collected in three to four steps. The first step uses a combine harvester to harvest the grain which then discharges the residues into a windrow behind the combine (Figures 23, 24A). Once in windrows, the material begins to dry reducing the moisture content to less than 20 percent (Savoie et al., 2002) before being processed into bales. Additional field drying can be achieved by turning or fluffing the crop once it is partially dry. Natural drying occurs when a crop is left standing in a field beyond maturity (Brown 2003).

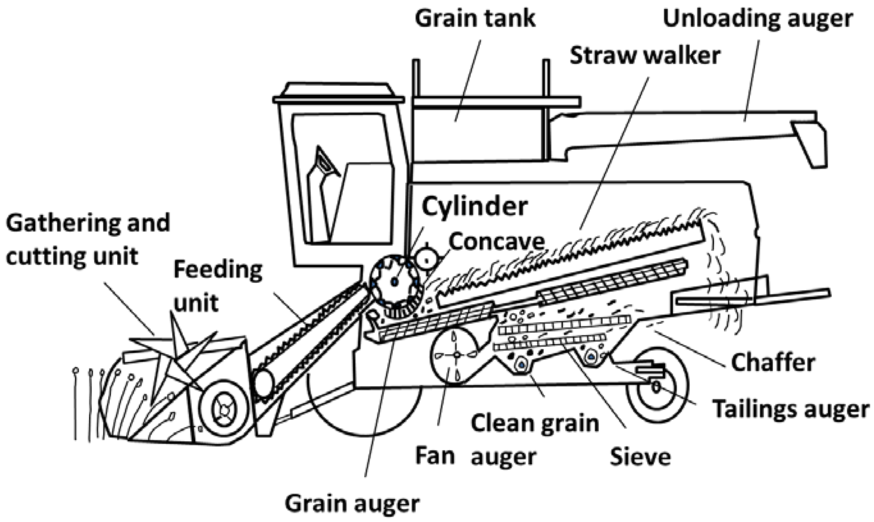

Figure 23. Combine harvester showing some details of the three main parts: gathering and cutting unit, threshing unit and cleaning unit. (Brown 2003)

Figure 24 illustrates a supply chain for the production and transportation of straw, a significant component of agricultural residues generated in Eastern Washington. Bales of straw also can be ground and transported as shown in Figure 25. Modern machinery can synthesize the steps of mowing and windrowing (Brown 2003).

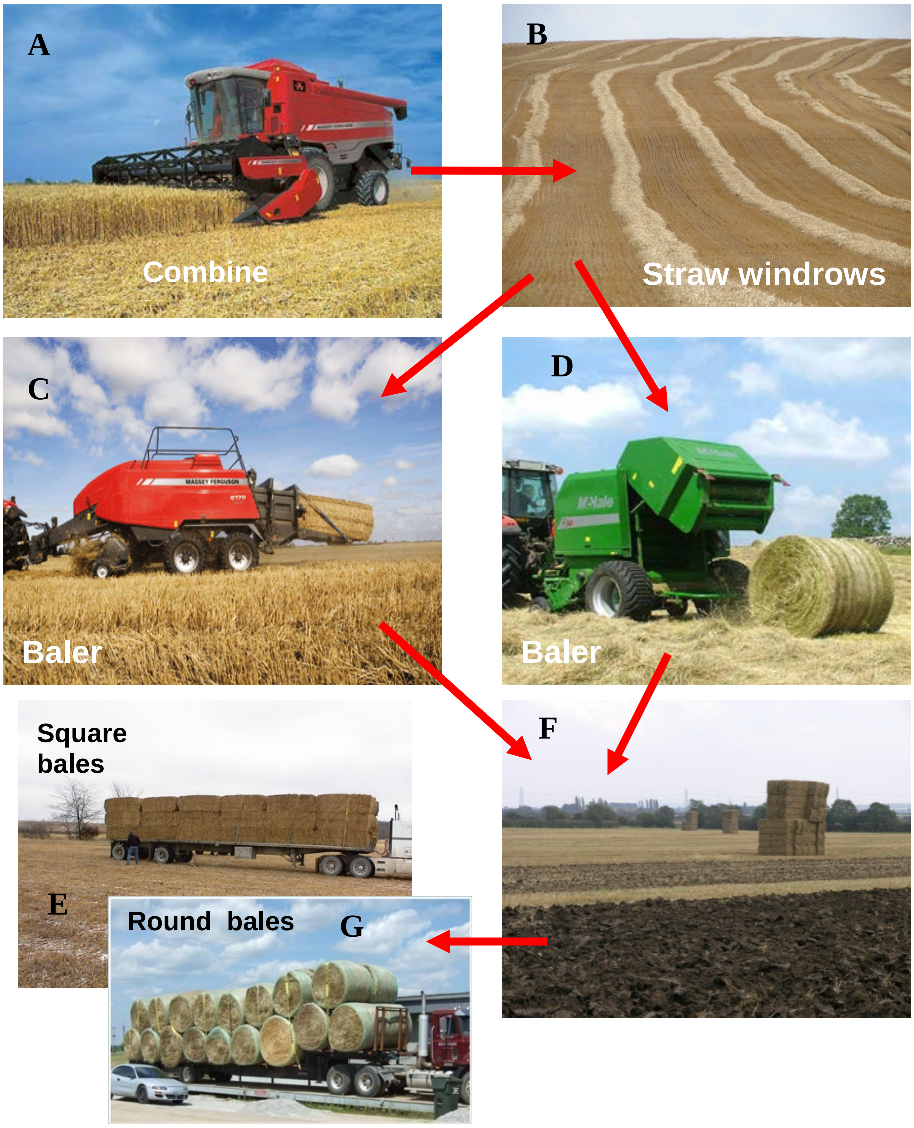

Figure 24A-G. Supply chain for the production and transportation of bales. (Sources: Fig. 24A http://images.farmingads.co.uk/ch.jpg; Fig. 24B: http://en.wikipedia.org /wiki/Windrow; Fig. 24C: http://www.fwi.co.uk /Articles/2008/ 03/12/109738/Latest-machinery-for-big-bale-contractors.htm; Fig. 24D: http://www.mchale.net/uploads /images/default product/gallery/129F560%20Fully %20 Automatic %20 Baler 1.jpg; Fig. 24E: http://iowaswitchgrass.com/__images/pictures/6qeqatransporting 1174900508.jpg; Fig. 24F: http://upload.wikimedia.org/wikipedia/commons/a/a0/ RareSquare_Bales_-_geograph.org.uk_-_239863.jpg; Fig. 24G: http://farmenergy.org/wp-content/uploads/2009/05/smec-biomass-delivery.jpg.)

Figure 25. Grinding bales into chips for transport (Tagore and Hess 2005).

Tagore and Hess (2005) highlight several challenges of the harvesting process. It is important to reduce or eliminate negative impacts such as soil compaction and to reduce the costs of harvesting while meeting sustainability requirements. Soil compaction results from degradation of soil structure due to tillage, residue removal, and repeated trips across the field, thus methods that minimize the necessary of repeated trips will mitigate this environmental problem.   Additionally, high concentration of alkalines (potassium, sodium calcium, magnesium, etc.) in herbaceous crops negatively influences the pyrolysis process for bio-fuel production when compared to woody energy crops (van Loo and Koppejan 2008) which is further discussed in Section 3.10.

2.4.1. Bales from Agricultural Biomass

Baling in the form of either squares or rounds (Figures 24C and 24D) is the most conventional means for collecting agricultural waste. Hess et al., (2006) provide further information on baling operations. A desirable bale is well-shaped and as dense as possible (Huhnke 2011), reducing expense in producing and handling as well as potential spoilage. Rectangular big balers (Figures 24A and 26) make bales with a density range between 180 – 230 kg/m^3 (11 – 14 lb/ft^3) and a length of 2.4 m (2.6 yards) (Brown 2003). Round balers (Figures 24D and 27) make bales with a density range between 130 – 250 kg/m^3 (8 – 13 lb/ft^3). There are two types of round balers: loose core and compact core (Figure 27). The first one forms the round bale in a fixed volume chamber while the second one uses a variable volume compression chamber.

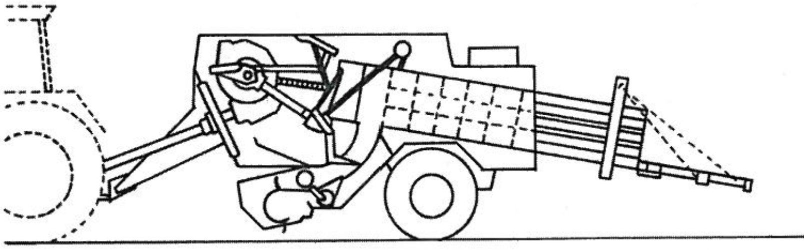

Figure 26. Rectangular big baler (Brown, 2003)

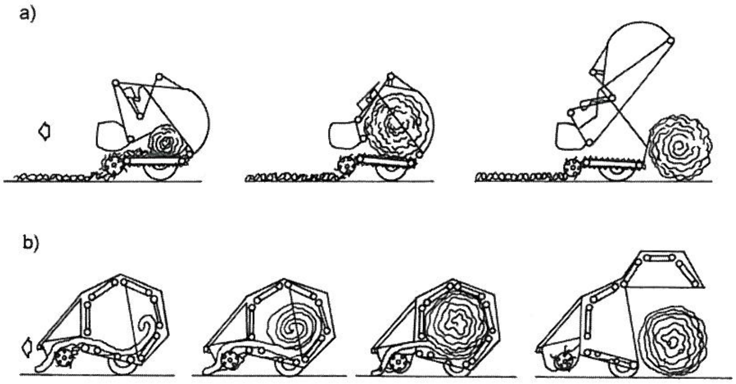

Figure 27. Round balers: a) Varible chamber, core compact, b) Fixed chamber, loose core (Brown 2003)

There are trade-offs between round and square bales for both labor and storage. Round bales can be handled by one operator and have fewer storage requirements, such as polyethylene sheets (Sokhansanj et al., 2009). However, round bales tend to deform during storage and cannot be properly loaded for long-range trucking (Sokhansanj et al., 2006). Square bales can take multiple operators and typically require enclosed storage to reduce spoilage (Huhnke 2011). Once bales are formed, an automatic bale collector such as a stringer stacker (Figure 28) is driven cross the field to collect and transport the bales to the roadside where they are stacked and covered (Hess et al., 2006). In the absence of an automatic bale collector, a front end loader and a flat bed truck may act as a substitute (Hess et al., 2006). In order to overcome the limitations of the bale system at a larger scale, a bulk collection system needs to be designed and developed (Department of Energy 2003). The use of baled biomass reduces its bulk volume and increases its bulk density (Table 2) reducing transportation costs. Baling straw increases bulk density from a range of 20-40 kg/m^3 (1.15-2.50 lb/ft^3) (Table 2) to 110-200 kg/m^3 (6.85-13.71 lb/ft^3). Taking into account the high heating value of the straw of 17.3 MJ/kg (7,86 MJ/lb) (McKendry, 2002) and using bulk density values reported in Table 2, it can be calculated that energy density of bales is 3 times that of bulk chopped straw.

Figure 28. Stringer stackers for bales recollection. (source: http://www.stingerltd.com/index-1.html, http://www.usagnet.com/manufacturers/85/3400.jpg)).

2.4.2. Chops from Agricultural Biomass

Alternative to baling is dry chop harvesting and piling (Kumar and Sokhansanj 2007, Brown 2003). In a *dry chop* system the harvester passes over the windrows of dry biomass picking up and chopping the material into smaller pieces (2.5 -5 cm, 1-2 in), collecting the pieces in a forage wagon (Kumar and Sokhansanj 2007). Brown (2003) state that, for harvest hay, some chopping systems (Figure 29) produces length of hay between 20 - 40 cm (8 – 16 in) long for barn drying and 8 – 10 cm (3 – 4 in) long for silage. *Wet chop* (silage) systems are unsuitable for fast or slow pyrolysis (Sokhansanj 2009, Sokhansanj et al., 2006).

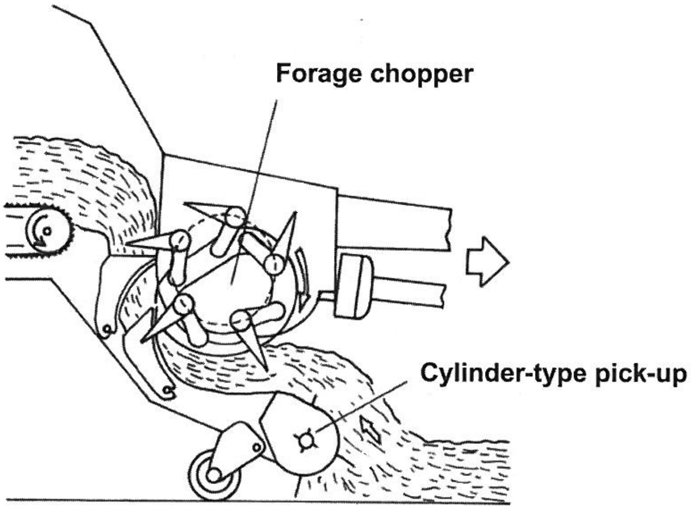

Figure 29. Self-loading wagon for hay harvest (Brown 2003)

Collection and harvest of agricultural residues in a “single pass harvesting” system along with grain harvest would significantly improve economic and environmental performance of agricultural biomass collection (Figure 30), with the key concern being managing moisture content (Sokhansanj et al., 2006, Department of Energy 2003).

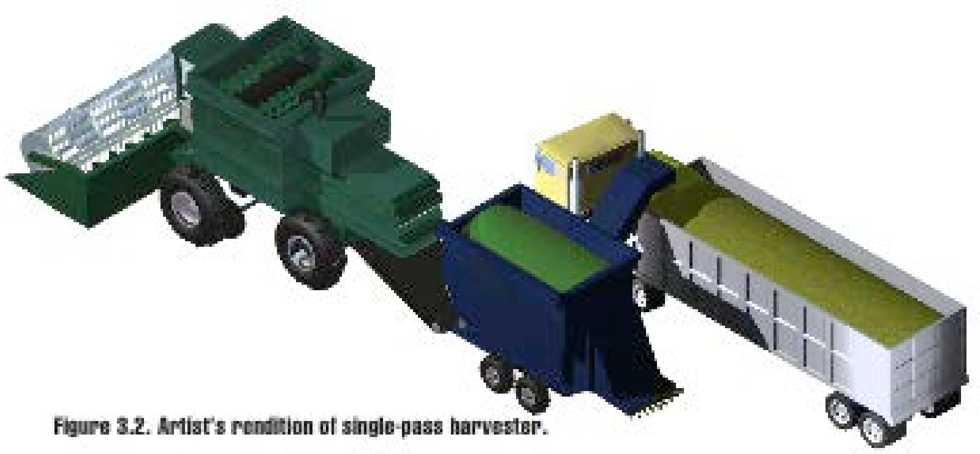

Figure 30. Several operations are merged with a single pass harvester (Department of Energy 2003).

2.5. Energy Crops

Although energy crops contribution to the total bio-energy production is still relatively small, it is expected that a rapidly grow due to their potential to contribute to climate change mitigation, to decontaminate soils, and reduce energy demand (Sims et al., 2006). The energy crops can be divided into: herbaceous energy crops and short rotation woody crops. Both are relevant for the conditions of Washington State and could complement the waste materials for the production of fuels and chemicals.

2.5.1. Herbaceous Energy Crops

Herbaceous energy crops (like sugar cane, corn) have specific ways of harvesting, densification and transportation. For example, sugarcane is collected in chops after the cane has been separated from the leaves. Figure 31 shows some of the existing schemed to harvest, collect and densify energy crops such as straw, whole crops, grass or miscanthus (van Loo and Koppejan, 2008).

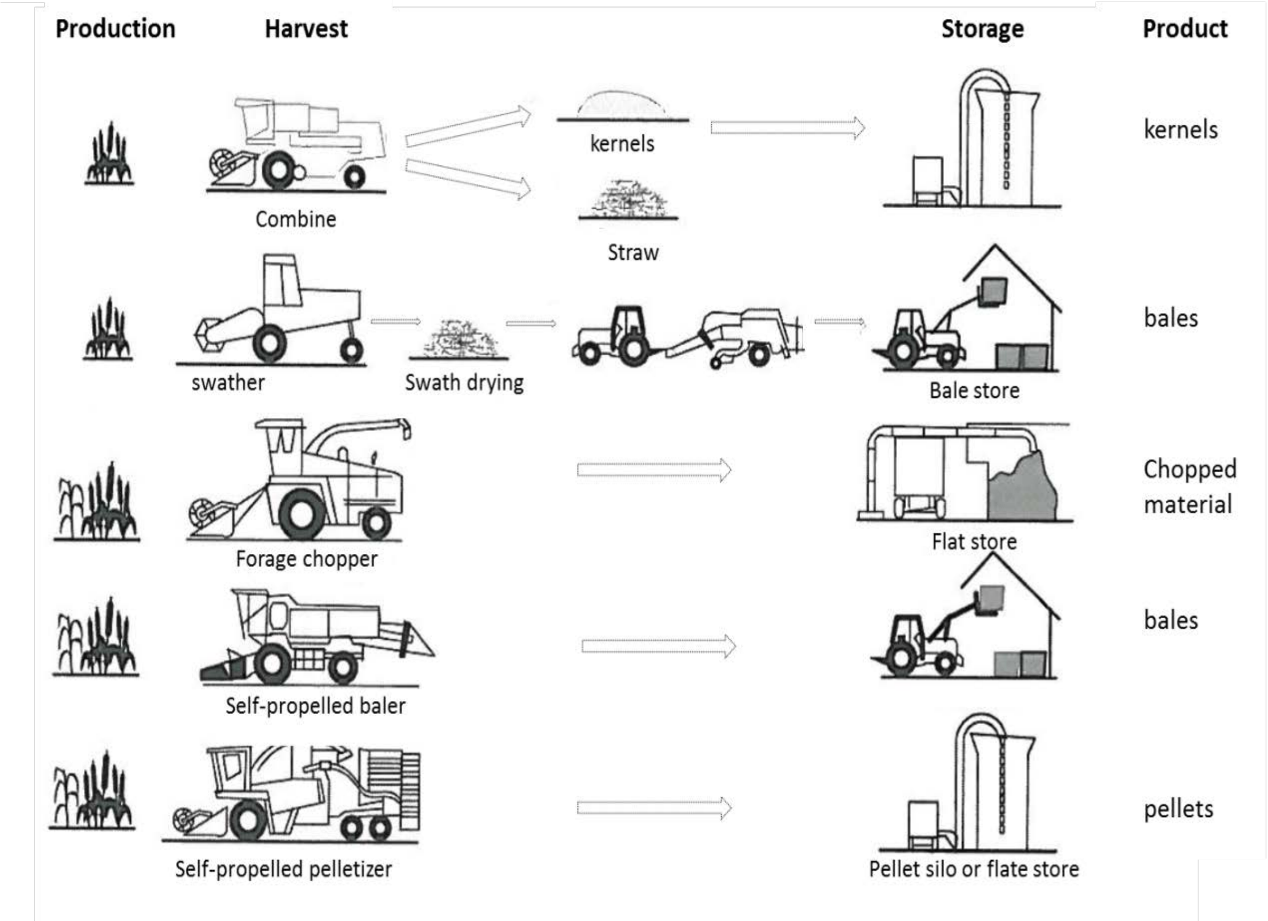

Figure 31. Harvesting processes for herbaceous biomass fuel (van Loo and Koppejan, 2008; Hartmann 1996).

For new energy crops, like Arundo Donax, new strategies have to be developed. Portland General Electric Company has been testing some strategies to collect and bale this material (Lei et al., 2011, http://www.futureenergyconference.com/_uploads/presentations/2011-Seattle/4D-Lei.pdf). The approach Portland General Electric has been testing is swathing, raking and baling using conventional equipment to obtain rectangular bales of 3x4x8 ft(1x1.2x2.4 m) with a weight of 1200 lbs (Bulk density of 12.5 lb/ft^3, 200 kg/m^3) (Figure 32). Another approach could be chopping and field drying similarly to the procedure used for grains. Field drying to obtain moisture less than 15% is also being studied by PGE (Lei et al., 2011).

Figure 32. Production, bailing and on field storage of Arundo Donax used by Portland General Electric. Source: http://www.futureenergyconference.com/_uploads/presentations/2011-Seattle/4D-Lei.pdf

2.5.2. Short Rotation Woody Crops (SRWC)

Short Rotation Woody Crops (SRWC) is defined as woody biomass planted and harvested for energy production (Brown, 2003). Equipment for harvesting SRWC have been developed and optimized in the past years. However, research is needed to prevent soil damage and for reducing capital and operational costs (van Loo and Koppejan, 2008). Commercial equipment that can cut and produce bundles of cut coppice shoots or cut and chip the crop and produce chips or chunks are available (van Loo and Koppejan, 2008). Several methods for harvesting and collecting SRWC are shown in Figure 33.

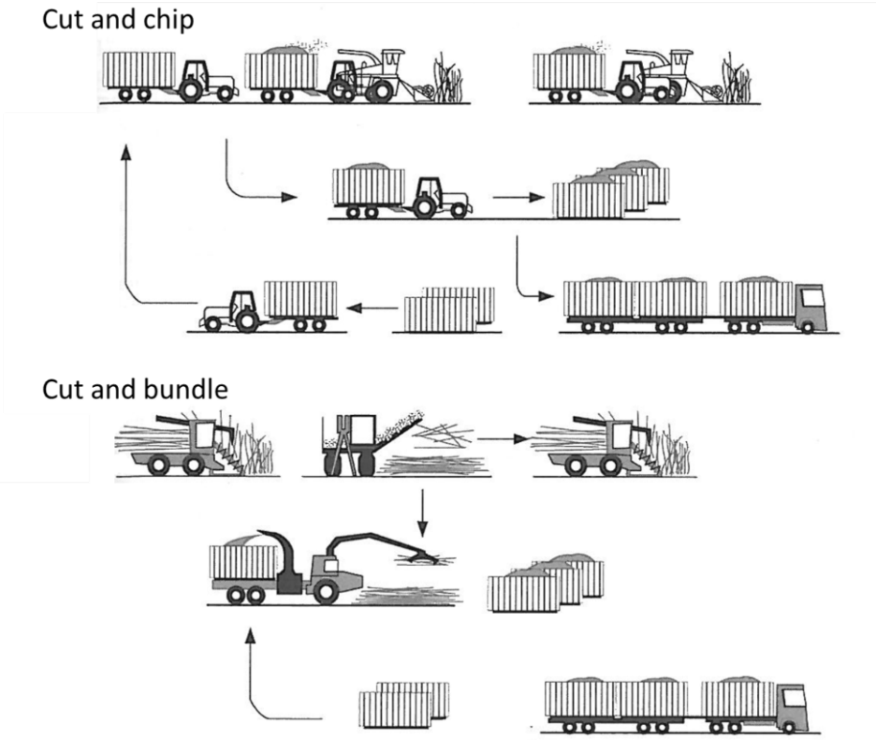

Figure 33. Processes for harvesting short rotation woody crops. (van Loo and Koppejan, 2008, Danfors 1996).

Eucalyptus and hybrid poplar are very good candidates forSRWC in the United States due to theirs high growth rates (20 – 43 Mg/ha/yr) (Brown 203). Of particular significance to the Pacific Northwest region is the production of hybrid poplar. It is a new addition to the Pacific Northwest agricultural economy with over 60,000 acres (24,300 ha) currently in production (Stanton et al., 2002) mostly on land that previously have been hayed and pastured. The lands to be considered for Hybrid Poplar production are those not currently suited for cultivated crops. So far, plantations have been established east of the cascades on well drained, loamy, fine sands in the mid-Columbia River basin typically planted with drip irrigation of up to 40 in (1 m) per growing season and fertilization with nitrogen, phosphorus, zinc and iron. These plantations achieve grow rates of 600 ft^3 per acre per year (42 m^3/ha-year) on six to seven year rotations (37-55 dry tons per acre, 91-136 ton/ha)) (Stanton et al., 2002). Hybrid poplar is also being promoted to soil nutrient content (Burken and Schhnoor 1998). Of particular concern in the Pacific Nothwest are the nutrients derived from animal manure that have been shown to contribute to non-point pollution of ground water and ultimately leading to the degradation of water quality of our aquifers and streams. Hybrid poplar can be integrated into existing manure management systems to utilize nutrients, as a buffer adjacent to environmentally sensitive areas including riparian and wetland areas. Hybrid poplar plantations are also promoted for the potential as carbon sinks. The annual growth of an acre of poplar take up five to eight tons of atmospheric carbon, approximately double the carbon fixed by agronomic crops (Stanton et al., 2002).

2.6 Pellets

Pelletizing biomass can provide a uniformly dense and stable fuel capable of being transported long distances and improving handling efficiency (Uslu et al., 2008). Pellets can be made from pulpwood chips, sawmilling residues (planer shavings and sawdust), harvesting debris or logging residues (tops, limbs, and roots, and forest understory), energy crops, construction and demolition wood and organic fiber waste, land clearing, trimming and natural disaster woody debris (Marinescu and Bush 2009). Pellets are typically a hardened cylinder from 48 to 19.2 mm (3/16 to 3/4 in) in diameter and 12.7 to 25.4 mm (1/2 to 1 in) in length (Figure 34) with a bulk density ranged from 500 to 750 kg/m^3 (31 – 47 lb/ft^3) (Sokhansanj et al., 2006, McKendry 2002).

Figure 34. Wood pellets (source: http://highheatpellets.com/products).

The main steps forming a pelletization process are drying, milling (grinding), conditioning, pelletizing, and cooling (Sokhansanj et al., 2006).

1. *Drying*. Small feedstock particles (maximum 3-20 mm, 1/8 - ¼ in) and moisture content below 10-15 percent are required for the production of pellets. Depending on the type of wood used, the moisture content of the raw material must be between 8 and 12 mass percent before entering the pellet press to avoid material weakening (too wet) and burning the binders (too dry). [Pellets with moisture content up to 20 percent can be produced using a piston press.] Once the optimal moisture content is obtained, mechanical densification is applied at approximately 150 ºC (Uslu et al., 2008, van Loo and Koppejan 2008).
2. *Milling*. Fine grinding mills (centrifuging through a fixed screen and grinding drum) or hammer mills (carbide tipped hammers which sheer the material) are used in order to produce particle sizes below 5 mm. Hammer mills are quite powerful and are less sensitive to small metal parts (e.g. nails) compared to chippers (van Loo and Koppejan 2008). Milling is more energy intensive than chipping.
3. *Conditioning*. In order to improve adhesion, the particles are covered with a thin liquid layer by exposing them to steam (van Loo and Koppejan 2008). Conditioning varies widely based on the operator, the mill, the wood characteristics, etc. in some cases no conditioning is done. Many operators simply condition with steam. Steam preheats the wood so that not all the lignin softening must come from the friction of the die.
4. *Pelletizing*. Flat die or ring die pelletizers are used to create pellets at rates ranging from 100 kg to 10 tons per hour (van Loo and Koppejan 2008).
5. *Cooling*. Pellets leaving the press are carefully cooled in order to guarantee high durability (van Loo and Koppejan 2008). Cooling is required to set the lignin and to create a hard durable pellet.

The entire energy consumption of the pelletizing process is about 2.5 percent of the high heating value (HHV) (excluding drying), and jumps to about 20 percent including drying. National standards for pellets and briquettes have been established by several European countries (Austria, Germany and Sweden) (van Loo and Koppejan 2008). As a rule of thumb, 100 hp are required for every 1 t/h pelletized processed. Pelletization can occur on site with a mobile pelletizing unit (Figure 35). By pelletizing, it is possible to increase the efficiency of MJ/m^3 during the transportation 3 times when comparing with bales transportation (Table 2 using straw as an example).

Figure 35. Transportable pelletizers (IMG Pellets Systems) (Mason et al., 2009).

2.7. Transportation to the Pyrolysis Unit

Trucks are the cheapest mode of local transportation (< 160 km, 99 miles), but rail and / or barge are cheaper modes for long-distance transportation (Sokhansanj et al., 2009). For rail and barge transportation, loading and unloading terminals are a major fixed cost component compared to actual operating costs of loading and unloading. Pyrolysis units with large capacities are best supplied by rail.

Trucks are typically classified as: 1) dump trucks, 2) live-bottom (self-unloading) semi-trailer vans, and 3) standard semi-trailer vans. The capability to "self-unload" is a major advantage (Figure 36) (Badger 2002). Trucks transporting baled materials are seen in Figure 37. Flatbed truck trailers are required to transport bales.

Figure 36. Technology and infrastructure for efficient handling of bulky biomass (http://jcwinnie.biz/wordpress/?p=2813).

Figure 37. Transportation of square bales and transporting of round bales (Sources: http://iowaswitchgrass.com/images /pictures /6qeqatransporting1174900508.jpg and http://farmenergy.org /news/bcap-funding-for-2009-announced).

Biomass typically has a sufficient value to cover transportation costs to a landing or storage area, an investment defined by the distance. The profitable haul distance depends on the conditions of the market for biomass, the price of fuel, the availability of trucks, etc., which are all subject to change on a daily, weekly or monthly basis.

For example, in the USFS Southern Region (R-8) of the United States, a 30-mile haul distance is considered a *profitable haul* distance (Wynsma et al., 2007). Energy consumption for transportation is 4.8 percent to 6.3 percent of the energy content of switchgrass. The energy content consumed during farming is an additional 1 percent (Kumar and Sokhansanj 2007). Market price fluctuations have a continual impact on the biomass that is recoverd.

Once at the pyrolysis unit, the bales are unloaded, stacked, and ground into 6 mm (1/4 in) particles. Grinding the bales can take place onsite or at a centralized facility, inside or outside the pyrolysis plant; however, a distance less than 75 km (47 miles) between the grind location and the pyrolysis plant is ideal (Hess et al., 2006). The possibility of the bales catching fire in a populated area during transportation raises serious safety concerns, and therefore needs to be carefully studied and controlled (Atchison and Hettenhaus 2003). If bales are ground at the farm, the ground material is loaded into a truck box and transported to the pyrolysis unit where it is dumped into piles. A similar process is used to transport pellets (Sokhansanj et al., 2009). Air permits may be required. For example, in Idaho, field grinding operations require no air permits, however, unloading operations are required to control particulates (emissions of < 100/yr qualify an operation for “minor source” status) (Hess et al., 2006). The air permitting requirements for Washington State are presented in a subsequent report.

Appropriate supply chains (for MSW, forest wastes, and agricultural wastes) for the conditions in Washington State need to be developed to control biomass composition for pyrolysis. Of the biomass transportation and storage challenges noted by Tagore and Hess (2005), the most important are to optimize the number of storage locations, to integrate low-cost transportation into the supply chain, and to maintain the integrity of the feedstock. Supply chains must take advantage of existing highway and railroad infrastructure in Washington while avoiding traffic disruption (Atchison and Hettenhaus 2003). The most economical transportation method used for the collection and hauling of biomass involves a collaboration of land owners, farmers, waste collectors and contractors (Wynsma et al., 2007). Cost information and test business propositions for biomass fuel supply contracts need to be developed by potential fuel suppliers and the state (Campbell 2008).

3. From Gate to Pyrolysis Unit: Biomass Storage and Pre-Processing

Equipment and layout of a pyrolysis plant varies depending on the size of the installation, the location, and the type of pyrolysis unit and bio-oil refinery. This section describes important aspects for delivery and reception, pre-processing, and storage of biomass once it has reached the gate of the pyrolysis plant.

Preprocessing configurations depend on the type of biomass received and the capacity and type of reactor used (slow or fast pyrolysis). Weighing and sizing the biomass, removing metals and other noncombustible materials, grinding, and drying are common steps of biomass processing (Figure 38). Intermediate and large-scale handling systems as well as systems for handling dirty fuels are similar to the one in Figure 38 with the addition of one or more whole-truck dumpers. Size reduction is not included since it is not crucial for slow pyrolysis.

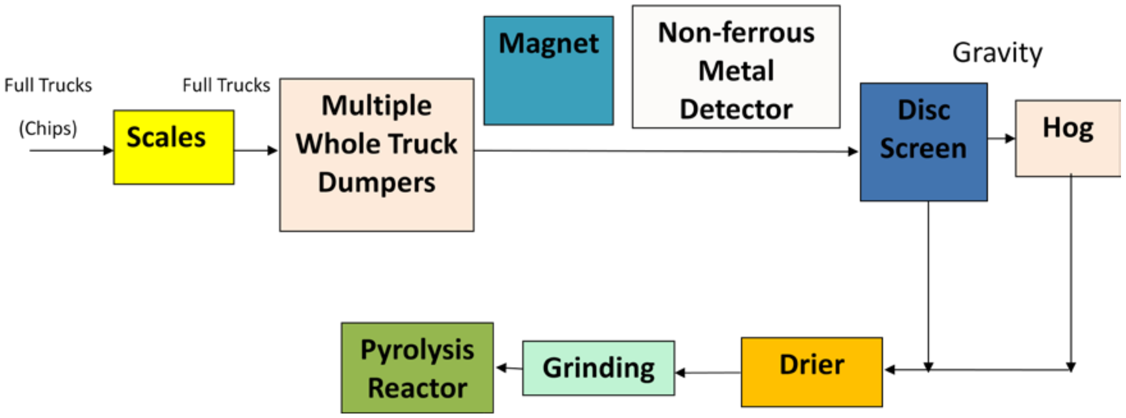

Figure 38. General pre-processing sequence to process chips, pellets, and fine particles (Badger 2002).

Pre-processing including storage and transportation of biomass feedstock takes place in the prep yard, which consists of four major components (Badger 2002): 1) receiving (truck tipper, conveyor, and radial stacker and scale); 2) processing (reclaim feeder, conveyor, metal separator, dryer, screener, and grinder); 3) temporary (buffer) storage (24 hours); and 4) fuel metering (conveyors, meters, and pneumatic transport).

After a truck enters the gate, drive-on scales measure the weight of the biomass load (mechanical scales have lower maintenance costs than electronic) (Badger 2002, Hess et al., 2006). Energy content can be estimated based on the weight and moisture content of the load (van Loo and Koppejan, 2008). After it is weighed, the biomass is then dumped either into a dumper or an area assigned to storage. Enclosing truck unloading and biomass handling operations can minimize dust and moisture issues (Hess et al., 2006). Immediately after dumping, storage is provided by most installations before further processing of the biomass (Badger 2002).

Some of the schemes implemented in Japan to pre-process municipal solid wastes to be converted via slow pyrolysis to generate heat and bio-char are shown in Figure 39. To facilitate the handling and combustion of the material the Municipal solid waste should be received in a form of a refuse derived fuel or separated fractions. Some carbonization installations in Japan receive municipal solid wastes and process it inside the pyrolysis unit (Hwang & Kawamoto, 2010).

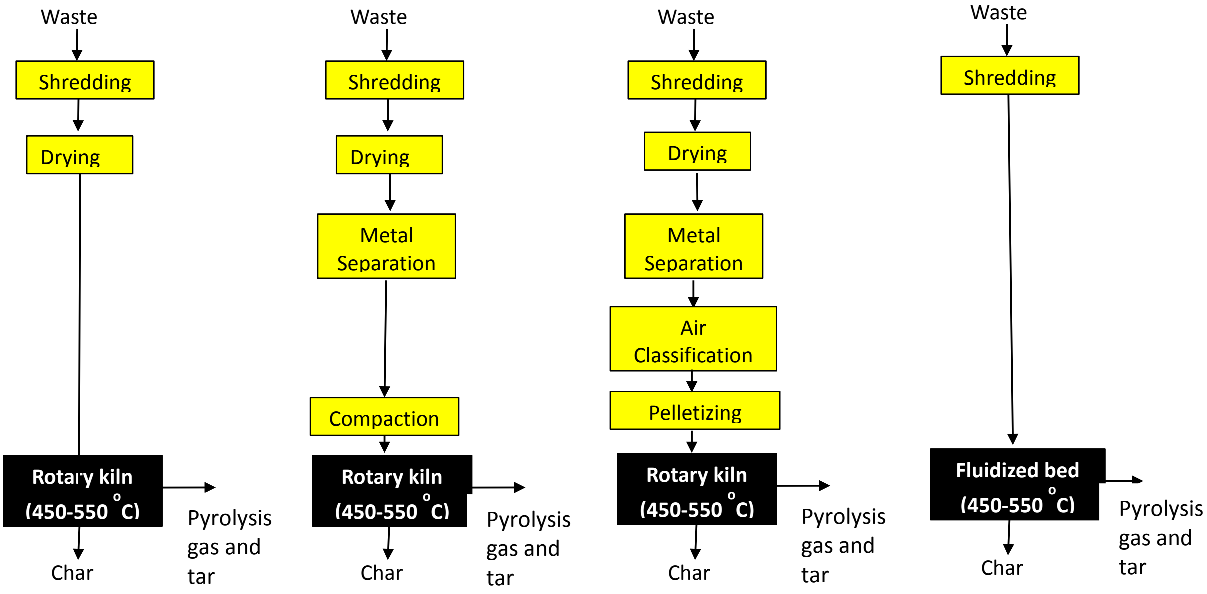

**Figure 39. Waste pretreatment of four carbonization facilities in Japan (Hwang & Kawamoto, 2010) **

3.1 Selection Criteria for Biomass Reception, Storage, and Preparation Systems

Several factors to consider when designing a fuel storage facility (Badger 2002, Schmidt 1991) include:

- the location of the available storage area in relation to the pyrolysis room
- the biomass properties (i.e., particle size, moisture content, etc.)
- additional biomass preparation facilities needed
- reliability of the biomass source
- site weather conditions
- availability of additional personnel.

The size of the storage area should allow for a 30-day supply of biomass in order for the plant to operate during possible supply shortages. Assuming the wood has an average density of 641kg/m^3 (40 lb/ft^3), an area between 1,161 and 8,710 m^2 (0.30 and 2.15 acres) with a height of 3.7 m (12 ft) (for the 100 metric t/day and 680 metric tons/day systems respectively) is required to ensure a 30 day supply. The larger of these two areas (more than two football fields) is required on site for large facilities (Badger 2002). Smaller systems that use mill residues and are located in milder climates require only two to three days of storage, enough for weekends and holidays. Using suppliers located in different directions from the plant, along with using multiple access roads and numerous different wood waste suppliers is one way to mitigate supply disruptions (Badger 2002).

This section highlights criteria for selecting a reactor that is suitable for processing various types of biomass. Many varieties of biomass may need to be reduced in size before processing (van Loo and Koppejan 2008). The particle size and shape of the biomass delivered to the pyrolysis plant also depends on the equipment used during pre-processing. Table 3 summarizes maximum capacity of several reactors, particle shape and size, and moisture content for the most common pyrolysis reactors.

Table 3. Biomass specifications for different pyrolysis reactors (San Miguel et al., 2011).

	Fixed bed	**Fluidized Bed**	**Circulating Bed**	**Ablative Reactor**	**Rotary drum**	**Moving Bed**	**Auger Reactor**
Max. Capacity (t/day)	500	200	100	48	200	84	50
Particle Shape	Logs	Fine particles, pellets	Fine particles, pellets	Sawdust, Chops	Fine particles, pellets, chips, chops	Fine Particles, Pellets, Chips, Chops	Fine Particles, Pellets, Chips, Chops
Particle Size	1-2 m (3-6 ft) long; 3-10 cm (1-4 in) diameter	< 2 mm (1/16 in)	< 2 mm (1/16 in)	3-10 cm (1-4 in) diameter	1-50 mm (1/8-20 in) long	1-50 mm (1/8-20 in) long	1-50 mm (1/8-20 in) long
Feeding Moisture content	10 - 50 %	< 10 %	< 10 %	< 10 %	< 10 %	< 10 %	< 10 %

For example, the moisture content of waste wood or straw is usually below 15 wt. %, while the moisture content of fresh wood is above 50 wt. %. Standing switchgrass can have a moisture content ranging from 40% (late fall) to greater than 70%; and depending on the weather, can drop from 43% to around 10-17% in three to seven days (Sokhansanj et al., 2009). Moisture content of fuel in the storage area should be below 30% in order to avoid problems with dry matter loss and biological degradation during long-term storage of wet biomass fuel (van Loo and Koppejan 2008). Natural drying during storage can prove significant (e.g. reduced moisture in piled logs from 50 to 30 wt. % over summer, straw from several days of drying in the field prior to baling) (van Loo and Koppejan 2008). Moisture content for typical MSW in US ranged from 20 to 30% (El-Fadel et al., 2002; Brunner, 1994).

The various shapes and sizes at which the biomass can be received, the pyrolysis unit capacities, the different storage methods and preparation systems, the various particle sizes that can be fed into the reactor as well as the reactor types and different products obtained are all shown in Table 4. Depending on the machine used to produce the bales, the pyrolysis plants may receive bales of different sizes (Sokhansanj et al., 2006). All of these factors should be considered when selecting the layout to be used for the pyrolysis unit.

Table 4. Biomass reception, storage and pre-treatment factors for MSW, forest and agricultural wastes. Each column represents the gradient of possible conditions or outcomes for each factor.

Type	Raw size of biomass unit	Installation size (plant capacity)	Storage	Biomass preparation	Other pretreatment	Biomass size fed to the pyrolysis reactor	Reactor type	Final products
Bales	Small rectangular: 0.4x0.4 x0.1 m (16x16x4 in)	Very small (< 10 t/day)	Silos	Drying	Torrefaction	1-2 m (3-6 ft) length <2 mm (5/64 in)	Fixed bed	Bio-oil
	Large rectangular: 0.9x1.2.x2.4 m (3x4x8 ft)		Bunkers				Fluidized bed	
	Round: 1.5 m (5 ft) wide by 1.8 m (6 ft) diameter	Small (10 – 50 t/day)	Enclosed metal storage bin			< 2 mm (5/64 in)	Circulating bed	Syn-Gas
Chops	25-50 mm (1-2 in)		Live-botton delivery trucks	Size reduction	Removing alkaline cations			
Wood Chips	25x25 mm (1x2 in)	Intermediate (50 – 100 t/day)				3-10 cm (1 1/8-4 in) length	Ablative auger	Biochar
Logs	0.5-2 m Length (20-78 in)	Large (>100 t/day)	Covered storage systems					
Fine Particles	0.5 – 6 mm (1/64x ¼ in)		Radial stacker loader			1-50 mm (1/32-2 in)	Rotary drums	
Pellets	4.8-19 x 12.7-25.4 mm (3/16 – ¾ x ½ - 1 in)	Large (> 100 t/day)	Open uncovered piles	Screening	Adding Additives		Moving beds	Heat

The appropriate delivery and feeding systems for different pyrolysis reactors should be selected using criteria listed in Table 5.

Table 5. Suitable fuel-feeding systems according to shape and particles size of the biomass fuel (van Loo and Koppejan 2008).

Material shape	Maximum particle size	Delivery system	Pyrolysis technology
Bulk material	< 5 mm (3/16 in)	Direct injection, pneumatic conveyors	Circulating Fluidized Bed (CFB)
Bulk material	< 50 mm (2 in)	Screw conveyors, belt conveyors	Grate furnaces, Bubbling Fluidized Bed (BFB), CFB
Bulk material	< 100 mm (4 in)	Vibro conveyors, chain through conveyors, hydraulic piston feeder	Grate , BFB
Bulk material	< 500 mm (20 in)	Sliding bar conveyors, chain through conveyors	Grate furnace, BFB
Shredded or cut bales	< 50 mm (2 in)	Cutters/shredders followed by pneumatic conveyors, screw conveyors or belt conveyors.	Grate furnace, BFB, CFB
Bales, sliced bales	Whole bales	Cranes, hydraulic piston feeders.	Grate furnaces, cigar burners
Pellets	< 30 mm (1 ¼)	Screw conveyors, belt conveyors	Grate furnaces, BFB, CFB
Briquettes	< 120 mm (3/16 in)	Sliding bar conveyors, chain through conveyors	Grate furnaces, BFB

3.2 Delivery and Reception

Biomass delivery and receiving methods vary according to installation size: small, intermediate, and large. *Small units* (10 to 50 t/day) use self-unloading semi-trailer vans and are often mobile units located near biomass resources. *Intermediate installations* (50 – 100 t/day) increase capacity by adding a light-duty, frame-tilt hydraulic dumper for unloading the fuel and front-end loaders or bulldozers. *Large installations* (> 100 t/day) use hydraulic dumpers that tilt an *entire* truck to an angle of 75° to empty the total load in minutes and then fuel is conveyed from concrete pad to woodpile using a live-bottom receiving hopper and stacked with an automated storage radial stacker (Badger 2002). Figure 40 shows an older, 200 t/day pyrolysis plant (Bunbury 1923). The factory shown had twelve retorts, each pyrolyzing about 15 t per day. Larger capacity plants may be challenged to collect enough biomass to operate throughout an entire year (Badger 2002). Other considerations for storage facilities include onsite truck refueling, a Storm Water Pollution Prevention Plan (Hess et al., 2006), and a rail capacity for large systems (Badger 2002) and air emission controls.

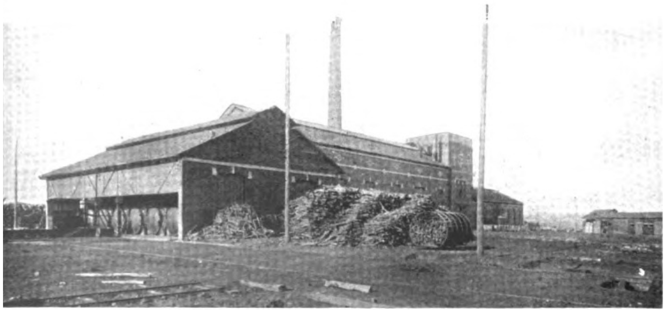

Figure 40. Older 200 t/day pyrolysis plant (12 retorts, each distilling 15 t/day) (Bunbury 1923).

Clearly defined reception procedures are essential to ensure suitable quality biomass, including minimization of contaminants (sand, earth or stones) and appropriate particle size (Badger 2002, Van Loo and Koppejan 2008). A visual inspection of the biomass at reception and a laboratory to collect and analyze samples are necessary (Hess et al., 2006). Assessments and payments (or penalties) for biomass based on energy content and quality (ash content and cellulose and lignin content) may be helpful in ensuring quality control on delivered biomass (Van Loo and Koppejan 2008).

3.3. Storage

Storage systems are critical to ensure that pyrolysis facilities, which are expensive to operate, are not idle during any part of the year. If biomass is exposed to the elements after harvest, a majority of it will rapidly degrade (Brown 2003). Several common fuel storage facilities include: open, uncovered piles; sheds with partial cover; indoor storage; and enclosed storage bins such as silos and bunkers. Enclosed bins (hoppers, silos or bunkers) are more likely to be used for small installations as they provide increased protection for small quantities of fuel. Enclosed bins are also used where storage space is minimal or where pollution regulations require them. Unless climate conditions dictate covered storage, the greatest storage volume for the lowest cost is achieved by using open, uncovered piles. Appendix A describes covered and uncovered storage systems in further detail.

3.4. Conveyance of Fuel from Storage to Processing

Fuel can be moved by a number of different methods including cranes, wheel loaders, belt and screw conveyance, bucket elevators and pneumatic transport. Methods for retrieving fuel from storage depend on the method of storage, the volume to be moved, the cost of the retrieval systems as well as the operating and maintenance requirements. Additional criteria specified by van Loo and Koppejan (2008) include:

- Fuel characteristics (particle form and size distribution; and moisture content)
- Transportation distance
- Managing height differences
- Duct explosion and fire risks
- Transportation capacity
- Cost of operation, maintenance, and investments
- Feeding and handling systems.

Conveyance systems are described further in Appendix B.

3.5. Metal, Stone and Dirt Removal

Removing metal and other debris early on in the fuel preparation process can prevent equipment damage. Various types of magnets can remove ferrous metals. A stationary magnet mounted above a conveyor can be used to remove occasional ferrous tramp metals. In order to facilitate the removal of the extracted metals from the magnet, a metal or canvas plate attached between the magnet and the conveyor is used. Selfcleaning magnets operate using a magnet conveyor system. These magnets are mounted between the belts of a rapidly moving conveyor positioned above and perpendicular to the wood conveyor, thus, any metals attracted to the magnet are carried to the side by the magnet's conveyor. Typically, this style of magnet is found in applications with excessive loadings of ferrous metals, like at wood recycling centers (e.g. recycling pallets). They are not usually found at biomass processing plants since the wood received at this point should be mostly free of metals (Badger 2002).

The removal of non-ferrous metals involves the use of a non-ferrous metal detector. Once detected, the conveyor is stopped so the operator can visually identify and remove the metal. Detectors must be located on the conveyor since they operate on the eddy-current principle and the metal frame of the conveyor would otherwise interfere with its operation. Occasionally, detectors are mounted on a plastic section added to the conveyor bottom to prevent any interference with the metal frame (Badger 2002).

Despite the various types of equipment to remove stones and dirt from wood residues, very few facilities have them. Most facilities instead rely on their contract with the fuel supplier, which dictates the absence of stones and debris to ensure clean fuel. This could be a significant constraint on pyrolysis facilities set up to process MSW.

3.6. Size Reduction

Using shear, impact, or attrition, biomass can be reduced to the desired size (Naimi 2006, 2008). The size reduction of wood particles can be accomplished using a device called a "hog". Knife chippers and hammer-mills (Figure 41) are two of the most common devices used for comminuting biomass to the appropriate size for thermochemical conversion. The following attributes must be considered when choosing a hog (Badger 2002, Makansi 1980):

- Both the maximum and average quantity of wood waste to be processed;
- The maximum size of the incoming particle;
- The product particle size required; and
- Any special design considerations that may be required by the nature of the wood waste.

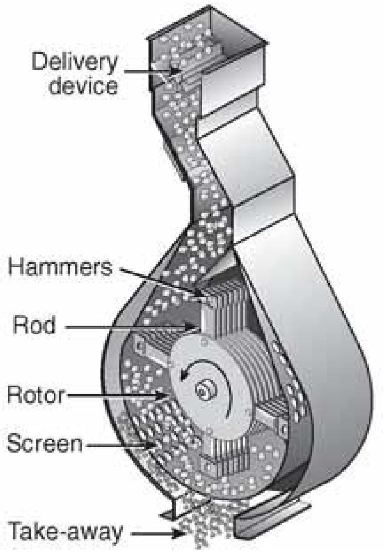

Figure 41. Cross-section of a hammer mill (http://www.feedmachinery.com/glossary/hammer_mill.php).

Chippers are better suited for grinding wood and use a high-speed rotary device that operates at speeds up to 1800 rpm. The wood is broken into smaller pieces once it enters the cavity which houses a rotating cylinder where stationary and rotating cutting blades are attached to the cylinder (Cummer and Brown 2002).

Hammer mills also use a rotary device to reduce the size of material. As the biomass descends through the hammer mill, large pieces are crushed against a breaker plate by spinning hammers. The screen at the base of the hammer mill determines the size of the final comminuted particles. Most hammer mills are capable of grinding biomass to a size small enough to pass a No. 30 sieve (Cummer and Brown 2002). Hammer mills operate most efficiently when the initial feedstock entering is less than 4 cm (1.5 in). Typically, an auxiliary crusher is necessary in order to meet this requirement (Cummer and Brown 2002). Hammer mills utilize electric motors ranging from 75 to 220 kW that operate at a high torque and high speed and usually drive a horizontal shaft and swing-hammer. They typically produce biomass at a rate of 20-55 t/hr with particle sizes in the range of 25-125 mm (1-5 in). However, they are limited to the use of dry wood only (Donovan, 1994, Badger 2002). Excessive fines should be avoided because it creates a dusty environment (Miles 2011).

Size reduction of grasses has some unique features. Bitra et al., (2009a, b) examined the effect of knife mill operating factors on particle size distribution of switchgrass and concluded that the knife mill screen size was the controlling factor in determining the particle size of switchgrass chops. Altering the feeding rate and speed showed only a moderate effect on the particle size distribution of the material. The Rosin-Rammler equation best describes the size distribution of the chopped switchgrass (Bitra et al., 2009). The knife mill energy requirements for the comminution of several biomasses: miscanthus, switchgrass, willow and energy cane was studied by Miao et al., (2011). An instrumented hammer mill used by Bitra et al., (2009) measured the mechanical energy consumed in grinding switchgrass, wheat straw, and corn stover. The particle size distribution obtained with these mills was also studied by the same group (Bitra et al., 2008). The size distribution of this data was well fit by the Rosin-Rammler equation. For the production of a particular size of switchgrass, wheat straw, and corn stover, the application of the data reported by Bitra et al., (2008) should be included to the factors for the selection of a hammer mill. The energy requirements for the comminution of several feedstocks (miscanthus, switchgrass, willow and energy cane) studied by Miao et al., (2011) as well as studies carried out by Bitra et al., (2009) were done using a commercial-scale hammer mill. Both studies concluded that the hammer mill was more efficient than the knife mill given a specific milling screen. Grinding tends to be difficult especially on bark (Miles 2011)

3.7. Screening

Screens are used to size feedstock particles by allowing only certain particles to pass through, decreasing energy consumption and wear on the hog. Other methods to ensure proper material size include floatation which uses buoyancy, and air classification which relies on pneumatic principals to separate different material sizes (Cummer and Brown 2002).

Oscillating, or shaker deck screens (Figure 42), disc screens (Figure 43) and drum screens (Figure 44) are commonly used and horizontal or inclined deck screens are less commonly used. In order to increase screening capabilities, the use of multiple screen levels may be implemented. Depending on the wood characteristics and the type and size of deck, outputs from oscillating screens can vary significantly (Donovan 1994). Oscillating screens are not suitable for wet materials and require frequent maintenance (Badger 2002). The disc screen, which consists of a series of rapidly rotating disks (typically 55-65 rpm) mounted on several parallel horizontal rotating shafts, is the most common screen used for energy applications (Makansi 1980). The disks interlace with each other as they are equally spaced apart on each shaft, and the rotating shafts are offset from one another. The material is assisted across the surface formed of the tops of these disks which are either slightly star-shaped or consist of fingers to help grab the material and move it (Badger 2002).

Figure 42. Oscillating screen used to separate different sized biomass (http://www.sf-gmbh.de/screening-plants/oscillation-screening-machines/?album=5&gallery=62 &nggpage=2).

Figure 43. Disc screen used to separate different sized biomass (http://greenbd.info/screen+wood+chips/).

Figure 44. Screening equipment (Courtesy of the WA Department of Ecology)

3.8. Drying

Feedstock must be properly dried to ensure reliable and consistent feeding as well as to optimize gasification products. Biomass with moisture content below 10 percent is ideal for pyrolysis. Some forms of sizing equipment may require the feedstock to be dry, while some dryers may require the feedstock to be sized prior to drying. Several stages of drying and sizing may be necessary to achieve desired moisture content and size (Cummer and Brown 2002). Moisture can exist as free water within the pores of the plant material, or as bound water absorbed in the interior structure of the material. Drying biomass also removes enough moisture to prevent degradation and mass loss from microorganism growth. Drying is a very energy intensive process (Brown 2003) and reduces the overall efficiency of a plant due to the large amounts of thermal energy required (Cummer and Brown 2002). Due to the importance of drying in the pyrolysis process, drying is address in further detail in Appendix C.

3.9. Torrefaction

Torrefaction is a thermal pretreatment technology which is carried out at atmospheric pressure with the absence of oxygen at temperatures between 200 and 300 °C. The result is a solid uniform product with very low moisture content and a high calorific value (Uslu et al., 2008). In the pretreatment process, torrefaction takes place after drying but before grinding and pyrolysis (Figure 45). Torrefaction uses a reactor similar to that used for pyrolysis of biomass. It can be conducted in the pyrolysis reactor or in an additional reactor.

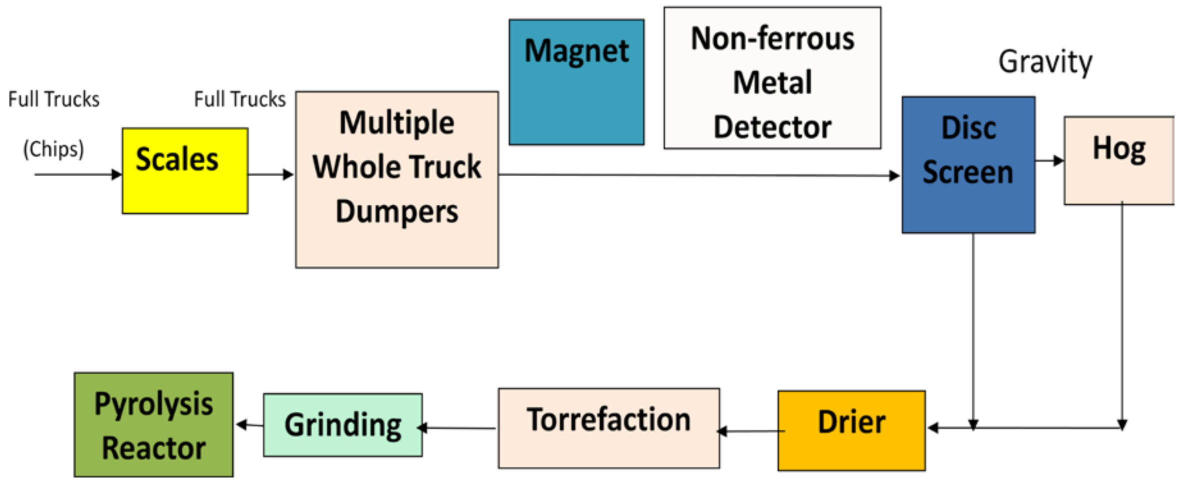

Figure 45. Biomass pretreatment system, including torrefaction, for a fast pyrolysis unit.

Biomass loses its mechanical strength during torrefaction and becomes easier to grind or pulverize (Uslu et al., 2008). Torrefaction can reduce the energy required for size reduction by up to 70-90 %, compared to conventional grinding (Figure 46) (Uslu et al., 2008, van der Drift et al., 2004).

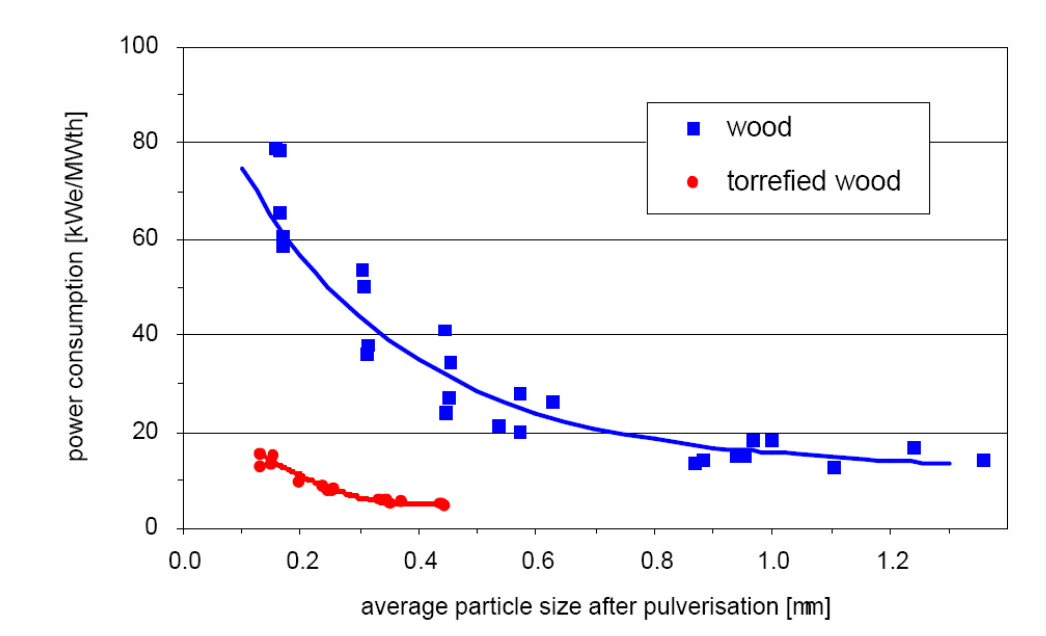

Figure 46. Size reduction power consumption for untreated wood and torrefied wood (Van de Drift 2004).

Torrefaction increases the energy density, hydrophobic nature, and grindability of the pretreated biomass (Van de Drift 2004). Biomass that has been torrefied contains 70 percent of its original weight and 90 percent of its original energy content. Torrefied biomass has a limited moisture uptake (1-6%) (Uslu et al., 2008) as it loses its capacity to form hydrogen bonds with water due to the destruction of OH groups caused by dehydration reactions. The torrefied biomass also becomes hydrophobic due to the formation of non-polar unsaturated structures. Depending on the initial biomass density and the torrefaction conditions, the torrefied biomass may become porous with a volumetric density of 180-300 kg/ m^3(11 – 19 lb/ft^3)

3.10. Removing Alkaline Cations for Fast Pyrolysis

High ash content (mainly alkalines cations, potassium, sodium, calcium and magnesium) in herbaceous crops (corn stover, wheat straw, etc) negatively influence the pyrolysis process for bio-oil production when compared to woody energy crops (Van loo and Koppejan 2008). The ash catalyses bio-char formation, so high ash content may be desirable is the main purpose is to produce heat and bio-char. The presence of alkaline cations in biomass during fast pyrolysis can affect thermal decomposition by causing primary fragmentation of the monomers that make up natural polymer chains, rather than the predominant depolymerization that takes place in their absence. As a result, quite different compositions of liquid products (bio-oils) are obtained which may be used for a variety of different purposes. Extensive research has been done on the mechanism changes that occur due to the absence and presence of alkaline cations during fast pyrolysis (Mourant et al., 2011). The resulting compositional changes in the bio-oil produced have also been studied (Scott et al., 2001). The principal effect of removing alkaline or alkaline earth cations for fast pyrolysis is to produce an anhydrosugar rich liquid. These anhydrosugars are principally levoglucosan (anhydroglucose) and anhydropentoses (Scott et al., 2001).Levoglucosan yields decrease as the content of alkalines increases.

Most alkaline cations can readily be removed from biomass using a dilute acid. A hot water wash can readily remove most potassium and some calcium present in biomass. However, an ion exchange is required for a high degree of removal of much of the calcium and a minor amount of the potassium. Hence, two forms of these cations appear to be present in the wood, possibly soluble salts and cations bound to reactive sites in the wood, most likely functionalities of cellulose or acid groups found in other biomass components. The effect of temperature appears to be minor if any. Cellulose and other biomass components would be expected to readily exchange cations with a strong acid because they can function as weak ion exchangers in this case. Thus, a majority of the ion exchange occurs at less than two residence times before a breakthrough of acid (Scott et al., 2001). All known wet methods for cation removal are very costly because the biomass will need to be dried before it can be pyrolysed.

Recently the group of Professor Robert Brown at Iowa State University (Brown 2011) has proven that the catalytic effect of alkaline cations can be passivated through pretreatments by adding small amounts of acids. The passivation effect was explained by the formation of stable salts. They proved that there is a correlation between the amount of minerals in biomass and the amount of acids required to achieve the maximum yields of levoglucosan (Brown 2011). In this way, polycondensation reactions responsible for bio-char formation can be minimized, and the yield of some precursors of transportation fuels (like levoglucosan) increased.

4. Conclusions

The main reasons for the large number of alternative concepts to harvest, collect, dry, densify, store and feed biomass materials into pyrolysis reactors stems from the diversity of the waste materials generated in the state and the large number of potential pyrolysis technologies that can be used.

Little has been published about the supply chain and quality standards for the biomass supplied to pyrolysis units despite the quality documentation of the characteristics and properties of the waste biomass resources available in the state. The impact of a pretreatment method and a chosen supply chain on the properties (particle size, moisture content, ash content) of the feedstock to be pyrolysed and how these affect the yield and quality of the products obtained via slow and fast pyrolysis should be more thoroughly studied.

The chain of equipment and operations needed to collect, separate, densify, and transport waste and biomass materials available in Washington State to the gate of potential pyrolysis units are well known. What is not known is the effect that these operations will have on the composition of the materials that will be pyrolysed and the effect of these compositional changes could have on the yield and characteristics of the bio-oil and bio-char produced. This is a developing area that needs to be studied more carefully.

There is enough information available in the literature regarding the conversion of biomass in slow or fast pyrolysis reactors to propose rational schemes for the preprocessing of the woody fraction of MSW and the agricultural wastes generated in our state. While the particle size and moisture content of the biomass will be controlled by the pretreatment scheme chosen, uniform particle size and low moisture content are desirable. Moisture should be held in the range of 8 to 12 mass % for pelletizing and no more than 15 % for fast pyrolysis. Investigations are ongoing into the chemical and ecological attributes of bio-char which include processes to create engineered bio-char with specific capabilities that will enhance environmental cleanup and ecological function. The affect of grinding and feedstock preparation (such as pelleting) on the physical attributes of bio-char need to be considered. Further assessment is needed in the use of torrefaction as a pre-treatment scheme to reduce grinding energy. The affect of washing or use of acid additive to passivate the undesirable catalytic effects of alkalines on both the bio-oil and the bio-char should be more thoroughly studied.

Pre-processing MSW (shredding, metal separation, drying, classification, compaction, etc) is an activity that has been increasing in the last few years due to the increment of Municipal Recovery Facilities. Similar pre-processing operations are used in the wood industry and in the biomass handling in biomass power generation facilities. Equipment from agriculture and forest systems can be applied to MSW but documentation is limited. A comparative study should be done in order to optimize MSW pre-processing steps to obtain fractions that can be processed via fast or slow pyrolysis.

Appendix A: Storage

Improper storage leads to high biomass loss. One of the sources of biomass loss is the microbial decomposition that occurs in the presence of high moisture content, oxygen availability and specific temperature conditions (Diaz et al., 1994). When the biomass in baled, in the absence of enclosed storage, penetration of a round bale by rain and melting snow or water wicking up into the bottom of the bale from the soil results in loss. When the bales do not have time to dry between storms (i.e. in winter) the water is allowed to soak deeper and deeper into the bales developing the most losses (Rayburn, 2011). The storage losses based on the form in which the biomass is presented are shown in Table A1.

Table A1. Large round hay bale losses affected by storage method (Rayburn 2011)

Storage	Dry Matter (Loss Range) (wt. %)	Average (wt. %)
Barn	3-8	5
Additional losses with outside storage		
Covered on pallet	5-10	8
Uncovered on pallet	28-39	34
Uncovered on gravel	4-46	22
Uncovered on ground	7-61	33

Uncovered Storage

Unless climate conditions dictate covered storage, the greatest storage volume for the lowest cost is achieved by using open, uncovered piles. Uncovered storage systems can be used to store bales of herbaceous materials and logs (Figure A1). Baled woody biomass can be stored outdoors because it tends not to degrade biologically and is less sensitive to moisture absorption. Sloped storage pads, typically composed of concrete (front-end loaders can gouge asphalt), facilitate runoff and prevent introduction of rocks and soil to the pile (Badger 2002). It is not necessary to provide roofing for the intermediate storage stage. However, long-term storage of woodchips and bark with a moisture content >20-30 wt. % can result in heat from biological and biochemical degradation and in some instances chemical oxidation and self-ignition (Van Loo and Koppejan 2008). A general view of a wood yard is seen in Figure A1 (Bunbury 1923).

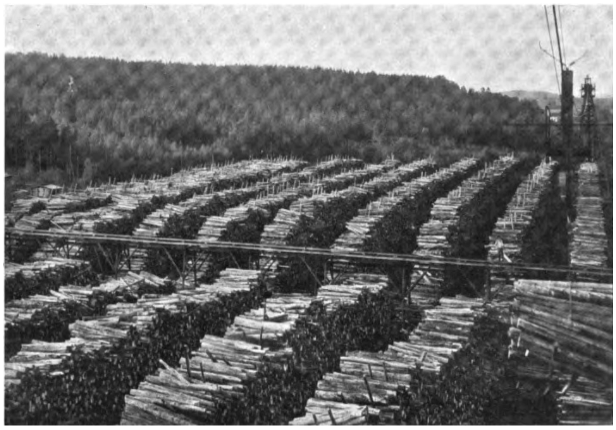

Figure A1. Bale and log storage (http://roadshow2010en.blogspot.com/2010/07/ washington-sunny-time-in-sunnyside.html) (Bunbury 1923)

The length of the woodchips stored in a pile impacts temperature, drying, mold formation and mass and energy loss during long-term storage (van Loo and Koppejan 2008). Longer woodchips result in decreased pile temperature, moisture content, dry mass loss, and energy loss (van Loo and Koppejan 2008). Longer woodchips also show a decrease in the amount of thermophile mold. Energy loss is the most important parameter with regard to thermal utilization. Energy loss amounts to anywhere from 20-30% per year for fine woodchips (Mean diameter16 mm, 5/8 in). Due to a lower dry loss and the reduction of moisture content during storage, this loss is anywhere between +/- 5% for coarse woodchips (mean diameter >120 mm, 5 in). In order to minimize energy loss and mold formation, woodchips should have a minimum average length of 100 mm (4 in). If medium or fine woodchips must be stored in a pile, the minimization of mold formation can be achieved by limiting storage to less than two weeks (van Loo and Koppejan 2008). The retrieval of fuel from large open piles or open shed storage systems is usually performed using front-end loaders (Figure A2).

Figure A2. Storage for wood chip bio-fuel (http://www.dreamstime.com/ item.php?imageid=7026729).

Temperatures in piles of fresh wood chips or bark typically rise to around 60 ^{o}C within the first day sometimes leading to self-ignition, whereas no temperature increase is experienced when storing particles of 20 mm (1 in) or greater (Van Loo and Koppejan 2008). Self-ignition can also be reduced by keeping pile height <8 m (26 ft), storing less than five months and reducing compaction (Van Loo and Koppejan 2008).

Radial stacker: Some smaller and intermediate scale storage systems use a radial stacker loader system. A linear pyramid-shaped woodchip pile in the form of an arc is produced using a cleared belt conveyor with an anchor point at its lower end allowing it to pivot, and a frame on wheels allowing the inclined conveyor to swing in a 175 degree arc (Figure A3). The conveyor to the radial stacker comes from either the truck dump or disc scalping-hog operation. Conveyors with a 20 degree incline maximum and a length of 15 to 20 m (49 to 65 ft) are available. Up to 900 tons of wood can be stored using a radial stacker loader with a 15 m (49 ft) belt and a discharge height of 7.5 m (25 ft) (Badger 2002).

Figure A3. Radial stackers (Source: http://www.ports.co.za/news/article_2008_04_13_1946.html).

Covered Storage

Covered storage systems include plastic or canvas, indoor storage, silos, and bunkers.

Plastic or Canvas Cover. Plastic is a very cost effective covering, but has several drawbacks. It does not "breathe" and can result in the development of mold and excessive heating which can lead to high losses and poor forage quality if moisture content is high (> 20%). Reinforced plastic can last over three years with proper handling and storage, and it is able to better withstand punctures and tears (Huhnke 2011). Covers used to protect material in stored concrete bunkers are seen in Figure A4.

Figure A4. Covered material in concrete bunkers (source: http://www.hansonsilo.com/precast .php)

Large round bales stored outside and covered with plastic or canvas will sustain much less deterioration. Storage configuration is critical to improving efficiency in storage material use (Huhnke 2011). The upper layer of a bale can be protected when covered with a tarpaulin though the lower layer will remain exposed to moisture. Better protection is provided by facilities with flying roofs (retractable roofs, or sliding roof) since only the top bales are exposed to moisture.

Indoor Storage: Despite the lower cost that represents the uncovered storage, depending on weather conditions, it is necessary to use indoor storage. Although indoor storage is expensive, it is the best option for maintaining the quality of baled biomass (Figure A5). Square bales are less expensive to store due to better volume utilization (Van Loo and Koppejan 2008).

Open shed systems allow for easiest access when using front-end loaders, the least expensive method for moving fuel (Badger 2002). However, losses of up to 10 percent can occur when storing bales in an open-sided barn (roof only) for over a year. To minimize dry matter loss and to maintain good hay color (a visual indicator of quality), most commercial hay producers use enclosed barns with no more than one open side. The storage space should be open and clear to eliminate working around interior columns. Any new construction should take place on a well-drained site (Huhnke 2011).

Figure A5. Indoor storage for chips (left) and bales (right). (Sources: http://www.greenhousecanada.com/ content/view /2589/62/ and http://iowaswitchgrass.com /cofiringcycle~ transporting.html, respectively).

All large, round bales have protection benefits. However, several factors must be considered to justify the cost of providing this type of protection including: the value of the material, projected storage losses, local environmental conditions, and where the material is to be used (Huhnke 2011). Particular building designs work best for round bale storage. The interior height clearance should be at least two feet higher than the finished stack height for any form of bale (Huhnke 2011).

Silos: Silos are vertical cylinders ranging in height from 2 to 2.5 times the diameter (Figure A6). Silos may be constructed of metal, concrete stave and ring, or poured concrete. It is generally more cost effective to use steel for silos with diameters 6.5 - 12 m (21-39 ft), and concrete for silos with diameters > 15 m (49 ft) (Badger 2002). Silos require minimal space and provide ease of fuel retrieval.

Figure A6. Silo for wood chips (source: http://www.columbiantectank.com/ app_cat _sub_show.asp?id=23).

Unless carefully designed, silos are subject to bridging and "ratholing" (Schmidt 1991). To prevent bridging, silos are usually equipped with agitators such as chain flails or augers since most wood fuels have poor flow characteristics. Freezing of wet or green fuels stored in silos may occur resulting in the fuel adhering to the silo wall. Constructing the silo so its lower 6 m (20 ft) are within a heated building is one method to minimize freezing problems (Badger 2002).

To avoid dust emissions, sawdust and fine wood waste is stored in closed silos up to 40 m high and 15 m (49 ft) in diameter. Rotating screws or inclined screws with agitators are often used to automatically discharge these silos (Van Loo and Koppejan 2008, Hess et al., 2006).

Bunkers. Bunkers are buried rectangular concrete structures with the top at ground level that can be used with wet or dry fuels. The burial of the bunker facilitates truck unloading directly into the bunker and minimizes fuel-freezing. Bunkers utilize a live-bottom for fuel removal (Badger 2002).

Appendix B: Conveyance Systems

Crane systems (Figure B1) allow for a fully automatic operation and work best with woodchips, pellets, or bales, but can cause a high degree of heterogeneous particle sizes (i.e. they are not recommended for mixtures of bark, sawdust and woodchips).

Figure B1. Cranes used for handling bales in power stations (http://warehousenews.co.uk /?p=6326).

The easiest and most flexible way of handling nearly all kinds of bulk materials (sawdust, woodchips, bark or waste wood) is with the use of *wheel loaders* (Figure B2). The bucket of a wheel loader can hold up to 5 m^3 (176 ft^3). Wheel loaders require personnel, making a fully automatic plant operation impossible (van Loo and Koppejan 2008).

Figure B2. Bales loaded on a conveyor using a wheel loader (http://iowaswitchgrass.com/cofiringcycle ~processing.html).

Belt conveyors are the most efficient way to move large quantities of bulk material inside the plant (Figure B3) (Hess et al., 2006). Belt conveyors are simple and inexpensive to construct and allow for installation of a conveyor belt weighing system. However, avoiding dust emissions can be costly, they are not suitable for inclined conveyance, and they are sensitive to external influences like the accumulation of dirt on the pulleys and temperature changes (Van Loo and Koppejan 2008).\

Figure B3. Moving material by a belt conveyor (Atchison and Hettenhaus 2003).

Bucket elevators convey material vertically to a height up to 40 m (131 ft) with a capacity of up to 400 tons per hour. However, bucket dimensions limit the particle size of the material to be transported (Badger 2002). Transporting sized fuel long distances can be done effectively using *pneumatic transporting methods*. Despite the high-energy consumption required to generate the necessary air pressure, the capital costs are fairly low (Badger 2003).

Chain conveyor systems (trough conveyor or a scraping conveyor) are highly flexible systems for transporting bark and sawdust for horizontal or inclined transport up to 90° (Van Loo and Koppejan 2008). However, relatively high power demand, low conveying capacity (due to a low hauling speed), and a great deal of wear to the chain and coating of the trough during operation are disadvantages of this system (Badger 2003, Van Loo and Koppejan 2008).

Rubber tube belt conveyors can help reduce dust emissions for distances up to 2,000 meters (1.24 miles) (Badger 2003, Van Loo and Koppejan 2008).

Screw conveyors (Figure B4) are relatively cheap and have small dimensions and reduce dust emissions. They are typically used to transport fuel particles < 50 mm (2 in) over short distances. Disadvantages include a relatively high power demand, sensitivity to mineral impurities and metals in the fuel, and malfunction caused by pieces of stones or metal. Another disadvantage of these conveyors is that they are not suitable for the transportation of bark that is stringy. They are recommended for fuels with well defined particle sizes that are relatively fine and clean (Badger 2002, Van Loo and Koppejan 2008).

Figure B4. Screw conveyor (http://www.indiamart.com/malindustries/heavy-structural-machinery.html)

Appendix C: Drying

Energy Considerations: Drying is a very energy intensive process, theoretically requiring 2,442 kJ of energy per every kilogram (1,110 kJ/lb) of moisture removed at 25 ^{o}C. In practice, drying is often performed at a temperature slightly higher than 100 ^{o}C which requires about 50 % more thermal energy than theoretical consumption due to both the sensible heat of the biomass and air used. To dry one ton of biomass at 50 percent moisture down to 10 percent moisture, which represents about 18 percent of the total energy content of the fresh biomass, requires about 1.5 GJ of energy. For this reason, the use of field drying (natural) should be taken advantage of whenever possible (Brown 2003). Drying reduces the overall efficiency of a plant due to the large amounts of thermal energy required; however, this can be mitigated by directing the waste heat from the pyrolysis process to the dryers. Hot producer gas, heat exchanger exhausts, and the combustion of by-products are all sources of heat in a plant (Cummer and Brown 2002).

Natural Drying: Natural drying utilizes moisture gradients established between the particle and its natural environment, such as air drying. This technique consists of stacking biomass in a way that allows for continuous and uniform airflow through the pile. Drying also can be accomplished by ventilating a pile of bulk material with ambient or preheated air.

Artificial Drying: Artificial drying typically involves kilns. Vaporization of volatile components in the biomass or the thermal degradation of the biomass in the dryer can cause volatile organic compounds to be produced, especially when feedstock exceeds 100 $^{\circ}$C. Thus, the exhaust from the drying systems must be monitored. A hazardous, slightly smoky exhaust plume known as “blue haze” is formed when these volatile components are released. Selection of commercially available dryers depends on several factors including: particle size, drying capacity of the system, and fuel type (woody or herbaceous biomass) (Cummer and Brown 2002). Biomass fuel drying can only be economic and efficient if a cheap heat source is available such as solar energy or heat from flue gases (Van Loo and Koppejan 2008).

Continuous Drying Technologies: For the production of pellets or briquettes, continuous drying is necessary for the conditioning of woodchips or sawdust. Some of these technologies include belt driers, drum driers, tube bundle dryers and superheated steam dryers. The use of flue gas from a combustion process, indirect hot water, steam or thermal oils can be used to supply heat (Van Loo and Koppejan 2008).

Mechanical or hydraulic press. A mechanical or hydraulic press provides a simpler method for drying biomass. Pulp-and-paper mills use mechanical presses to dry bark. These devices can only reduce moisture content to approximately 55 percent by squeezing the water from extremely moist feedstock. These machines also require a great deal of maintenance and are energy intensive (Cummer and Brown 2002).

Perforated floor bin dryers. The simplest drying system for drying biomass is offered by perforated floor bin dryers (Figure C1). This type of dryers can dry feedstock in batches and is suitable for smaller biomass plants

(< 1 MW). A fixed bed sitting above the perforated floor is formed from the wet feedstock. It is recommended that a shallow bed depth of 0.4 – 0.6 m (16 – 24 in) be used. To avoid gaseous emissions, the inlet gas temperatures should be less than 100 °C (Cummer and Brown 2002).

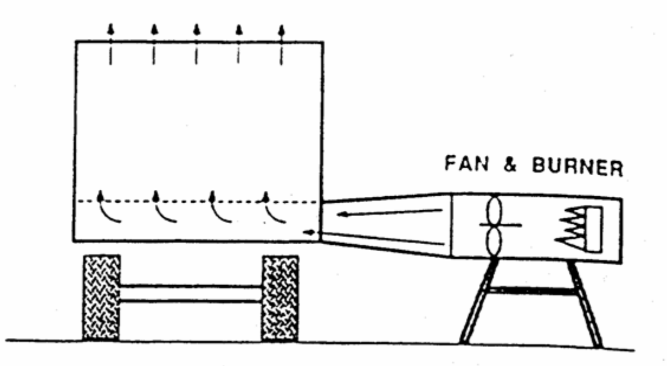

Figure C1. Perforated floor bin dryer (http://www.fao.org/docrep/009/ae075e/ ae075 e22.htm).

Figure C2 shows the use of waste heat to dry biomass. In these cases the drying is conducted by ventilating the pile with ambient preheated air (van Loo and Koppejan 2008).

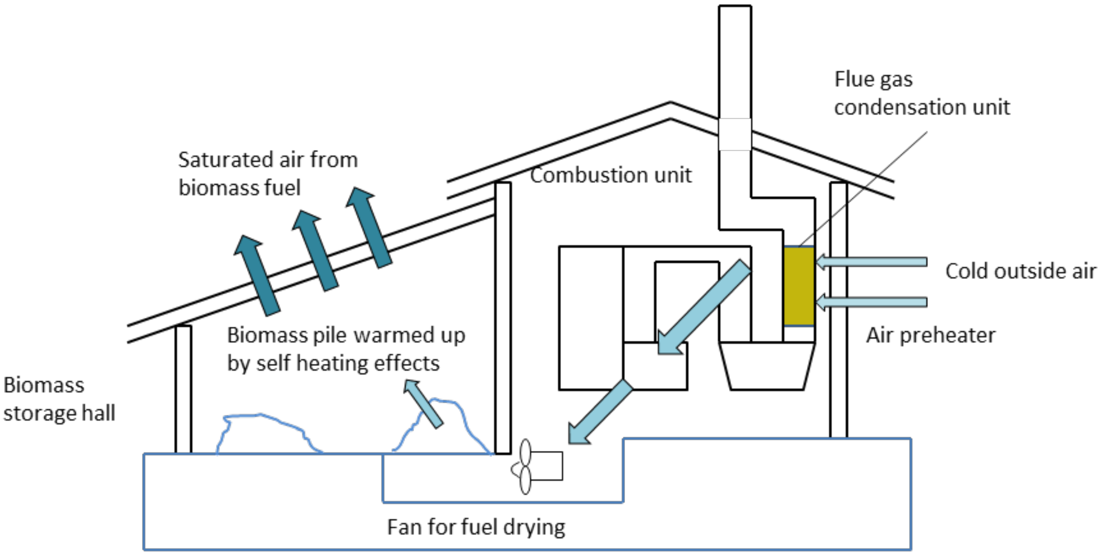

Figure C2. Biomass drying during short term storage using preheating air (Van Loo and Koppejan 2008)

Band conveyors dryers. Bank conveyor dryers are similar to the simplicity of the perforated floor dryers but allow for a continuous stream of feedstock to be dried. A permeable band carries the feedstock through a drier while a drying medium is blown through the band and feedstock by fans (Figure C3). The shallow depth of the feedstock on the band (2 – 15 cm, 1 – 6 in) allows for the material to be dried in a uniform manner. The feedstock may be transported through the dryer multiple times where the gas may have an upward or downward flow or multiple bands can be stacked with each band discharging onto the one above or below it, or they may be arranged side by side in series. Different sections of the band conveyors allow for a different drying medium to be continuously added. By adjusting the speed of the bands the residence times can be regulated.

Figure C3. Perforated band conveyor drying system (http://www.lp-machinery.com/en/ Products Details .aspx).

Depending on the technology used, belt dryers may operate at a low heat with an input gas temperature of 90-110 ^{o}C and an output gas temperature of 60-70 ^{o}C. These low temperatures eliminate the emissions of odors and volatile organic compounds released from the biomass (Van Loo and Koppejan 2008).

Rotary cascade dryers. The most common drying device that can handle a wide range of materials and is widely used in industry is a rotary cascade dryer (Figure C4). These are the most common in large-scale biomass gasification projects and large wood-chip combustion plants. Material moves due to the slight inclined orientation through a cylindrical shell (1 – 10 rpm) as it slowly rotates. Due to a lower efficiency of heat transfer, the rotary cascade dryer requires a much larger gas volume than those in through-circulation systems which is one of this dryer's drawbacks. Because of the unavoidable entrainment of feedstock particles in the drying medium, rotary cascade dryers require cyclones and/or bag filters (Cummer and Brown 2002).

Figure 59. Rotary dryer (http://www.avmsystech.co.in/rotary-dryer.html).

Drum dryers are directly heated and operate at a relatively high temperature. Because of the high operation temperature, these dryers release water along with volatile organic compounds during the drying process (Van Loo and Koppejan 2008) and must be outfitted with a complex flue system for gas cleaning. This represents loss of potential products of heat. Furthermore, the flue gas used in this directly heated drum dryer contains fly ash which will remain in the sawdust leading to higher ash content and heavy metal contamination in pellets.

Fluidized bed steam dryer. A more advanced fluidized bed steam drying system is used for larger scale operations (> 10 MWe). A bed of moist feedstock is fluidized by superheated steam from the heat ex-changer entering the cells. The moisture in the feedstock is vaporized by the superheated steam and then entrained. In order to remove the entrained particles, the steam passes through an internal cyclone. The excess steam from evaporation is then discharged after the cyclone stage. The steam is cycled through a large heat exchanger where it is reheated to 200 ^{o}C before it is returned to the fluidized bed. This operation should be done with care to avoid volatile losses. The excess steam (150 ^{o}C) may then be transported elsewhere to be utilized in another process (Cummer and Brown 2002).

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