WOOD 2 ENERGY

A State of the Science and Technology Report

U.S. Endowment for Forestry and Communities

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About

Wood is a concentrated form of stored sunlight (solar energy). This energy can be released and used as a fuel. Wood has always been an important source of energy for people. Even today, wood is the most important source of renewable energy in the United States and a primary source of fuel for much of the world. Whether it is as simple as a campfire, or as sophisticated as producing ethanol, wood has a number of inherent advantages that ensure it will continue to be an important bio-fuel in the future.

The University of Tennessee (UT) Office of Bioenergy Programs, with funding provided by the U.S. Endowment for Forestry and Communities Inc. has produced a report on the state-of-the-science of woody biomass to energy conversion processes in North America, including a literature review and a database of industrial facilities utilizing wood as a fuel source. This project was completed with the assistance of additional valuable partners, including the USDA Forest Service Forest Products Laboratory and Southern Research Station, as well as the regional centers of the Sun Grant Initiative.

This State of the Science report accomplishes two primary objectives related to the state of the science in wood to energy research and industry. The literature review provides a complete overview of the state of wood to energy science and technology, including characterizations of process design, stage of development or commercialization, and suitability for the marketplace. The review also provides an analysis of market sustainability, including opportunities and barriers, of wood to energy production.

Please visit our website: **www.wood2energy.org** for more information.

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Executive Summary

Wood has been and will continue to be the primary source of biomass for energy for the United States (U.S.) and Canada. Traditionally, technologies to convert wood to energy at the industrial scale have been practiced by the wood utilization industry. Using residues from process streams and other sources, industries have produced heat, steam, and power for internal processes. However, with the renewed emphasis placed on renewable energies in recent years, wood is poised to be a significant source of energy for the general populace. The use of woody biomass to produce bioenergy involves several steps including availability of the resource, biomass harvest/collection, transport and storage, preprocessing, pretreatment, and conversion to energy or products.

The availability of woody biomass is critical to the entire energy industry. Canada and the U.S. both have significant acreages of forest resources that have the ability to produce large volumes of woody biomass on an annual basis. Two of the most significant sources of woody biomass for the energy industry will be logging/in-woods residues and short-rotation woody crops. Logging and in-woods residues include residues removed during forest health treatments, such as fuel reduction. These resources are typically under-utilized and currently markets are lacking for small diameter materials. However, significant challenges exist related to harvesting these materials. Even in systems where the harvesting of biomass is conducted simultaneously with the harvest of sawtimber or other products, the low bulk density of residues makes collection and transport difficult and expensive. Short-rotation crops offer fast growth and high volumes of biomass per acre for harvesting. Challenges exist in short-rotation woody crops and are primarily related to establishment costs in many species and the lack of cost-effective harvesting equipment for the shrub species. Residues from wood processing has been and will continue to be a source of fuel for those facilities but is not expected to be a significant source of wood for new bioenergy facilities. The wood processing industry has been particularly hard hit by the recent economic climate and expansion of the industry will be limited.

Once woody biomass has been harvested, the logistics of moving the biomass to a wood to energy facility become critical. The relatively low bulk density of wood, particularly in-woods residues, creates challenges for cost-effective transportation. More densification at the time of harvest could increase efficiency in transportation. These densification steps include current and potential technologies such as in-woods chipping, bundling, or conversion to a pyrolysis oil. The geographical relationship between the biomass and end use facility is also critical to an effective transportation network. Care in siting new biomass using facilities must be taken to maximize efficiencies.

Woody biomass preprocessing and pretreatment will also be required for most energy conversion technologies. Preprocessing can be as simple as drying and grinding biomass or as advanced as pelletization. It is typically done to improve storage and handling of biomass in the thermochemical conversion process. Pretreatment generally follows preprocessing and is more critical to conversion processes that rely on specific components within the biomass. Pretreatment technologies are often directly tied to biochemical conversion processes that rely on cellular deconstruction to access components like cellulose while removing process inhibitors. Many processes exist for pretreatment; however, there are challenges in improving efficiency of pretreatment to reduce overall conversion costs.

Converting wood to energy has been and continues to be through thermochemical methods. Direct combustion and cofiring with coal or other resources have been the primary technologies employed for the conversion of wood to energy. These processes continue to develop and the addition of advanced gasification and pyrolysis technologies brings the ability to fractionate biomass into specific chemical components and products have expanded the reach of thermochemical technologies. Pyrolysis and

gasification offer thermochemical technologies with high efficiencies and flexible or multipurpose end products. Another area of advancement for wood to energy technologies is the biochemical conversion pathways. Though these processes are not new, technological advances in the last several years have increase efficiencies, both in energy output and economics.

Challenges exist in both thermochemical and biochemical conversion. In thermochemical processes, gasification conversion efficiencies can be affected by tar formation during the process and processes to treat this problem can be very expensive. Pyrolysis oils are very dense, improving transportation efficiencies. They can be processed into other products and chemicals, but do have low heating values, are high in ash, and have other characteristics that make them challenging to work with as fuel or chemical feedstocks. In bioechemical processes, enzymatic hydrolysis for liquid fuels and chemicals is the primary technology that has been refined in recent years. This process has traditionally been very expensive compared to grain-based fuels and other processes. Enzymes used in the process are optimized for particular feedstocks and thus making a facility less flexible for feedstock types. Recent research in enzymes has led to the development of enzymes that remain viable for repeated processing and are less expensive to produce. The development of an enzyme that efficiently breaks down multiple feedstocks would represent a significant leap forward for the technology.

Though there is not a clear front-runner in wood to energy conversion technologies, the primary result of this review shows that multiple successful technologies exist. The selection of a specific conversion technology depends on a variety of factors, the combination of which is unique to each specific situation. Factors include desired end product, feedstock availability and type (will the supply be solely wood or are multiple feedstocks required), supply chain restraints, scale of conversion facility, and a myriad of other factors. The selection of conversion technologies has become broader in recent years. The conversion technologies, though not perfectly refined, have become more optimized and more economical in the last decade. Continued research and refinement of each technology should yield significant improvement in conversion efficiencies and economics, both capital and operating costs, in the near future.

Evaluating the potential impacts of an expanded wood to energy industry is more difficult than evaluating specific technologies. Currently, an expansion of the wood to energy industry would be heavily reliant upon federal state, and/or provincial policies such as subsidies and mandates. The rapidly changing nature of federal policies along with the uncertainties around incentive programs, industry regulation, and market demand make it difficult for the industry to make decisions regarding new energy projects. Many industrial projects, especially biopower, have taken a wait-and-see approach with regards to carbon regulation and other regulatory issues. However, other sectors such as liquid fuels have received more governmental attention and have more incentives/programs in place.

Projecting the impact of the expanding bioenergy onto wood supply and demand is difficult. Regional variation in markets dictates that industries considering a wood to energy conversion facility carefully evaluate existing resources, demands, and other issues. As the industry expands, there will be increased demand for the wood resource. In some regions, this increased demand will create markets for wood that previously did not exist. In other regions, increased demand will be placed upon an already well utilized resource. In those cases, it is expected that prices for the resource will rise, though not at significant rates. The portions of the existing wood products industry that will be most affected by the change will be the pulp and panel industries. The pulp industries that are already taxed and facing difficulties due to the current economic climate could see significant negative impacts as would the panel industry who demands wood similar to that used for energy. However, the change in consumer demand and economics may provide the opportunity for the industry to expand their scope to explore new opportunities and take advantage of new technologies. Existing industries could integrate bioenergy technologies into their existing operations. To survive in the current industry, expanding operational focus may be one way a company could survive.

There are challenges and opportunities throughout the wood to energy sector. From producing biomass, harvesting, preprocessing, conversion technologies, and policy, there are efficiencies to be gained, new technologies to be developed and new opportunities for the industry. Any new opportunity has inherent challenges and trade-offs, which must be carefully considered when planning or operating on wood as a feedstock. Wood to energy may not only revolutionize the wood industry, but also impact the energy and economic security of the U.S. and Canada for generations to come. The current state of wood to energy is good as we are developing and advancing technologies for the future.

Introduction

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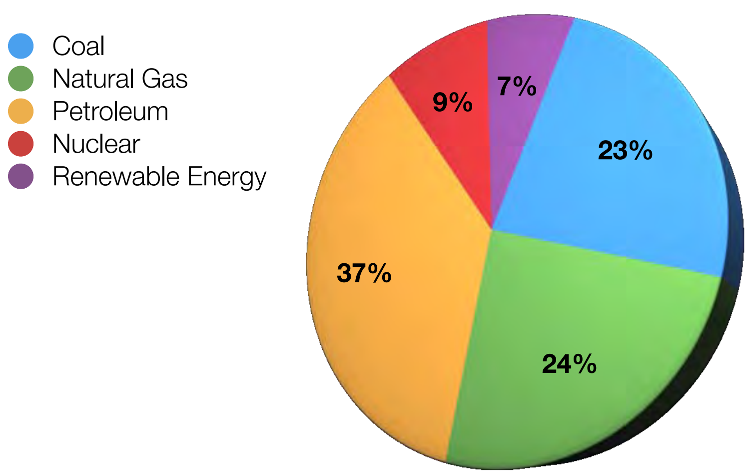
In recent years, energy security, climate change, and other environmental concerns have sparked interest in reducing fossil fuel use through the use of renewable fuels. Recent policies mandate the increased use of renewable energy, including biomass materials such as wood.

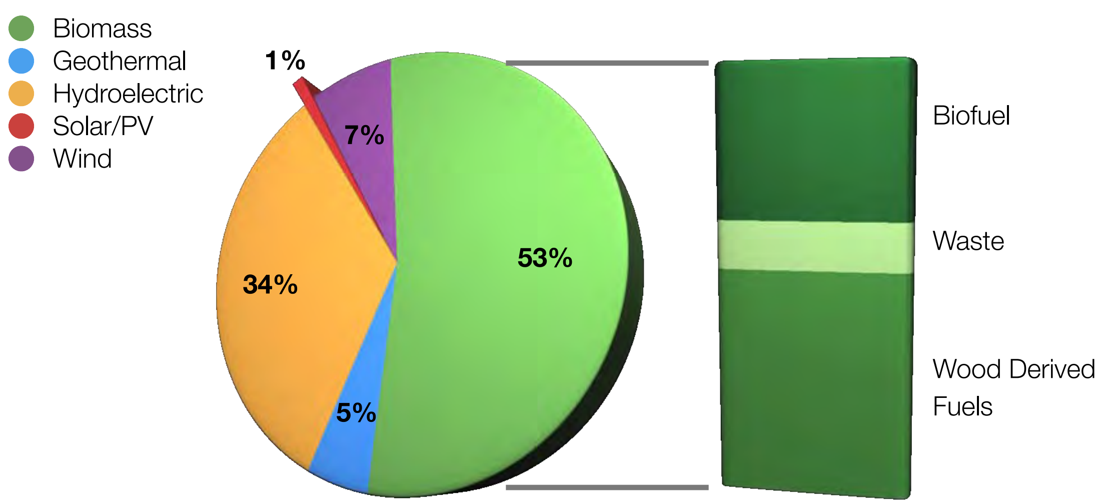
Wood is used worldwide to produce energy for electricity, heat, and cooking. In the U.S, wood provides about 3% of total energy usage and 1/3 of the total renewable energy consumed (Figures 1 and 2) (1, 2).

Figure 1. U.S. Energy Consumption by Source, 2008



Source: Reference 2

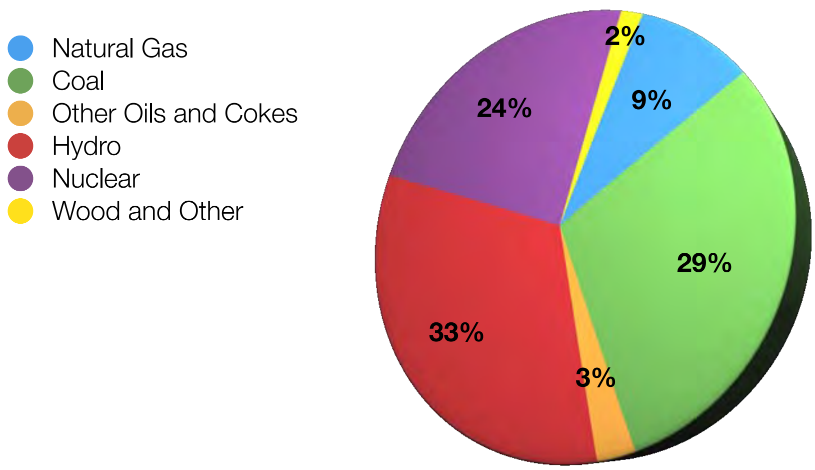
Figure 2. U.S. Renewable Energy Consumption by Source, 2008



Source: Reference 2

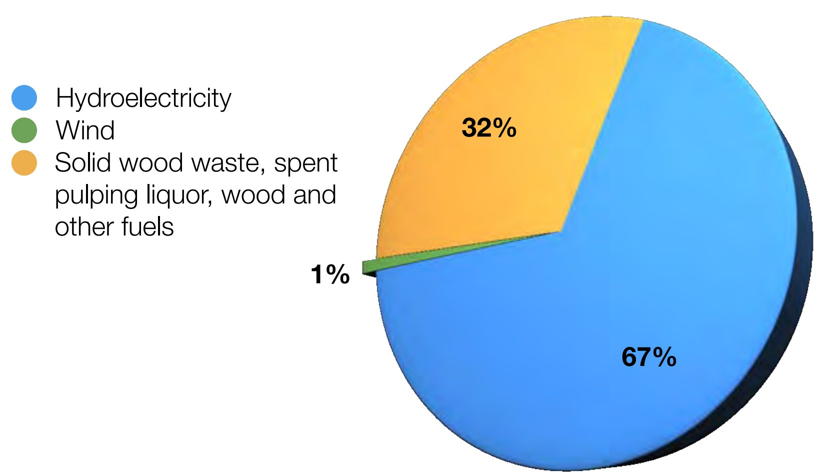
Similarly, in 2008, nearly 11% of Canadian electricity was generated from renewable sources, 32% of which was derived from wood, solid wood waste, spent pulping liquor, and other biomass sources (Figures 3 and 4). In total, 6% of Canada's total energy consumed was derived from biomass in 2008. Canada's renewable electricity production in 2010 is estimated to be 62% of total production (Figure 5).

Figure 3. Canadian Electricity Consumption by Source, 2007



Source: Reference 9

Figure 4. Canadian Renewable Energy Consumption by Source, 2008



Source: Reference 9

Figure 5. Canada's Renewable Electricity Generation by Fuel Type

	2004	2010*
Fuel Type	TWh	TWh
Renewable	310.3	365.5
Biomass	4.8	7.5
Total	532.5	589.6
Percent of Total Renewable	58%	62%

**Projected; Source: Reference 8*

Currently, most North American wood-derived energy is generated by the wood products industry, which uses mill residues and black liquor to produce heat, steam, and electricity to dry wood and supply the process energy needed in pulp mills (Figures 6 and 7). The pulp and paper sector is Canada's largest producer of bioenergy and in 2004, used 507 PJ of bioenergy (8). However, the use of woody materials by utilities and biorefineries to produce electricity (combustion or co-firing), liquid biofuels, and chemicals is expected to increase.

Figure 6. Contribution of U.S. Forest Industry to Energy, 2006

Industry	Energy Source	Biomass Energy Consumption (Trillion Btus)			Net Generation (Million Kilowatt hrs)
		Total	Electricity	Useful Thermal Output	
	Total	1966.043	357.655	1608.388	28,897
Lumber	Wood/Wood Waste Solids	251.865	16.824	235.041	1,326
Paper and Allied Products	Black Liquor	853.151	220.683	632.467	17,949
	Wood/Wood Waste Solids	363.462	107.182	256.280	8,768

Source: Reference 3

Figure 7. Contribution of Canadian Forest Industry to Energy, 2007

	Production (Terajoules)
Total Manufacturing Energy	2,298,906
Wood	192,319
Black liquor	189,157

Source: Reference 4

Numerous sources of woody biomass materials can be used for bioenergy. Mill residues include sawdust, planer shavings, slabs, cut blocks and bark from sawmills and secondary wood manufacturing facilities. Black liquor is the waste produced from Kraft pulping (the dominant wood pulping process), and contains inorganic pulping chemicals and a complex mixture of dissolved wood components (mostly lignin and hemicelluloses). Forest materials (i.e., wood grown in natural forests) include small diameter trees not suited for other markets, pulpwood, and residues produced during harvesting operations (slash such as tops, bark, and limbs). Roundwood materials are derived from thinning trees in long rotation plantations. Wood from short-rotation plantations are typically grown and harvested using rotations of 8 years or less. Urban and industrial wastes include recycled paper, wood from construction or demolition projects, and wood generated from homeowners (e.g., tree trimming or removal). While potential sources of material, many urban wastes are currently recycled and used for non-energy purposes (e.g., mulch).

Woody biomass is flexible in that it can be converted to heat, steam, electricity, liquid biofuels, and organic chemicals. Numerous thermal and biochemical technologies are under development to produce bioenergy from wood. However, the use of biomass for energy is complicated by its relatively low energy density, transportation logistics issues, and the structural complexity of the material. Compared to nonrenewable energy sources, biomass materials contain less energy per mass. The energy content of dry woodchips ranges from approximately 17 MJ/kg (7300 btu/lb) (5) or alternatively 20 MJ/kg (8500 btu/lb) (6). Black liquor has an energy content of about 14 MJ/kg of solids (6000btu/lb), and for each ton of pulp, about one ton of black liquor is produced (7). Bituminous coal contains nearly 33 MJ/kg. Additionally, fossil fuel resources are more spatially concentrated and more energy is available per physical area (e.g., per acre) than for biomass resources. Because of the lower energy and bulk density of biomass relative to fossil fuels, similar transportation systems deliver proportionally less energy per unit time and volume. The moisture content of biomass resources is also an issue as it further reduces the energy content per unit of weight. Moisture content varies by woody biomass source. A number of technologies are available to dry and densify woody biomass materials, improving their energy density. Pretreatment processes decrease the structural complexity of biomass materials by reducing them to smaller and more structurally uniform materials that can be more readily converted into final products.

The use of woody biomass to produce bioenergy involves several steps starting with availability of the resource, and proceeding to biomass harvest/collection, preprocessing (to increase energy density, reduce moisture), transport and storage, pretreatment, and finally conversion. Improvements in each step of the supply chain are needed. This report discusses the availability of woody biomass for bioenergy and provides an overview of the status and industry potential of the primary technologies associated with converting wood to energy.

Citations

1. Bowyer JL, R Schmulsky and JG Haygreen. Forest Products and Wood Science: An Introduction. 2007. Blackwell Publishing. 558pp.
2. US Energy Information Administration. Annual Energy Review. US Department of Energy, 2009. http://www.eia.doe.gov/emeu/aer/overview.html
3. US Energy Information Administration. Wood/Wood Waste. US Department of Energy, 2008. http://www.eia.doe.gov/cneaf/solar.renewables/page/wood/wood.html
4. Statistics Canada. Energy fuel consumption of the manufacturing sector, by fuel type. Her Majesty the Queen in Right of Canada, 2010. http://www40.statcan.gc.ca/l01/cst01/prim74-eng.htm
5. Biomass Energy Foundation. Fuel Densities. 2001. http://www.woodgas.com/fuel_densities.htm
6. USDA Forest Service. Fuel Value Calculator. US Department of Agriculture, 2004. http://www.fpl.fs.fed.us/documnts/techline/fuel-value-calculator.pdf
7. Biermann CJ. Handbook of Pulping and Papermaking: Second Edition. 1996. Academic Press, New York. 754pp.
8. Natural Resources Canada, Analysis and Modelling Division. Canada's Energy Outlook: The Reference Case 2006. Her Majesty the Queen in Right of Canada, 2006. 218 p.
9. Natural Resources Canada, Office of Energy Efficiency. Electricity Generation Sector Canada Table 1. Her Majesty the Queen in Right of Canada, 2010. http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/tablestrends2/egen_ca_1_e_4.cfm?attr=0

Woody Biomass Supply

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Forestry is a major economic sector in both Canada and the U.S. Forest lands can provide a variety of biomass resources useful for bioenergy, biofuel and bioproduct applications including forest residues from harvesting operations (logging residues) and intermediate thinning operations on plantations, as well as residues generated through processing wood into fiber products (pulp and mill residues). Additionally, opportunities to produce dedicated wood energy crops exist.

Canadian Forest Biomass Resources

Samuel Jackson, University of Tennessee

Residues, such as chips are an important source of woody biomass for energy production.

Approximately 44% (993 million acres) of Canada is forested (1), of which 93% is publicly owned (77% by provincial governments and 16% by the federal government). It is estimated that sufficient biomass resources occur on Canadian forestlands to displace current fossil fuel energy demand levels (8.24 EJ/yr) for 69 years (2).

Wood was harvested on 1.8 million acres (728,434 hectares) of forestland in 2008, producing over 5.7 billion cubic feet of all woody materials (3) which were used to produce fiber products and more than 20 million tons of wood pulp (11 million tons consumed in country and the remainder exported) (4). Forest harvesting operations generate 20 million dry tons of residues per year. Over 21 million bone dry tons of process (mill) residues were generated in 2004, 2.7 million dry tons of which were not used for process energy (1). Processing facilities could potentially produce an additional 15.7 million dry tons of hog fuels annually (1). Other wood-based biomass resources include pine beetle salvage materials (27 million dry tons per year, much of which is in excess of current pulp manufacturing capacity). Additionally, short rotation woody energy crops may also be a source of biomass. One study estimated that British Columbia can potentially produce 4 million dry tons of wood/year from dedicated wood energy crops (14).

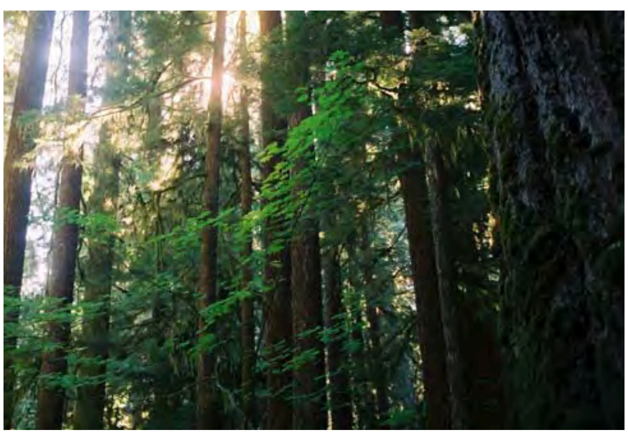
Table 1 summarizes forestry statistics by Canadian region. Provinces with significant forest resources and high levels of biomass production are presented individually while others are grouped together. Wood is not a significant commodity in the Yukon, Northwest Territories, and Nunavut--less than 300 hectares (741 acres) are harvested annually in these regions.

Table 1. Canadian Forest Data, by Province

Region	Forestland	Forest Production	Pulp and Mill Residues
1. British Columbia	158.8 million acres; 16% of national forestland; 415,500 acres harvested	Estimated sustainable annual production of 13 million dry tons; 22.9% of national harvest	6.5 million dry tons ; 1.8 million dry tons unused
2. Quebec	209 million acres; 22.4% of national forestland	38.4 million cubic yards; 21% of national harvest	6.7 million dry tons ; 100,000 dry tons unused; 5.6 million dry tons bark
3. Alberta	89.9 million acres; 9% of national forestland; 136,000 acres harvested	98.7 million cubic yards; 7% of national harvest	2.4 million dry tons; 487,000 dry tons unused
4. Ontario	168.7 million acres; 17% of national forestland	19.4 million cubic yards; 10% of national harvest	2.6 million dry tons; 121,000 dry tons unused; 6.7 million dry tons bark
5. Manitoba/ Saskatchewan	75.6 million acres; 64,000 acres harvested	5.8 million cubic yards	805,000 dry tons; 177,000 dry tons unused; 2.9 million dry tons bark
6. Atlantic Provinces	77.9 million acres; 334,000 harvested	21.9 million cubic yards	2.2 million dry tons; 44,000 dry tons unused; 424,000 dry tons bark

Forestland and forest production data for Alberta, Ontario, Manitoba/Saskatchewan, and the Atlantic Provinces from Reference 3. Forestland and forest production data for Quebec from Reference 3.
Forestland data for British Columbia from Reference 3 and forest production data from Reference 15.
Pulp and mill residue data for all provinces from Reference 1.

U.S. Forest Biomass Resources



Samuel Jackson, University of Tennessee

The abundant forestland in the US and Canada provides a tremendous amount of biomass for energy and products.

The U.S. includes nearly 749 million acres of forestland (2/3 classified as timberland) which accounts for nearly 1/3 of the total land area. Unlike Canada, nearly 71% of U.S. timberland acres are privately owned (5). U.S. forestlands were estimated to contain 24.1 billion tons of live biomass in 2007, and in 2006, forest operations created 4.5 billion cubic feet of material.

Roundwood harvest from U.S. forests has stabilized recently, with annual removal of about 15 billion cubic feet from 10.8 million acres (90% from privately owned forestland (6, 7). The national growth to removal ratio was 1.72, one indication that forests are not being over-harvested or pushed to their productive limits (7). The removal ratio correlates to the timber product output, which nationally, has decreased by 9 percent since 1996.

Several studies estimate woody biomass supplies for individual states and regions, but methods (e.g., data collection, assumptions, and biomass category definitions) differ substantially among studies, making direct comparisons difficult. This paper summarizes a few select national and regional studies.

Perlack (2005) estimates that 368 million dry tons of woody biomass could be available annually for bioenergy (5). This estimate includes the 142 million dry tons of wood residues currently used for heat and power by the forest industry. Additionally, the report estimates that 35 million dry tons of woody biomass from forests is currently being used by the residential and commercial sectors for heat and by the electric power sector. The report also cited the availability of increased residues from industrial processes, with estimations built upon demand projections at the time of publication. However, the recent economic downturn has reduced overall demand, leading us to conclude that an expectation for dramatic expansion of process residues is not feasible at this time. After removing the amount of woody biomass currently being used and the demand projections from the report, the Billion Ton Supply report still indicates 137 million dry tons of woody biomass would potentially be available for energy production.

The remaining 137 million dry tons came from forest management operations (logging residues and other removals including thinning materials); fuel treatment materials (wood removed to improve forest health and reduce the risk of forest fires); unused primary and secondary wood processing mill and pulp and paper mill residues; construction and demolition wood wastes; and municipal solid wood waste (yard trimmings, wood packaging, and durable consumer wood products). Table 2 summarizes the estimated quantities by source.

Table 2. Potential unused sources of woody biomass, by type.

	Forest Management	Fuel Treatment	Unused Mill Residues	C&D Wood Wastes	MSW Wood Wastes	Total
Estimated Quantities (million dry tons)	41	60	8	20	8	137

Source: Reference 5

In contrast, Milbrandt (2005) estimates annual available woody biomass quantities of 168 million dry tons (8). The lower estimated quantities are due, in part, to the exclusion of quantities currently used by the forest industry. Table 3 summarizes U.S. forestry statistics by region.

Table 3. U.S. Forest Data, by Region

Region	Forestland	Annual Forest Residue Production	Annual Pulp and Mill Residues
Northeast	93 million acres; 12% of total US; 83% privately owned	9.8 million dry tons of forest residues; 7.9 million dry tons of urban wastes	6.45 million dry tons; 962,450 dry tons unused
Central	81.5 million acres; 11% of total US; 67% privately owned	15.5 million dry tons	6.97 million dry tons; 852,000 dry tons unused
Western	359 million acres; 48% of total US; 30% privately owned	13.1 million dry tons	24.8 million dry tons; 1.01 million dry tons unused
Southeast	214 million acres; 28% of US total; 88% privately owned	41.2 million dry tons	42.4 million dry tons; 1.4 million dry tons unused

Northeast includes CT, DE, DC, ME, MD, MA, NH, NJ, NY, OH, PA, RI, VT, and WV; Central includes IL, IN, IA, KS, MI, MN, MO, NE, ND, SD, and WI; Western includes AK, AZ, CA, CO, HI, ID, MT, NV, NM, OR, UT, WA, and WY; Southeast includes AL, AR, FL, GA, KY, LA, MS, NC, OK, SC, TN, TX, and VA.
Source: Reference 8

Abe (2003) estimates that at a price of $ 3.50/MMbtu, the Northeastern region could produce 26.3 million dry tons woody biomass annually (11). At lower prices ($1.40/MMbtu or $22.40/ton, assuming 8000 btu/lb), an estimated 15 million dry tons/year could be available.

The Western Governor's Association estimates there are sufficient forest residues in the western U.S. (22 million dry tons/year, including 7.5 million dry tons from fuel treatment activities and 4.7 million dry tons from logging residues) to produce 71 GWh of power (10). Skog (2009) estimates that 20.7 million dry tons/year could be available in the Western region (11). Of this quantity, 5.2 million dry tons are from fuel treatment on timberland, 5.3 million dry tons from logging residues, and the remainder from pre-commercial thinning and other forest management practices. Less than 200,000 dry tons of mill residues are available annually.

The Southeastern region could potentially be a major source of woody biomass for bioenergy uses (6). Current softwood pulpwood production levels are 89 million dry tons per year and are projected to increase by 8% to over 96 million dry tons by 2020. Pine plantation forestry will be the principal source of softwood material and is estimated to increase by 12% in the next decade. Thinning operations on these sites will account for nearly three-quarters of the overall softwood pulpwood supply, with final harvest of the stands providing the remaining quantities. Hardwood pulpwood supplies are projected to decrease from the current annual average of 34 million short tons to 30 million short tons annually over the next decade due to an expected decline in the number of hardwood mills in the region. An estimated 17.7 million short tons/year of woody biomass could potentially be available in the Southeast for bioenergy uses by 2020, without significantly impacting or altering existing markets. Materials are derived primarily from harvest residues (10 million short tons/year; over 50% from softwood resources). Mill residue production is projected to increase slightly (from 56 to 59 million short tons per year) by 2020, but only about 1.5% of these residues are currently unused. An additional 3 million short tons/year could be available from urban wood wastes (6).

Galik (2009) estimates that Virginia, North Carolina, and South Carolina can supply 5.9 million dry tons of woody biomass annually (12). Jackson (2007) using USDA Forest Service data, estimates that 25.8 million dry tons of logging residues could be available annually in the Southeast and that 10.1 million dry tons/year of urban wood wastes could also be available (13).

Citations

1. Bradley, D. Canada Biomass/Bioenergy Report. 2006, Climate Change Solutions, Ontario. 20 pp.
2. Wood, S.M. and Layzell, D.B. A Canadian Biomass Inventory: Feedstocks for a Bio-based Economy. 2003, BIOCAP Canada Foundation, Ontario. 42 pp.
3. Natural Resources Canada. The State of Canada's Forests Annual Report 2009. 2009. 64 pp.
4. Natural Resources Canada. Estimated Production, Consumption and Surplus Mill Wood Residues in Canada – 2004 A National Report. 2006 60 pp.
5. Perlack, R.D.; Wright, L.L.; Turhollow, A.F.; Graham, R.L.; Stokes, B.J.; and Erbach, D.C. Biomass as feedstock for a bioenergy and bioproducts industry: The technical feasibility of a billion-ton annual supply. 2005, US Department of Energy. 78 pp.
6. Forest2Market. US South Forest Biomass Outlook and Price Forecast. 2008, Forest 2 Market Inc. 90 pp.
7. Oswalt, S.; Thompson, M.; and Smith, W.B. U.S. Forest Resource Facts and Historical Trends. 2009, USDA Forest Service FS-801. 60 pp.
8. Milbrandt, A. A Geographic Perspective on the Current Biomass Resource Availability in the United States. 2005, U.S. Department of Energy, National Renewable Energy Laboratory. http://www.nrel.gov/docs/fy06osti/39181.pdf
9. Abe, J.; Chaytors, R.; Clark, C.; Morgan, E. Securing a Place for Biomass in the Northeast United States: A Review of Renewable Energy and Related Policies. 2003, Xenergy, Burlington, MA. 106 pp.
10. Western Governor's Association. Biomass Task Force Report. 2006, Western Governors' Association. 66 pp.
11. Skog, K.E.; Rummer, R.; Jenkins, B.; Parker, N; Tittmann, P.; Hart, Q.; Nelson, R.; Gray, E.; Schmidt, A.; Patton-Mallory, M.; Gordon, G. A Strategic Assessment of Biofuels Development in the Western States In: McWilliams, Will; Moisen, Gretchen; Czaplewski, Ray, comps. 2009. 2008 Forest Inventory and Analysis (FIA) Symposium; October 21-23, 2008: Park City, UT. Proc. RMRS-P-56CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 1 CD.
12. Galik, C.S.; Abt, R.C.; and Wu, Y. Forest Biomass Supply in the Southeastern United States -- Implications for Industrial Roundwood and Bioenergy Production. 2009, Journal of Forestry 107(2): 69-77.
13. Jackson, S. 2007. Southeastern Biomass/Bioenergy Overview. In: Hubbard, W.; L. Biles; C. Mayfield; S. Ashton (Eds.). 2007, Sustainable Forestry for Bioenergy and Bio-based Products: Trainers Curriculum Notebook. Athens, GA: Southern Forest Research Partnership, Inc.
14. Ralevic, P. and Layzell, D.B. An Inventory of the Bioenergy Potential of British Columbia. BIOCAP Canada Foundation, Ontario, 2006. 8 pp.

Current Technologies for Harvesting Forest and Plantation Woody Materials for Energy Production

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Forest and tree plantation materials can potentially be a significant source of woody biomass for bioenergy uses. However, these materials can be challenging to harvest, collect, and utilize in energy conversion facilities. As a result, in-woods residues are not typically collected for bioenergy use, although interest in such activities is increasing. In operations that require slash clean-up prior to replanting, bioenergy uses can provide new markets for the slash and reduce the overall cost of the forest operation.

Harvesting In-Woods Material

The collection of in-woods biomass for energy, when added to the harvest of traditional wood products, can increase income from the sale of additional materials and from reduced costs for post-harvest clean-up and site preparation for subsequent reforestation. The establishment of new markets for woody biomass presents opportunities for landowners to improve forest management and to adopt cost-effective practices for stand improvement.

One and two pass harvest systems to remove in-woods material have received the most research and development focus. The number of passes refer to the number of times harvest equipment enters the stand to remove materials.

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A biomass bundling system collecting forest slash materials with biomass bundle ready for transport.

One-pass methods use traditional forest harvest equipment in combination with a densification step. Harvest operators can add bioenergy collection activities to their traditional operations with relatively little investment in new equipment. One pass systems can be used in situations where bioenergy uses are the primary market and trees destined for other products are harvested with other equipment and handled separately, or where some trees are left unharvested. This system typically involves using feller-bunchers to harvest the whole tree at one time, followed by transport to a landing site where they are densified. One-pass systems allow for maximum collection and use of materials from the forest. In operations where the trees are used primarily for fiber products and bioenergy uses are the secondary use, one-pass systems involve whole-tree harvest and moving (skidding) the trees to the landing site where the limbs are removed and made available for bioenergy. Other one-pass harvesting systems use harvesters that cut the tree, delimb it, and pile the logs in the forest. This approach creates separate piles of traditional wood products and biomass products. A forwarder or skidder moves the materials to the landing for further densification and/or transport. Typically, this system removes only the tree trunk and leaves the tree tops and limbs in the forest.

Two-pass harvesting systems involve entering the forest stand twice. One entry involves harvesting trees for traditional fiber uses, and the second pass is to collect materials for bioenergy use. The material used for bioenergy can be collected prior to or during thinning operations or following harvest for fiber uses (logging residues). Pre-harvest operations remove the biomass with a whole-tree harvester and move (skid) the tree to a landing site for densification and transport. Trees (roundwood) destined for other markets are left standing for harvest at a later time. This system reduces the amount of existing vegetation in a forest stand, making it easier to maneuver and harvest traditional products.

Post-harvest collection operations involve returning to a forest stand following harvest for traditional fiber uses to collect tree limbs, tops, and other materials. These materials are then moved to a landing site and densified. Post-harvest collection involves operating machinery in heavy debris from the earlier harvest, making it less efficient.

One-pass harvest systems are preferred because they involve entering the forest stand just once and integrate all desired harvesting activities which improves operational efficiency and reduces cost. The same harvesting crew can collect material for both traditional and bioenergy uses simultaneously, improving logistics, scheduling, and overall forest maintenance. However, the moisture content of materials collected in one-pass systems can be high (ranging from 45 to 94%) (1, 2), resulting in storage issues (mold, decay), and increasing transport costs due to higher weights. Use of a two-pass system that chips materials left in piles following harvest allows the material to dry as it ages, reducing the risks associated with high moisture materials (2, 3). In-woods drying may reduce downstream costs associated with moisture requirements for specific uses, and piling permits residue storage to mitigate seasonal availability issues.

Bundling Operations

Traditional logging operations involve wood in log form which is relatively easy to handle, stack, and transport. In-forest residues are often loose and scattered pieces. Machinery to collect and assemble this material into bundles or composite residue logs (crl) has been developed. The equipment improves residue handling and is mobile, but is relatively expensive.

Bundling operations are limited in North America, but more common in Europe where crl bundlers typically produce 11 to 24 bundles/hour (3 meters long; 60-90 cm in diameter). Bundling productivity is a function of the amount of residue available, the residue size, and the distribution of the residue across the landscape (4). Bundling operations are typically used in clearcut situations on level sites as use in mountainous situations or thinned stands may present accessibility and operational challenges (5).

In North America, bundling trials have been conducted and focus on optimizing bundle size to meet existing transportation resources and improving the productivity and economics of bundling. Equipment exists to create short bundles for stacking on trucks or long bundles to fit into existing log trailer bunks. Analysis estimates the cost of creating a crl is $16/dry ton assuming a productivity rate of 20 bundles/hour (bundlers can typically produce 10-30 bundles/hour) (5). Addition of transportation and chipping costs increase the wood cost to $29-30/dry ton excluding the purchase price for the biomass.

Densification of In-Woods Residues

The low energy density of wood residues (small diameter trees, tops, limbs, and other residual materials) substantially increase the cost of transporting the material, and they usually undergo some type of densification at the log landing site or at the harvest site prior to hauling to end-users or collection points. Adding a densification operation to an existing roundwood operation does not significantly reduce output

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In-woods chipping of harvesting residues.

from the existing operation and can generate additional income (1). Traditional densification options include chipping, grinding, or shredding the woody materials.

Chippers use high-speed blades to slice off small pieces of woody material. Grinders come in a variety of forms (e.g., horizontal or tub forms) and can accept woody materials encompassing a wide range of sizes. Grinders consist of a hammermill-type processor that uses metal hammers to break material into a desired size. Screens (sieves) can be used to sort the ground material into different size categories. The materials may undergo additional processing and are blown or conveyed into piles or trailers. Chipping or grinding can be performed in-woods, at log landings, and at regional collection points. If located at an end-user facility (power generator, fuel producer, etc), both chips and whole wood materials can be delivered to the facility which expands the availability of feedstocks. In-woods chipping at the time of harvest can reduce costs by \$56.76 to \$216.76 per acre when compared to operations that cut, pile, and mulch, due to reduced handling of the material over time (2), but as discussed above high moisture content can be an issue. Biomass contaminants from foreign materials such as rocks, soil, or other debris can cause significant wear on machinery.

Short Rotation Woody Crop Harvesting

In North America, short rotation woody crops (e.g., poplar, sweetgum, sycamore, and eucalyptus) have been planted primarily for fiber, but these systems could be a source of material for bioenergy uses. When grown for fiber, short rotation wood crops are grown in rotations sufficiently long to produce trees of a size that can be readily harvested and handled with existing forestry equipment. However, bioenergy uses generally assume shorter rotation lengths (3-5 years), particularly for species that are coppiced (such as willow). Machinery to process small diameter stems (cut and bundle systems) have been successfully used in

Europe, but are not cost effective and require excess handling of the material. New equipment that permits cutting and chopping of material in the field is expected to improve efficiency and reduce costs.

Shrub willow is being developed as a dedicated bioenergy wood crop. It is planted in a double-row configuration and harvested using modified crop harvesters such as a Claas-Jaguar or Bender harvester (6) which cut and chip the stems. In Canada, the Anderson Group has developed a baling system for short rotation woody crops. The Biobaler functions similarly to an agricultural round baler but will cut, grind, and bale woody materials in plantations and wooded settings. The machine cuts, collects, and bales materials up to a 4 inch diameter. The bales created are 4 foot in diameter and can be easily stored and transported. The Canadian Forest Service, along with a variety of partners, has focused on the development of different types cutting heads for harvesting machines (11). This research is ongoing, but offers significant promise for the harvesting of willow and poplar in plantation and agroforestry settings.

Willow harvesting and transportation costs are estimated to be 39-60% of the delivered cost of the delivered product (7, 8). Improving harvesting efficiency by 25% can reduce the delivered cost of biomass by $7.50 per delivered ton (1). When combined with improved varieties, reduced harvest costs can improve the future economic viability of short rotation wood crops (9). Other research is being conducted to optimize systems related to hybrid poplar and eucalyptus harvesting (10). Much of this research aims to reduce overall harvesting and transportation costs, evaluating trade-offs between cost of harvesting, densification, and transport.

Citations

1. Keoleian, G.A.; Volk, T.A. Renewable Energy from Willow Biomass Crops: Life Cycle Energy, Environmental and Economic Performance. Critical Reviews in Plant Science, 2005. 24: 385-406.
2. Jackson, B.; Ashton, S.F.; Schroeder, R., Baker, S. Module 4: Introduction to Harvesting, Transportation, and Processing in Sustainable Forestry for Bioenergy and Bio-based Products. Southern Forest Research Partnership, 2007.
3. Mitchell, C.P.; Stevens, E.A.; Watters, M.P. Short-rotation forestry – operations, productivity and costs based on experience gained in the UK. For. Ecol. Manage, 1999. 121: 123-136.
4. Rummer, B.; Len, D.; O'Brien, O. Forest Residues Bundling Project: New Technology for Residue Removal. 2004, Forest Operations Unit, Southern Research Station, USDA Forest Service.
5. Cuchet, E.; Roux, P.; Spinelli, R. Performance of a logging residue bundler in the temperate forests of France. Biomass and Bioenergy, 2004. 27: 31-39.
6. Westbrook Jr, M.D.; Greene, D.W.; Izlar, R.L. Utilizing Forest Biomass by Adding a Small Chipper to a Tree-Length Southern Pine Harvesting Operation. Southern Journal of Applied Forestry, 2007. 31(4): 165-169.
7. Abrahamson, L.P.; Volk, T.A.; Kopp, R.F.; White, E.H.; Ballard, J.L. Willow Biomass Producers Handbook. State University of New York, 2002. 31 p.
8. Stokes, B.J.; McDonald, T.P.; Kelly, T. Transpirational drying and costs for transporting woody biomass - a preliminary review. IEA/BA Task IX, Activity 6: Transport and Handling, 1993. P. 76-91.
9. Tharakan, P.J.; Volk, T.A.; Lindsey, C.A.; Arahamson, L.P.; White, E.H. Evaluating the impact of three incentive programs on the economics of cofiring willow biomass with coal in New York State. Energy Policy, 2005. 33(3): 337-347.
10. Spinelli, R.; Hartsough, B. Harvesting SRF poplar for pulpwood: Experience in the Pacific Northwest. Biomass and Bioenergy, 2006. 30 (5): 439-445.
11. Canadian Forest Service. Mechanization of harvesting for short-rotation intensive culture (SRIC). Natural Resources Canada, 2010. http://cfs.nrcan.gc.ca/subsite/ecoeti/mechanization

Transportation of Woody Biomass

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Introduction

Logistics activities constitute a large part of the total cost, energy use, and environmental impact of producing bioenergy and biofuels from wood. Transportation costs play a major role in optimally locating bioenergy facilities, and can provide an upper constraint on optimal facility capacity (1, 2).

Major Cost Variables

Woody biomass weight and density impact transportation costs. Weight affects density and can determine the maximum payload per trip. The moisture content (percent water) and ash content (percent nonorganic matter) of the wood contribute to its weight and volume, but not its energy content. Moisture content is especially important to decide if, when, and how to dry the wood (3).

Mass per volume density dictates whether weight or volume determines the quantities of woody biomass that can be transported in a single payload. If the density of the woody biomass is greater than (less than) the ratio of the truck weight capacity to truck volume capacity, weight (volume) determines quantity per payload (4) and the number of trips required to supply a facility (5). It is an important component for deciding if, when, and where to further densify or liquefy woody biomass. The energy per unit volume density (heating value) determines the amount of woody biomass required to produce a unit of energy output. Table 1 summarizes moisture, ash, and density properties for select woody biomass resources.

Table 1. Woody biomass properties, by type

Woody Biomass Properties				
	Bulk Density ($kg\ m^{-3}$)	Moisture Content (%)	Ash Content (%)	Energy Density ($MJ\ kg^{-1}$)
Mill Residues, sawdust	-	13	0.75	16
Forest Residues, green chips	350	50	1.94	10
Densified Residues, pellets	640	10	-	17
Liquefied Residues, bio oil	1200	25	0.1	18

Where ranges were provided, the average of the range is presented.

Source: Adapted from references 13, 14, 23, and 24.

Travel time and location geography affect transportation costs and are key in determining the optimal biorefinery location and mode of wood transportation. Location geography includes physical and infrastructural characteristics at the biorefinery and wood supply sites, and the transportation network connecting them. Physical barriers to transportation (such as large lakes) reduce the economic appeal of an area (6). The transportation infrastructure impacts costs and affects which transportation modes are economically feasible for a specific site (e.g., rail transport requires local access to a rail terminal) (7). This factor is particularly important for woody biomass obtained from forest logging/thinning operations, as these sites may not be accessible by large trucks (8). Road infrastructure, geographic constraints, and local regulations (1, 9) affect overall travel time through impacts on travel distance and speed. Geographic

Information System (GIS) tools are required to manage, analyze, and visualize the large amount of spatial and transportation data needed to estimate transportation costs (10, 11). Woody biomass handling activities incur costs associated with both time and equipment needs, as well as material losses which may occur during loading/unloading woody biomass from trucks, rail cars, and/or ships, bundling, and densification procedures (10), and is an important factor in logistics decisions.

Logistic Flow

Transportation logistics are determined by the supply source (e.g., mills, forests, plantations) and form (e.g., chips, slash, pellets, wood liquids) of the woody biomass. Supply source typically determines the form. Sawmills produce sawdust, shavings and solid wood waste while forest logging/thinning and tree plantation operations produce slash and small diameter trees.

The optimal form of woody biomass to minimize total cost includes consideration of the trade-off between transportation costs, and the cost of altering the material form. Each processing step incurs capital (equipment) and operational (labor and fuel) costs (12). Densified forms of woody biomass have lower transportation costs, but higher processing costs than raw biomass forms, such as slash (13, 14). As a general rule, woody biomass densification becomes more beneficial as transportation travel time increases (13).

Processes to alter woody biomass form include cleaning, communition, compression, and liquefaction. Cleaning includes segregation and sorting operations to separate unwanted tree parts and/or impurities from the woody biomass. Communition processes break the woody biomass into smaller, more uniform pieces though cutting, chipping and/or grinding. Compression applies pressure to the woody biomass in order to form smaller, denser and more uniform pellets or bundles. Liquefaction involves subjecting the woody biomass to a thermochemical or biochemical transformation process that produces a liquid (13, 14, 15). A communition process is required in most supply situations because raw woody biomass is rarely suitable for transportation or further processing. A compression or liquefaction process is used when the resulting reduction in transportation costs exceeds the increased costs associated with these processes.

Once the optimal form and necessary processes are determined, the location where the processing occurs must be decided (6). Processing can occur at the supply site, at a centralized location between the supply site and the bioenergy facility, or at the bioenergy facility. Due to economies of scale, process costs will generally be lowest at the bioenergy facility and highest at the supply location (16). Intermediate locations take advantage of process scale economies, but have higher transportation costs resulting from increased handling and decreased payload capacity during transport to the process facility. Additional considerations include whether to use mobile, relocatable, or stationary process equipment (13).

Woody biomass will typically need to be stored to account for variations in supply and to manage a facility's inventory levels. Supply levels may vary due to seasonal and weather fluctuations that affect logging/thinning operations; national and global market demands for wood products which affect plantation and forest harvesting decisions and mill residue quantities; and other factors that affect the timing and overall supply such as accommodations for endangered species, disease and insect impacts, expansion of public lands, regulatory constraints, etc. Storage operations should be designed to minimize the costs, minimize biomass loss during handling, and protect the material from fire, moisture and biological degradation (17).

Transportation Modes

Trucking is the most common mode used to transport woody biomass. It is more flexible and requires less specialized infrastructure than rail or shipping, and may be used in combination with these modes of transportation. Heavy trucks consist of a tractor (driver cabin and engine) and a trailer for cargo. Trailers come in various sizes corresponding to different payload amounts. Tractors and trailers can be separated permitting loading/unloading of trailers and later transport as convenient (17).

Dry van trailers (i.e., large boxes) are most commonly used to transport woody biomass and come in a variety of types that accommodate different forms of woody biomass (such as chip vans for hauling wood chips) and different loading/unloading procedures. They are enclosed or can be made so by attaching a tarp over the open top, eliminating the need to bundle the wood to protect it from the elements during transport. Flat bed trailers (horizontal platforms) are also used to transport woody biomass bundled into rounded or irregular shapes that do not fully occupy the interior space of dry van trailers. Additional handling may be needed to protect and secure the biomass for transport. Though not currently a common transport method, stainless steel tanker trailers can be used to transport woody biomass in liquid form (such as bio-oil), and have comparatively lower per unit transportation costs than other trailer types due to greater energy density and ease of handling liquids.

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Interior view of a chip van being loaded with residue chips.

Studies to evaluate woody biomass transport by truck typically assume travel times of less than one day and estimate the maximum distance beyond which truck transport is not economically viable. They generally do not include driver down time which constrains the maximum distance for truck transport to that which can be traveled in the cumulative hours a truck driver is legally allowed to drive (11 cumulative hours followed by 10 consecutive hours off-duty in the U.S.) (18).

For transport over longer distances or which exceed the maximum travel time allowed for trucks, rail or ship transport can be used (19). Rail car payload capacities, while variable, are typically exponentially greater than for trucks, and ship payload capacities are exponentially greater than for rail cars. Truck transport requires less energy per weight-distances (e.g., ton-mile) than rail transport, but more than ship transport (7, 20, 21). Rail and ship transport require terminals/harbors to be located near biomass source and destination locations. Truck transport may be needed to/from terminals and harbors (22). The use of more than one transport mode for a single haul is called intermodal transport or transshipment. Due to additional handling costs, a minimum haul travel time for secondary transportation mode (rail or ship) is needed to offset these costs and lower overall cost per time-unit (19). The economically viable maximum travel time for trucks and the minimum travel times for rail and ship may not overlap.

Future Potential

Process improvements, information improvements and new transportation modes can reduce woody biomass transport costs. Process improvements include developing new harvesting, collection, densification and handling technologies; new conversion technologies; and/or improving the efficiency and/or mobility of existing technologies. Information improvements include developing new or improved ways to locate and utilize information such as developing more accurate data and models that analyze the data. New communities, associations or websites that improve communication, collaboration, and transactions among bioenergy participants can improve information exchange.

New transportation modes could involve developing new technologies for handling woody biomass and infrastructure advances. Chip vans and walking floor trailers are in wide use and are effective, however, new technologies for increased efficiencies, lower costs, and handling of liquid forms of biomass are all possible. Alternatively, existing infrastructure can be used in new ways. For example, woody biomass could be converted to liquid or gas forms (e.g., hydrogen gas, bio-oil, ethanol, and methanol) and transported via pipelines similar to methods used by traditional energy producers. The cost of constructing new pipelines for woody biomass is high (15), and use of existing pipelines should be explored.

Logistics are a major component of establishing a woody biomass industry. Transportation needs significantly impact life-cycle energy use, greenhouse gas and other emissions, and bioenergy costs. Logistic factors, along with feedstock availability, are the determinants of bioenergy facility location. A well designed logistic flow can provide a competitive advantage to a bioenergy facility.

Citations

1. Khachatryan, H.; Jessup, E.L.; Casavant, K.L. Delivered Transportation Costs of Forest Residue for Cellulosic Ethanol Processing. International Food and Agribusiness Management Association (IFAMA), Monterey, CA, June 2008.
2. Kumar, A.; Cameron, J.B.; Flynn, P.C. Biomass Power Cost and Optimum Plant Size in Western Canada. Biomass and Bioenergy, 2003. 24: 445-464.
3. Frombo, F.; Minciardi, R.; Robba, M.; Rosso, F.; Sacile, R. Planning Woody Biomass Logistics for Energy Production: A Strategic Decision Model. Biomass and Bioenergy, 2009. 33: 372-383.
4. Jensen, K.; Menard, J.; English, B.; Park, W.; Wilson, B. The Wood Transportation and Resource Analysis System (WTRANS): An Analysis Tools to Assist Wood Residue Producers and Users. Forest Products Journal, 2002. 52(5): 27-33.
5. Perpina, C.; Alfonso, D.; Perez-Navarro, A.; Penalvo, E.; Vargas, C.; Cardenas, R. Methodology Based on Geographic Information Systems for Biomass Logistics and Transport Optimisation. Renewable Energy, 2009. 34: 555-565.
6. Graham, R. L.; Liu, W.; Downing, M.; Noon, C.E.; Daly, M.; Moore, A. The Effect of Location and Facility Demand on the Marginal Cost of Delivered Wood Chips from Energy Crops: A Case Study of the State of Tennessee. Biomass and Bioenergy, 1997. 13: 117-123.
7. Hoque, M.; Sokhansanj, S.; Bi, T; Mani, S.; Jafari, L.; Lim, J.; Zaini, P.; Melin, S.; Sowlati, T.; Afzal, M. Economics of Pellet Production for Export Market. The Canadian Society for Bioengineering, 2006. No. 06-103.
8. Han, H.; Lee, H.W.; Johnson, L.R. Economic Feasibility of an Integrated Harvesting System for Small-Diameter Trees in Southwest Idaho. Forest Products Journal, 2004. 54(2): 21-27.
9. Moller, B.; Nielsen, P.S. Analysing Transport Costs of Danish Forest Wood Chip Resources by Means of Continuous Cost Surfaces. Biomass and Bioenergy, 2007. 31: 291-298.
10. Noon, C.E.; Zhan, F.B.; Graham, R.L. GIS-Based Analysis of Marginal Price Variation with an Application in the Identification of Candidate Ethanol Conversion Plant Locations. Networks and Spatial Economics, 2002. 2(1): 79-93.
11. Graham, R. L.; English, B.C.; Noon, C.E. A Geographic Information System-Based Modeling System for Evaluating the Cost of Delivered Energy Crop Feedstock. Biomass and Bioenergy, 2000. 18: 309-329.

12. Forsberg, G. Biomass Energy Transport Analysis of Bioenergy Transport Chains Using Life Cycle Inventory Method. Biomass and Bioenergy, 2000. 19: 17-30.
13. Polagye, B. L.; Hodgson, K.T.; Malte, P.C. An Economic Analysis of Bio-energy Options Using Thinnings from Overstocked Forests. Biomass and Bioenergy, 2007. 31: 105-125.
14. Badger, P. C.; Fransham, P. Use of Mobile Fast Pyrolysis Plants to Densify Biomass and Reduce Biomass Handling Costs - A Preliminary Assessment. Biomass and Bioenergy, 2006. 30: 321-325.
15. Pro, B. H.; Hammerschlag, R.; Mazza, P. Energy and Land Use Impacts of Sustainable Transportation Scenarios. Journal of Cleaner Production, 2005. 13: 1309-1319.
16. Spinelli, R.; Nati, C.; Magagnotti, N. Recovering Logging Residue: Experiences from the Italian Eastern Alps. Croatian Journal of Forest Engineering, 2007. Vol. 28.
17. Rawlings, C.; Rummer, B.; Seeley, C.; Thomas, C.; Morrison, D.; Han, H.; Cheff, L.; Atkins, D.; Graham, D.; Windell K.. A Study of How to Decrease the Costs of Collecting, Processing and Transporting Slash. Studies for Three Sites in Montana. Montana Development Council, 2004. 21 p.
18. "Federal Motor Carrier Safety Regulations." Federal Motor Carrier Safety Administration Part 395. www.fmcsa.dot.gov
19. Mahmudi, H.; Flynn, P.C. Rail vs Truck Transport of Biomass. Applied Biochemistry and Biotechnology, 2006. 129(1-3): 88-103.
20. Hamelinck, C. N.; Suurs, R.A.A.; Faaij, A.P.C. International Bioenergy Transport Costs and Energy Balance. Biomass and Bioenergy, 2005. 29: 114-134.
21. Borjesson, P.; Gustavsson, L. Regional Production and Utilization of Biomass in Sweden. Energy, 1996. 21: 747-764.
22. Eriksson, L.N. Comparative Analyses of Forest Fuels in a Life Cycle Perspective with a Focus on Transport Systems. Resources, Conservation and Recycling, 2008. 52: 1190-1197.
23. Heller, M. C.; Keoleian, G.A.; Mann, M.K.; Volk, T.A. Life Cycle Energy and Environmental Benefits of Generating Electricity from Willow Biomass. Renewable Energy, 2004. 29: 1023-1042.
24. Food and Agriculture Organization of the United Nations. Economic analysis of wood energy systems. 2002. Rome, Italy. www.fao.org

Preprocessing and Pretreatment of Wood for Energy Production

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Preprocessing and pretreatment procedures may be undertaken to make wood more suitable for energy uses, and include physical and chemical processes to change wood characteristics (e.g., bulk density, particle size, moisture content, chemical structure). Physical preprocessing technologies such as drying, pelletizing/briquetting, and charcoal production are more typically used in thermal applications although they could also be used in biochemical applications. However, pretreatment technologies are critical for biochemical conversion processes.

Preprocessing Technologies

Drying Wood

Wood energy processes, particularly thermochemical processes, require consistent, low moisture materials (1). Dry wood contains more energy per pound than moister wood and increases combustion efficiency. Consistent moisture is needed to optimize the combustion process and minimize emissions resulting from incomplete combustion. Long term storage of moist materials may result in mold formation, rotting, or other deterioration of the material.

Wood piles can be dried by circulating air through the pile to prevent internal heat and condensation. Similarly, fresh air can be circulated through wood stored in bins and silos. These types of operations are typically time intensive and require large spaces to supply commercial operations, and are less commonly used than other methods.

Direct heating methods dry the wood using flue gases from combustion processes. It is an efficient process for operations where the flue gas can be directed to the dryer, and some of the dried material fed to the combustion unit, creating a self-contained system. Rotary drum dryers are commonly used as they can operate at high temperatures and quickly dry woody materials. Direct heat drying systems produce volatile organic compounds during combustion, necessitating emission cleaning systems, such as thermal oxidizers. Rotary drum dryers also increase the ash content of pelletized materials due to the fly ash in flue gas becoming attached to the material and subsequently being included in the finished pellets.

Indirect heating is more commonly used to dry wood for pelletization or other processes where the material is not directly fired, and uses hot water or steam. Belt conveyor, tube bundle, or fluid bed dryers are most commonly used. Belt conveyor dryers typically use heated air to dry material but can use direct heating sources as well. They operate at low temperatures and usually do not have emissions related issues. However, drying time can be much longer than for other dryers. Tube bundle dryers are less common. They also operate at low temperatures which reduces emissions, but increases drying time. Fluid bed drying is a promising new technology, more commonly used in Europe, but North American manufacturers are also developing these systems. In a fluid bed dryer, the wood flows through the system on a cushion of air forced from below through a perforated metal plate. This bed of air surrounds the wood particles and permits their movement, maximizing drying efficiency. Fluid bed dryers have short drying times, low emissions, and are efficient. However, bridging (interlocking of wood particles that stop material flow) can occur with larger sized wood particles.

Drying research and development activities focus on maximizing system efficiency (i.e., reducing time and energy use, increasing volume flow), reducing capital and operational costs, and reducing emissions.

Pelletization/Briquetting

Pelletizing arose as a means to handle wood waste materials such as sawdust. Though commonly used, their fine particle size and low bulk density cause handling problems and provides significantly less energy per unit volume. The pellet process compresses the material into higher bulk density units, typically ¼ inch to 5/16 inches in diameter for home heating, but larger sizes can also be made. Briquetting processes use a similar compression process as pelleting, but produce larger sized finished products. Pellets and briquettes are easy to handle and energy dense, and are increasingly being used to supply materials for heat and electricity. Manufacturers are also using larger sized wood particles (e.g., waste blocks from hardwood flooring) to create pellets and briquettes.

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A standard pellet mill system with preconditioner.

The wood pelleting process is simple, and similar to that used for agricultural feed pellets. For pelletization to be effective, the wood must be at a consistent moisture level (10-12%). Insufficient moisture causes overheating and charring of the pellet, while excess moisture creates pellets that don't hold their form and more readily break apart. Most pellet operations that consume green wood, dry the wood using rotary drum dryers. Following drying and if needed, the wood is reduced in size using a hammermill. The screen size used depends on pellet size and type being produced (i.e., smaller pellets require smaller die openings and smaller particle sizes). Particle sizes are typically less than ¼ inch. Following the drying and hammermill operations, the woody material passes through a conditioning unit which sits directly on top of the pelletizer. Here steam is added to moisten the wood surface (to aid binding and solid pellet formation), and chemical binding and/or lubricating agents are added to increase pellet durability. The material next moves to the pelletizer which uses rollers to force the woody material through holes or a flat die. The pellet die is often thick (greater than 1 ¾ inches) and the holes tapered to increase the pressure on the wood and raise its temperature. Hole diameter and taper significantly affect pellet durability and quality, and the pellet will not bind if the temperature is too high or too low. Mounted knives knock the pellets loose from the outside of the die, permitting cooling, usually with a counter flow cooler. The cooling process "sets" and hardens the pellet and reduces fines developed during handling.

Wood briquetting is similar, but simpler, than pelletizing. The dried woody material is pushed through a narrow opening which pressures the material to form large pieces that can be cut to size. Briquetting pressure and temperature are lower than for pelletization. A screw extrusion system is typically used to push the woody material through the opening, although some systems use hydraulic pistons.

Pelletization and briquetting are relatively common in Europe, and are becoming more prevalent in North America. Currently, 110 wood pelletization facilities have been identified in the United States and Canada (24). In Canada, wood pellet production in 2008 was 2 million tones of which 250,000 tons were used in the country, 450,000 tonnes were exported to the US, and 1.3 million tonnes were exported to Europe and other parts of the world (25). US pellet production was 1.8 million tonnes in 2008, with 80% of production being in the country and only 20% exported (24). Wood pellets are produced primarily for home use or small-scale heat production. Home heating pellets typically must meet several standards (2, 25) including:

- Density--pellets must have consistent hardness and energy content, and weigh at least 40 pounds/ cubic foot.
- Dimension—pellets must not exceed 1 ½ inches in length and be 1/4 to 5/16 inches in diameter to ensure predictable fuel quantities and prevent jamming.
- Fines—Pellets must limit the amount of material derived from fine materials (material capable of passing through 1/8 inch screen) to no more than 0.5 percent by weight. This limits dust resulting from breakage during handling and problems with pellet flow during operation.
- Chlorides—Pellets must not exceed 300 parts per million of salt to avoid stove and vent rusting.
- Net calorific value of 18.5 GJ/t

Pellets are available in premium and standard grades, which differ by ash content. Premium pellets contain less than 1% ash while standard pellets contain up to 3% ash by weight. Higher ash content leads to higher burner maintenance.

Research and development efforts focus on durability, ash content, and the use of binding agents. Europe is the primary market for North American home heating pellets and briquettes. Pellets must be durable to withstand extensive handling and prevent deterioration of pellet quality encountered during export and shipping activities. Binding agents (e.g., black liquor, lignin byproducts, glycerol, etc.) increase durability but may increase certain organic and inorganic compounds that can cause emission problems. In Canada and the U.S., pellets compete with heating oil, electricity, and other heat energy sources which are low cost relative to European fossil fuel prices. Lower production costs are needed to increase use in North America.

Charcoal Production

Charcoal is a widely used in the metallurgic, purification, and cooking industries, and has been produced for millennia (3). Charcoal is the carbon based byproduct that results when woody materials are heated to high temperatures under conditions of no or low oxygen (pyrolysis).

To make charcoal, wood is heated to high temperatures (above 527˚F; 275˚C), which releases water and volatile organic compounds. The wood begins to carbonize at this point. The process is exothermic and increases temperatures to the point that chemical reactions cease and charcoal is formed (over 662˚F; 350˚C). At this point, heat can be used to remove tar from the charcoal. The charcoal is then cooled and processed into briquettes or other forms for easier handling. Briquettes are formed by crushing the charcoal into a fine dust and adding a binder (typically starch or sawdust in 70-30 mixture) to hold the briquette together. The mixture is passed through a press to form the briquette and then dried (< 5% moisture) for home or industrial uses.

Traditional charcoal production uses either batch or continuous kilns. Continuous kilns are most common and average 2.75 tons of charcoal per hour using automated systems (4). Average charcoal yields of up to 20% per weight of biomass used can be achieved (5). Cyclone technologies are used to control particulate matter emissions, while gaseous emissions are reduced by afterburning (up to 80% reduction in VOCs and carbon monoxide) (4). Batch kilns are used in smaller operations and produce less charcoal and take longer than continuous kilns.

Modern facilities use a retort system to produce charcoal. In this system, the pyrolysis vapors (volatile organic compounds) are separated from the residual material early in the heating process. Originally developed to allow production of chemicals (e.g., acetic acid and methanol) from the separated vapors, the vapors are now used to produce the electricity and/or heat used throughout the production process. Use of the vapors also reduces emissions in addition to providing energy. Retort systems achieve higher charcoal yields (20-30%) compared to traditional techniques.

Opportunities to simplify retort technologies, thus reducing capital costs, exist. Yield improvements and production at larger scales can also reduce production costs (5). Combining charcoal and energy production through the use of vapors or through co-locating charcoal facilities with other biomass-to-energy facilities permits joint use of equipment, and could potentially reduce costs.

Pretreatment Technologies

Pretreatment is a critical element of biochemical processes as it prepares the woody material for efficient conversion to fuels or chemicals, and determines the yield, quality, and reactivity of the resulting process streams. Lignocellulosic biomass is a complex mixture of cellulose, hemicellulose and lignin. The primary goal of pretreatment is to remove lignin and other extractive compounds which inhibit further digestion or fermentation of the materials (6). Pretreating biomass increases hydrolysis sugar yields to nearly 90% of theoretical yields compared with less than 20% without pretreatment (6). Not all pretreatments work equally well for all biomass materials. In general, woody biomass is more difficult to pretreat than agricultural materials, and certain processes (e.g., acid, organosolv, and acid mediated steam explosion) are more effective for wood than agricultural residues. Ineffective pretreatment is primarily responsible for low enzymatic conversion rates in softwood (6). Several reviews describe the many pretreatment processes available for biomass (7-13).

Steam Explosion

Fiberboard production (i.e., hardboard or Masonite) have long used steam explosion to pretreat wood (14, 15). For energy uses, the steam pretreatment removes hemicelluloses, making the cellulose more accessible to hydrolysis enzymes, and thus easier to extract and convert (11).

In the steam explosion process, biomass is heated to high temperatures under high pressure conditions for a pre-defined time, causing acids contained in the biomass to hydrolyze the hemicelluloses to sugars, making them more accessible for further enzymatic hydrolysis. Steam is preferred as the heat method as it can rapidly heat the biomass while not diluting the hydrolyzed sugars (11). To conclude the process, the pressure and temperature are rapidly reduced, causing the biomass to fracture and become smaller in size. The change in biomass structure aids subsequent enzymatic digestion of cellulose, but does not significantly improve conversion efficiency (16). The remaining hemicellulose and other extractive materials can be removed prior to any additional hydrolysis.

Steam explosion, though effective, generates low sugar yields (17). Recent efforts that focus on adding a catalyst or chemicals (e.g., soaking in sulfur dioxide) prior to explosion to enhance cellulose accessibility have shown promise (18). Table 1 summarizes sugar yields for several dilute acid or acid impregnated steam explosion processes. Steam explosion is commercially used in the biofuels industry. Other similar pretreatments (e.g., hydrothermolysis which uses water in addition to steam) are being explored, but are still in the lab or pilot stage (17). A liquid hot water pretreatment process appears promising due to its relatively low costs, limited need for size reduction, and use of noncaustic agents (19).

Chemical Pretreatments

Table 1. Sugar yields from various dilute acid and steam explosion pretreatments of wood

	Yields of sugars as % of the theoretical in raw material					
Process	1	2	3	4	5	6
Pretreatment stages	1	1	1	2	2	2
Catalyst	SO_2	H_2SO_4	H_2SO_4	H_2SO_4	H_2SO_4	SO_2
Conditions	a	b	c	d	e	f
Glucose, P	13	33	21	57	41	35
Hemicellulose sugars, excluding glucose, P	52	55	79	84	96g	95g
Glucose, EH	58	39	31	17	36	45
Glucose and hemicellulose sugars, P + EH	66	67	75	82	77	80
Conditions: [a]210 C, 5.5 min 2.6% SO_2; [b]210 C, 1 min, 2.25% H_2SO_4; [c]215 C, 100s, 0.65% H_2SO_4; [d]Stage 1: 180 C, 4 min, 2.66% H_2SO_4; 2nd stage: 210 C, 1.5 min, 2.5% H_2SO_4; [e]Stage 1: 180 C, 10 min, 0.5% H_2SO_4; 2nd stage: 200 C, 2 min, 2% H_2SO_4; [f]Stage 1: 190 C, 2 min, 3% SO_2; 2nd stage: 220 C, 5 min, 3% SO_2						

Source: Reference 8

Chemical pretreatment focuses on cellular deconstruction, increasing access to cellulose by breaking the bonds between it and lignin, and increasing the surface area of material being processed to aid in enzyme access. Pretreatment of wood utilizing the addition of chemicals is a common technique to improve the release of sugars and other extractives from the plant material, specifically for liquid biofuel production.

Dilute Acid – Dilute acid pretreatment combines acids (e.g., nitric, sulfuric, hydrochloric) with water. Sulfuric acid has been most widely studied as it is inexpensive and highly effective (17). Dilute acid pretreatment is often conducted in conjunction with a steam explosion process. The impregnation of the woody material with an acid prior to steam applications significantly increases the release of sugar compared with steam explosion only. Acids are corrosive and require the use of steel tanks and pipes which increases capital investment costs (20). Byproducts such as salt, may also be produced and require disposal or subsequent processing (6).

Ammonia – Ammonia-based pretreatments have been studied extensively. Several different techniques, including supercritical ammonia, ammonia soaking, and ammonia fiber/freeze explosion (AFEX) have been utilized (17). The AFEX treatment is most promising as it produces near theoretical yields of celluloses at lower enzyme load levels (11). The process passes ammonia through the biomass in high temperature reactors where it reacts with lignin and separates it from the cellulose. The ammonia is recovered and recycled, further lowering costs. Removing lignin at the end of the process significantly increases the ability to hydrolyze biomass at even lower enzyme loadings, decreasing the overall process cost even more (21). This process produces significant delignification of woody biomass (22).

Alkaline – The use of high pH chemicals, such as sodium hydroxide and lime (calcium hydroxide) (23) to pretreat biomass has been shown to be relatively effective for agricultural residues but have not shown as much promise for woody biomass (17). Similar to other chemical pretreatments, alkaline chemicals combined with a steam explosion treatment show greater releases of hemicelluloses and lignin.

Solvent – The organosolv (solvent) process uses organic solvents (e.g., methanol, ethanol, acetone) to delignify the biomass and release hemicelluloses. The process has been developed and more thoroughly studied for wood pulping applications than bioenergy production. Organic solvents are expensive and the resulting materials are complex and more difficult to process.

Other-- Other chemical pretreatment techniques include sulfur dioxide, carbon dioxide, and a host of other chemicals. These techniques have been tested in small scale studies but have not moved beyond the lab scale, and currently offer limited promise for commercial applications.

Dilute acid, steam explosion, AFEX, and the liquid hot water pretreatments have received the greatest focus and are the most promising prospects for commercialization. Dilute acid pretreatment has much higher rates of cellulose conversion than steam explosion pretreatment, but also has higher costs and risks associated with its corrosive nature and the production of residues during the process (6). AFEX and liquid hot water treatments produce high cellulose conversion efficiencies but have not been as widely applied or studied as the other two processes. Table 2 summarizes select performance metrics for these pretreatment processes, and Table 3 summarizes a set of performance metrics by which the effectiveness of pretreatment processes can be measured.

Table 2. Performance metrics of select pretreatment processes

Pretreatment Process				
Feature	Dilute Acid	Steam explosion	AFEX	Liquid hot water
Reactive Fiber	Yes	Yes	Yes	Yes
Particle size reduction required	Yes	No	No	No
Hydolyzate inhibitory	Yes	Yes	No	Slightly
Pentose recovery	Moderate	Low	High	High
Low cost materials for construction	No	Yes	Yes	Yes
Production of process residues	Yes	No	No	No
Potential for process simplicity	Moderate	High	Moderate	High
Effectiveness at low moisture levels	Moderate	High	Very high	Not known

Source: Adapted from Reference 12

Table 3. Pretreatment performance metrics

Performance Metric	Description
Fiber Reactivity	Effective pretreatments approach or exceed 80% of theoretical cellulose conversion through subsequent enzymatic hydrolysis of hardwood feedstocks within a short (5 day) period of time
Pentosan recovery	High recovery of pentose sugars for ethanol production (80% of theoretical yield)
Extent of Hydolyzate Inhibition	Lower levels of residual inhibitors from pretreatment desired in hydrolysis conversion (can be removed after pretreatment if necessary)
Extent of Size Reduction Required	Pretreatments that require little size reduction are more efficient from a process and economical standpoint
Low-Cost Materials of Construction	Cost of equipment (i.e. reactor) necessary to prevent corrosion or other effects of caustic pretreatment processes
Production of Process Residues	Though often inert, residues produced through pretreatment must be disposed of properly
Potential for Process Simplicity	Using pretreatments that do not require reagent recovery or product cleaning reduces costs and improves process time
Effectiveness at Low Moisture Levels	High moisture increases energy requirements

Source: Adapted from Reference 12

Several barriers to commercializing pretreatment technologies exist. Many have been developed and tested only at a lab scale or pilot scale. Scaling the technology to commercial size will require significant engineering of reactors and other vessels (20). Processes that produce a residue or byproduct will require plans to dispose of, or use, potentially large volumes of material. Systems that combine physical and chemical preprocessing and pretreatment technologies need to be evaluated. And a better understanding of the mechanisms (at a molecular scale) by which pretreatment functions is needed to direct research to improve efficiency and lower cost (11).

Citations

1. Van Loo, S.; Koppejan, J. The Handbook of Biomass Combustion and Cofiring. Earthscan, London ,2008. 442 pp.
2. Pellet Fuels Institute. Fuel Grade Requirements. 2010. Available at: http://www.pelletheat.org/3/institute/standards/PFI%20Standards.pdf.
3. Toole, A.W.; Lane, P.H.; Arbogast, Jr, C.; Smith, W.R.; Peter, R.; Locke, E.G.; Beglinger, E.; Erickson, E.C.O. Charcoal Production, Marketing, and Use. USDA Forest Service Forest Products Laboratory, 1961. 2213, 141 p.
4. Environmental Protection Agency. Compilation of Air Pollutant Emission Factors, Volume 1: Stationary Point and Area Sources. AP 42, Fifth Edition, 1995. p. 10.7-1-7.
5. Doman, J.; Trossero, M. Industrial Charcoal Production. United Nations Food and Agriculture Organization, 2008. TCP/CRO3101.
6. Lynd, L.R. Overview and evaluation of fuel ethanol from cellulosic biomass: Technology, Economics, the Environment, and Policy. Annual Review Energy and Environment, 1996. 21: 403-465.
7. Wyman, C.E., What is (and is not) vital to advancing cellulosic ethanol. Trends in Biotechnology, 2007. 25(4): p. 153-157.
8. Galbe, M.; Zacchi, G. A review of the production of ethanol from softwood. Applied Microbiology and Biotechnology, 2002. 59(6): 618-628.
9. Chandra, R. P.; Bura, R.; Mabee, W. E.; Berlin, A.; Pan, X.; Saddler, J. N. Substrate pretreatment: The key to effective enzymatic hydrolysis of lignocellulosics? In Biofuels, 2007. 108: 67-93.

10. Hendriks, A. and G. Zeeman, Pretreatments to enhance the digestibility of lignocellulosic biomass. Bioresource Technology, 2009. 100(1): 10-18.
11. Mosier, N.; Wyman, C.; Dale, B.; Elander, R.; Lee, Y.Y.; Holtzapple, M.; Ladisch, M. Features of promising technologies for pretreatment of lignocellulosic biomass. Bioresource Technology, 2005. 96(6): 673-686.
12. Wyman, C. E.; Dale, B. E.; Elander, R. T.; Holtzapple, M.; Ladisch, M. R.; Lee, Y. Y. Coordinated development of leading biomass pretreatment technologies. Bioresource Technology, 2005. 96(18): p. 1959-1966.
13. Sanchez, O. J.; Cardona, C. A. Trends in biotechnological production of fuel ethanol from different feedstocks. Bioresource Technology, 2008. 99(13): p. 5270-5295.
14. Mason, W.H. Process and apparatus for disintegration of wood and the like. US Patent 1,578,609, 1926.
15. Saddler, J.N.; Ramos, L.P.; Breuil, C. In: Saddler, J.N. (Ed.) Bioconversion of Forest and Agricultural Plant Wastes, C.A.B. International, Wallingford UK, 1993. P. 73-92.
16. Brownell, H.H.; Yu, E.K.C.; Saddler, J.N. Steam-explosion pretreatment of wood: Effect of chip size, acid, moisture content and pressure drop. Biotechnology and Bioengineering, 1986. 28(6): 792-801.
17. Hsu, T.A. Pretreatment of biomass. In: Wyman, C.E. (Ed.), Handbook on Bioethanol, Production and Utilization, Taylor and Francis, Washington DC, 1996. P. 179-212.
18. Gregg, D.; Saddler, J.N. Bioconversion of lignocellulosic residue to ethanol: Process flowsheet development. Biomass and Bioenergy, 1995. 9(1-5): 287-302.
19. van Walsum, G.P.; Allen, S.G.; Spencer, M.J.; Laser, M.S.; Antal Jr, M.J.; Lynd, L.R. Conversion of Lignocellulosics Pretreated with Liquid Hot Water to Ethanol. Applied Biochemistry and Biotechnology, 1996. 57-58: 157-170.
20. Warner, R.E.; Mosier, N.S. Ethanol from Cellulose Resources. In: Walsh, M.E. (Ed.), BioWeb, 2007. http://bioweb.sungrant.org/Technical/Biofuels/Technologies/Ethanol+Production/Ethanol+from+Cellulose+Resources/Default.htm
21. Kim, T.H.; Kim, J.S.; Sunwoo, C.; Lee, Y.Y. Delignification aspect of enzymatic hydrolysis in the ARP process. In: Davison, B.H.; Lee, J.W., McMillan, J.D.; Finklestein, M. (Eds.), 24th Symposium on Biotechnology for Fuels and Chemicals, 2002.
22. Yoon, H.H.; Wu, Z.W.; Lee, Y.Y. Ammonia-recycled percolation process for pretreatment of biomass feedstock. Applied Biochemistry and Biotechnology, 1995. 51-52: 5-19.
23. Playne, M.J. Increased digestibility of bagasses by pretreatment with alkalis and steam explosion. Biotechnology and Bioengineering, 1984. 26(4): 426-433.
24. Spelter, H. and Toth, D. North America’s Wood Pellet Sector. 2009, USDA Forest Service Forest Products Laboratory, Research Paper FPL-RP-656. 21 pp.
25. Wood Pellet Association of Canada. www.pellet.org

Thermal and Biochemical Transformations of Wood and Forest Resources

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Biomass resources can be converted into power, biofuels, and chemicals through the use of thermal and biochemical processes. Thermal processes include conventional combustion technologies (direct combustion, co-firing) as well as advanced thermal technologies (gasification, pyrolysis, torrefaction), which produces gases and oils, that when combined with other chemical and biological processes, can produce fuels and organic chemicals. A number of overview articles that describe advanced thermal technologies are available (1-3). Biomass resources can also be converted to fuels, such as ethanol, using biochemical approaches. Several review articles describe the process technology, cost, energy balance, and research needs (4-13). Van Loo and Koppejan (2008) have conducted a comprehensive overview of boiler systems and their overview served as a significant resource in this review (14). Though this article focuses on woody biomass, these technologies can also use other lignocellulosic resources, such as grasses and agricultural crop residues.

Conventional Thermal (Combustion) Technologies

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Direct Combustion Technologies

Energy from woody materials most commonly uses direct combustion technologies. Direct combustion combines oxygen from the air with fuels to produce heat, CO_2, and H_2O. The amount of heat energy produced varies depending on chemical composition of the fuel and the moisture content of the material. The process also produces residues such as ash and incompletely combusted carbon. At an industrial scale, combustion occurs in fixed bed, fluidized bed, or pulverized fuel furnaces (boilers) (14). Fixed bed furnaces have been used most throughout history while pulverized fuels and fluidized beds furnaces are more recent technologies.

Fixed bed furnaces feed the fuel (biomass) through the side of the unit where it rests on top of a grate. Air is fed upward through the grate to increase the amount of oxygen available for combustion. Air is also inserted above the combustion bed to aid the combustion process and to increase the flow of heat and flue gas from the process. Ash falls through the grate and is removed. A variety of grates can be used (e.g., fixed grates, moving grates, rotating grates, and vibratory grates).

The efficiency of fixed bed furnaces is a function of the fuel characteristics (particle size, moisture content, type of biomass, etc.) and the furnace design. Because wood has a tendency to bridge and pile, creating an uneven distribution of fuel across the grate, vibratory grates or rotating grates provide higher combustion efficiencies and less ash and residues than other types of grates (14). The flow of fresh oxygen and flue gas within the furnace affects combustion efficiency and heat recovery efficiency. Recirculation of flue gases can increase combustion efficiency dramatically. Fixed bed furnaces generally have lower capital investment requirements and lower operating costs than other combustion technologies. However, their overall efficiency levels are lower, and they require a consistent fuel (little variation in size and characteristics) (14).

Fluidized bed furnaces are relatively new. They typically have a chamber with a perforated bottom plate to allow for the upward flow of air. A layer of inert material (e.g., sand, dolomite) rests on the bed. Fuel is inserted above the bed and air is forced upward through the bed creating a "fluid" state which constantly moves and mixes the fuel and the bedding material. This mixing increases the transfer of heat between the bedding material and the fuel, increasing the efficiency of combustion. Fluidized bed furnace types include bubbling and circulating beds, which differ by the amount and flow of air within the system. Compared to fixed bed furnaces, they have higher combustion efficiencies, require lower air and energy inputs, and operate at lower temperatures. They can utilize a wider variety of fuel types and characteristics (moisture), but require the fuel to have a small particle size (40-80mm) (14). Overall emissions are low, but the constant movement of materials increases the level of dust in the flue and facilities must have adequate dust collection systems (14). The bedding material must be replenished regularly as some material is removed when ash is cleaned from the system. Fluidized bed systems also have higher capital investment costs primarily because they involve larger scale facilities. Because of the large size of facilities, ash handling is more time consuming and costly.

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A direct combustion system fueled by wood waste with storage silo in foreground.

Pulverized fuel systems require fuels with small particle sizes (e.g., sawdust). The technology is widely used in coal powered facilities. Fuel is blown into the combustion chamber through the primary intake. The injection of the air/fuel mixture is usually conducted in a manner that causes the fuel to circulate in a vortex, particularly in systems where the flue gas is recirculated (14). As a result of the rapid air movement and fine fuel particle size, ash is expelled from the combustion chamber in the flue gas. The mixture of ash and flue gas then enters a cyclone where the ash is separated from the flue gas. The ash is precipitated out and is removed from the system while the flue gas is recirculated back into the combustion system. Challenges associated with pulverized systems include the requirement of a secondary fuel burner (natural gas or oil) to start combustion. Also, due to the risk of explosion associated with fine fuel particles, the fuel must be fed into the combustion chamber at a consistent and controlled rate. The fuel must be of a consistent quality (moisture content and particle size) for the system to operate efficiently.

Co-firing Technologies

In co-firing, a biomass fuel is mixed with coal (typically less than 10% by weight) in an existing coal boiler. Wood chips are similar in size to coal and can be relatively easily incorporated into existing systems with low capital investment. Wood co-firing can be used in several types of combustion systems, such as pulverized and fixed bed systems, and with a variety of coal types. Co-firing with wood is a relatively low cost method to reduce emissions as existing coal facilities can add woody biomass as a fuel source for a low capital investment.

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A spreader stoker coal boiler, a standard type of combustion system where co-firing will occur

Direct firing approaches mix the coal and wood prior to entering the boiler. In pulverized systems , for example, the wood is separately handled, reduced in size, and mixed with coal prior to entering the combustion chamber. Direct fire is the most common co-firing method (14). Indirect firing integrates gasification technology with coal combustion (14). The gas produced during the gasification process is injected into the coal combustion chamber, increasing energy output and reducing coal quantity requirements. Co-firing can also use a separate wood combustion chamber situated adjacent to an existing coal-fired boiler (14). The steam from wood combustion is combined with that of coal and cycled throughout the system.

Capturing Heat and Steam for Energy Production

Most electricity generated from wood combustion uses a closed thermal cycle in which the combustion heat energy is transferred through steam or gas turbines, steam engines, or other media to produce electricity (15). Closed thermal cycles are particularly effective for biomass combustion (14) as they separate the clean electricity production process from the relatively dirty combustion process (i.e., flue gas containing solid byproducts and ash). Open cycle energy production methods (e.g., internal combustion engine) require a clean gas or liquid fuel, and are not designed to handle dirty or contaminated fuel. Technologies to clean flue gasses will be needed for open cycle processes to be able to effectively use biomass resources (14).

Steam turbines and steam piston engines are the most common tools used to generate power. Steam turbine facilities can be large (up to 500 MW), while steam piston facilities are smaller scale (typically around

1.5 MW) (14). Nearly all steam processes use a Rankine cycle system which uses water as the medium to transfer energy. Heat from the combustion process superheats water to create high pressure steam in the boiler, which is then passed through expansion chambers to lower the pressure. The resulting kinetic energy turns a rotor and generates electricity. Residual steam and water are recovered and recycled through the process. Energy efficiencies are typically low for small facilities (less than 15%) and much higher at large, multistage turbine facilities (40%) (14).

Combined heat and power facilities (CHP) use the same combustion system to produce both heat and power. Conventional power facilities typically emit heat as a byproduct through ash streams or cooling towers. CHP facilities, also known as cogeneration facilities, capture the heat product and use it for industrial processes. CHP facilities typically use either a back-pressure or extraction technology to convert the steam to energy through steam turbines. Back-pressure plants use all of the waste heat generated from condensation at high pressures and temperatures, while extraction technologies use variable amounts of the heat and steam (14).

CHP facilities are becoming more common, especially at smaller scales. Small facilities are more suited to producing heat as the primary product with power as the secondary product as electricity generation is relatively efficient (10% conversion). Larger CHP facilities (tens of megawatts) generally produce electricity as the primary product due to higher conversion rates (25%) (14). Incorporating advanced technologies (e.g., complete drying systems; advanced steam cycles) can increase the power conversion efficiency up to 30%, but require up-front capital costs (16).

Alternative biomass combustion technologies include steam screw engines, Stirling engines, and closed gas turbines which are at different stages of development. An organic Rankine cycle technology may prove useful for woody biomass fuels. While similar to the water-based Rankine cycle, this process uses organic liquids rather than water as the medium. These liquids operate at lower temperatures and pressures, improving operational efficiency and scale. It has been used in geothermal applications, but not with biomass. Integrated gasification combined cycle technologies have high electricity conversion rates (up to 42%) (14), but need further testing and development before commercial scale facilities can be constructed.

Future Potential

In 2008, 49% of U.S. electricity was produced from coal and less than 3% was from renewable sources. In Canada, fossil fuels are used to produce 86% of electricity (20% coal and 56% oil and natural gas) with less than 1% produced from renewable resources. In total, 6% of Canada's overall energy is derived from biomass.

Policy, rather than technology, has been a greater impediment to the expanded use of wood in direct combustion and co-firing systems. Improved feedstock handling systems have made these systems more feasible, but still require up-front investment. New combustion and ash handling equipment may also be needed. Few federal and state policies have traditionally existed to encourage use of biomass materials, and many large public utilities are hesitant to invest in direct firing or co-firing systems without a clear tax or environmental benefit. The situation is changing. New environmental regulations and renewable energy policies are causing the energy industry to re-evaluate using biomass as an alternative to coal.

The U.S. is considering a national renewable electricity standard (RES). The U.S. Department of Energy projects that with an RES, electricity production from wood and other biomass resources will increase from 39 billion kilowatt hours in 2007 to 359-460 billion kilowatt hours in 2025, depending on how the program is structured (a 900% increase) (17).

Wood combustion emits lower levels of sulfur oxides, nitrogen oxides, and no net carbon into the atmosphere compared with coal (18). Depending on the technology, co-firing wood with coal can substantially reduce sulfur and nitrogen oxides relative to burning coal alone (19), and may reduce mercury emissions. Table 1 summarizes emissions for power facilities by boiler type and fuel used.

Table 1. Emissions for power facilities by boiler type and fuel source

Air Emissions from Power Production Facilities by Boiler Type and Fuel Source					
		Emission Category (lbs/MWh)			
Firing Technology	Fuel	Sox	Nox	CO	PM-10
Stoker Boiler	Wood Residues	0.08	2.1	12.2	0.5
Fluidized Bed	Biomass	0.08	0.9	0.17	0.3
Cofired Boiler	15% Biomass	12.2	6.17	0.35	0.32
Stoker Boiler	Bituminous Coal	20.2	5.8	2.7	0.62
Pulverized Boiler	Coal	14.3	6.89	0.35	0.32
Fluidized Bed	Coal	3.7	2.7	9.6	0.3

Source: Adapted from Reference 16

Advanced Thermal Technologies

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Gasification

Gasification technologies convert carbon based materials to a mixture of carbon monoxide and hydrogen (syngas) under conditions of high temperature and steam, air, oxygen, or some combination of them.

Gasification technologies are flexible in that they can use numerous feedstocks (e.g., wood and other biomass, oil, coal, natural gas) and depending on operating conditions, can produce syngas that can be converted to completely CO_2 and H_2 for fuels, or for other uses (e.g., coupled with a Fischer-Tropsch process to produce numerous hydrocarbon chemicals and fuels; low heat value mixtures for combustion or engine fuel applications; high heat value mixtures for chemicals) (20). Gasification technologies have been extensively studied for fossil fuel resources and several reviews exist. Examples of biomass studies include gasification for electricity generation (21), and the use of a Fischer-Tropsch process to convert poplar to chemicals (22). Table 2 summarizes the advantages and disadvantages of several gasification configurations.

Table 2. Comparative performance characteristics of various gasification systems

	Principal Advantages	Primary Technical Challenges
Gasifying agents		
Air	Partial combustion for heat supply of gasification; moderate char and tar content	Low heating value; Large amount of N_2 in syngas (e.g., 450% by volume); Difficult determination of ER (usually 0.2–0.4)
Steam	High heating value syngas; H_2-rich syngas	Requires indirect or external heat supply for gasification; High tar content in syngas; Requires catalytic tar reforming
Carbon Dioxide	High heating value syngas; High H_2 and CO in syngas and low CO_2 in syngas	Requires indirect or external heat supply; Requires catalytic tar reforming
Gasifier design		
Fixed/moving Bed	Simple and reliable design; Capacity for wet biomass gasification; Favorable economics on a small scale	Long residence time; Non-uniform temperature distribution in gasifiers; High char or/and tar contents; Low cold gas energy efficiency; Low productivity
Fluidized Bed	Short residence time; High productivity; Uniform temperature distribution in gasifiers; Low char or/and tar contents; High cold gas energy efficiency; Reduced ash-related problems	High particulate dust in syngas; Favorable economics on a medium to large scale
Gasifier operating parameters		
Increased Temperature	Decreased char and tar content; Decreased methane in syngas; Increased carbon conversion; Increased heating value of syngas	Decreased energy efficiency; Increased ash-related problems
Increased Pressure	Low char and tar content; No costly compression required for downstream utilization of syngas	Limited design and operational experience; Higher gasifier costs at small scale
Increased Equivalence Ratio	Low char and tar content	Decreased heating value of syngas

Source: Reference 23

The higher oxygen to carbon (O/C) ratio of biomass resources relative to other feedstocks such as coal, leads to greater thermodynamic losses during gasification. Modifications to biomass gasification (e.g., co-firing with coal, torrefaction prior to gasification, component separation and lignin gasification only) have been suggested as means to mediate these losses (24). Efficiency is increased if the biomass is first dried which prevents heat loss due to water evaporation during gasification (25).

Gasification reactor design and optimization, and reducing tar formation during biomass gasification (26) are the primary areas of research. Gasifier reactor designs include fixed, moving or fluidized bed systems. Fluidized bed systems introduce biomass into an inert heat transfer medium such as sand. Although more complex than other designs, they allow high and uniform heating rates, good temperature control and high throughput.

Tars produced during gasification can foul the reactor, poison catalysts used to convert the syngas to other products, and reduce gas yields, all which increase operating costs (26). Tars are condensable mixtures of aromatic and aliphatic hydrocarbons (such as organic compounds with a molecular weight higher than benzene) (27), and are formed during the gasification of all carbon feedstocks. However, tars formed during coal gasification include useful chemical products (benzene, toluene, xylene, coal tar), unlike the more oxygenated materials formed during biomass gasification for which no markets have yet been established. Tar removal and/or clean-up can exceed the cost of the rest of a gasification project, and constitute a significant impediment to biomass gasification.

Processes to reduce tar formation are being explored (27, 28) including primary processes to reduce tar formation during syngas production and secondary processes that, following gasification, clean the syngas in a separate reactor. Primary approaches include new reactor designs that minimize tar formation, and use additives to crack tars into smaller molecules during gasification. Additives such as Ni, charcoal, dolomite and olivine have been tested, and their characteristics reviewed (29). Plasma methods have also been tested in wood gasifiers (30). Primary conversion processes are not yet commercial, but potentially offer significant advantages by eliminating the need to include a separate unit for tar removal or cracking. Secondary processes are widely used in commercial operations, and include thermal or catalytic cracking of the tar, or mechanical separation and tar removal from the syngas. Chemical methods are preferred as they can catalytically convert the tar into additional syngas (28).

While normally conducted under high temperature steam conditions, gasification using supercritical water is being explored (31). Potential advantages include very low levels of char formation and the ability to use high moisture feedstocks. When coupled with a catalytic tar cracker, clean and nearly complete gasification of biomass is possible. The process has been demonstrated using biomass feedstocks. Simple feedstocks (e.g., corn starch) can be converted to hydrogen at near theoretical maximum yields, but more complex feedstocks (e.g., sawdust) have lower conversion rates which increases cost (32). No commercial systems have yet been built.

A detailed technoeconomic assessment of several different gasification technologies using poplar as a feedstock has been published (22). The focus of the evaluation is on Fischer-Tropsch conversion to chemicals, but the assessment describes a complete process in detail from biomass preparation to production of Fischer-Tropsch liquids.

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Pyrolysis oil is a highly complex mixture of over 200 chemical compounds.

Pyrolysis

Pyrolysis occurs in the absence of oxygen and converts the feedstock, such as biomass, into a mixture of solid, liquid and gas, the proportion of which depends on operating conditions. Several extensive and comprehensive reviews of biomass pyrolysis process conditions, reactor configurations, oil composition and potential use as a starting material for fuel and chemical production are available (33-38). A recent review describes biomass conversion to hydrogen by several routes including pyrolysis and gasification (39).

Biomass is preferentially converted to charcoal at relatively low temperatures and long reaction times (slow pyrolysis) or to a mixture of liquids, gases, and char at higher temperatures and short reaction times (fast pyrolysis). In contrast to gasification which produces small molecules, fast pyrolysis does not significantly reduce the complexity of biomass, but rather converts it to pyrolysis oil. Pyrolysis oil is a viscous material with a strong smoky odor and half the heating value of conventional fuel oil. Fast pyrolysis oil production is maximized at temperatures of around 500ºC, short reactor contact times (a few seconds), and conditions that promote rapid condensation of vapors. Oil yields of up to 80 wt% of the dry feedstock quantity have been observed. Fast pyrolysis systems lend themselves to distributed conversion in several small facilities, followed by transport to a larger centralized facility for further upgrading. Table 3 summarizes the composition of pyrolysis oil from several woody sources.

Table 3. Typical physical properties of pyrolysis oils

Biomass Feedstock Used to Produce Pyrolysis Oil				
Property	Birch	Pine	Poplar	Various
Solids (wt %)	0.06	0.03	0.045	0.01-1
pH	2.5	2.4	2.8	2.0-3.7
Water (wt %)	18.9	17.0	18.9	15-30
Density (kg/m^3)	1.25	1.24	1.20	1.1-1.3
Viscosity, cSt (50 °C)	28	28	13.5	13-80
LHV (MJ/kg)	16.5	17.2	17.4	13-18
Ash (wt %)	0.004	0.03	0.01	0.004-0.3
CCR (wt %)	20	16	---	14-23
C (wt %)	44.0	45.7	46.5	32-49
H (wt %)	6.9	7.0	7.2	6.9-8.6
N (wt %)	<0.1	<0.1	0.15	0-0.2
S (wt %)	0.00	0.02	0.02	0.00-0.05
O (wt %)	49.0	47.0	46.1	44-60
Na + K (ppm)	29	22	6	5-500
Ca (ppm)	50	23	4	4-600
Mg (ppm)	12	5	3	
Flash Point (°C)	62	95	64	50-100
Pour Point (°C)	-24	-19	---	-36--9

Source: Reference 40

The primary advantage of converting woody biomass to pyrolysis oil is to increase its energy density and improve its transportability. However, pyrolysis oil is highly complex and a mixture of several compounds (i.e., carbohydrate dehydration products such as hydroxycarbonyl compounds, acids and phenolics; oligomeric lignin derivatives; and 15 – 30% water). More than 200 different compounds have been identified, with no one compound present in higher than 10 wt% which makes it difficult to separate single, high value materials (41, 42). Additionally, the mix of compounds differs by biomass source and moisture content.

Pyrolysis oils have low heating values (due to the water content) and suffer from poor ignition performance, limiting their potential as fuels. And the presence of relatively high ash levels limits their use as petroleum substitutes to applications that use low-value heavy fuel oils. Pyrolysis oils are also thermally unstable, and become more viscous with heating. At room temperature, the viscosity of some oils can double within a year and exposure to temperatures of 60°C reduces the time to a week (40). Their low pH makes them highly corrosive to normal construction materials. They are insoluble in nonpolar petrochemicals, limiting their ability to be blended with existing fuel supplies. The complexity of pyrolysis oil suggests that its utility as a chemical feedstock may be limited (35), except in cases where it can be employed as a mixture (such as in the replacement of phenol in adhesive resins) (43).

Post-pyrolysis upgrading is being explored as a means to overcome some of the disadvantages inherent in pyrolysis oil, and as a way to capture value from the oils. Steam reforming of wood pyrolysis oils has been widely studied as a source of hydrogen, and as part of a larger integrated biorefinery concept (44-46). Hydrogen yields as high as 85% of theoretical have been achieved from poplar using commercial reforming catalysts (47). Hydrotreating can be used to upgrade pyrolysis oils. Fast pyrolysis of sawdust followed by hydrotreating in the presence of a sulfided Co-Mo-P catalyst, produced a hydrocarbon fuel (48). However, the need to add H_2 as a reagent increases the cost of this approach. Treatment of pyrolysis vapors with a variety of zeolite and mesoporous catalysts prior to condensation has been investigated as a means to alter the composition, structure and stability of the final product (49). Aromatic components increase markedly in these processes, and they have recently been examined as a way to produce aromatic compounds for use as fuel components (50).

Torrefaction

Torrefaction is a relatively new process that thermally treats biomass at low temperatures (200 – 300°C) in the absence of oxygen (51). It produces a solid material that retains most of the energy content of the starting biomass, but has much lower amounts of moisture, and a considerably lower O/C ratio. The process also generates a hydrophobic material resistant to the readsorption of moisture. Its physical characteristics render it more suitable for grinding or pelletizing, and thus for use in biomass/coal co-firing processes. Torrefaction reduces size reduction energy requirements by 50 – 80% (52). It has been used to pretreat biomass and increase gasification efficiency (25). A recent analysis suggests that when compared with pyrolysis or conventional pellet processes, torrefied biomass is more economic in a biomass-to-liquids gasification and subsequent Fischer-Tropsch conversion to liquids process (53). Table 4 summarizes the typical compositional changes that occur with wood torrefaction.

Table 4 - Compositional data for torrefied wood

	Wood	Torrefied wood (250° C, 30 min)	Torrefied wood (300° C, 10 min)
Carbon (%)	47.2	51.3	55.8
Hydrogen (%)	6.1	5.9	5.6
Oxygen (%)	45.1	40.9	36.2
Nitrogen (%)	0.3	0.4	0.5
Ash (%)	1.3	1.5	1.9
LHV(MJ/kg)	17.6	19.4	21.0

Source: Reference 24

Biochemical Technologies

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Ethanol

The U. S. Energy Policy Act of 2005 requires use of 7.5 billion gallons of renewable fuel in gasoline production by 2012 (which will be supplied mostly be corn ethanol) and 16 billion gallons of renewable fuel to be produced from cellulosic materials by 2022 (54). Canada has committed to 5% of gasoline being produced from renewable sources in 2010 and a 2% renewable content in diesel and home heating oil by 2012 though no specific cellulosic fuel goals have been set (77). Ethanol production from lignocellulosic materials via biochemical pathways includes first pretreating the materials using one of the processes described previously, followed by hydrolysis and fermentation.

Hydrolysis and Fermentation

Hydrolysis converts polysaccharides into monomeric sugars suitable for fermentation. Lignocellulosic hydrolysis uses a mixture of cellulase enzymes and produces glucose as the primary sugar. Alternatively, hydrolysis can use acid, such as direct treatment of cellulose with concentrated sulfuric acid, to produce glucose, but this approach is expensive and the acids are highly corrosive. Enzymatic hydrolysis is the focus of current research efforts. Following hydrolysis, yeast is used to ferment the glucose into ethanol. One glucose molecule is converted to two ethanol and two CO_2 molecules.

The economic production of ethanol from lignocellulosic materials requires that all sugars (both C_5 and C_6) be fermented. The mannose (C_5 sugar) contained in hemicellulose can be fermented with the same organisms used to ferment glucose. Softwood hemicellulose contains a higher proportion of mannose than do agricultural crop residues. It is estimated that softwoods can produce about 410 liters of ethanol/metric ton if only the C_6 sugars are fermented, and up to 455 liters/metric ton if both C_5 and C_6 sugars are used (55). Studies have evaluated several woody materials including *Pinus radiata* (56), loblolly pine (57), aspen (58), eucalyptus (59), poplar (60), Salix (61), and beetle-killed lodgepole pine (62). Table 5 summarizes recent fermentation studies of agricultural and forest feedstocks for several microorganisms.

Hydrolysis and fermentation can be conducted separately (SHF) or simultaneously (SSF). Studies indicate that for wood, SHF is more expensive due to higher capital costs and lower ethanol yields. SHF permits each process to be conducted at their respective optimal temperatures, but yields are limited due to glucose inhibition of cellulase. SSF processes operate at a temperature intermediate to optimal hydrolysis and fermentation temperatures, but avoid product inhibition by consuming the glucose as quickly as it is generated (55). The SHF process could be economically competitive if ethanol yields comparable to the SSF process can be achieved (64).

Economic analyses comparing Salix and spruce demonstrates the correlation between economic viability and high ethanol yield, the use of sugars from the hemicellulose fraction, and the ability to carry out SSF at high solids concentration (65). Consolidated bioprocessing (CBP) combines enzyme production, hydrolysis and fermentation in a single reactor system. Successful development of CBP could streamline the process and reduce costs, but this technology is still in the laboratory stage (66). A number of technical challenges to converting lignocellulosic materials to ethanol remain (11, 12, 55). Research needs are summarized in table 6.

Table 5. Typical results from fermentation of biomass hydrolyzates

Organism	Hydrolysate	Fermentation mode	Yield (g/g initial sugar)	Fermentation time (h)
E. coli KO11	Bagasse Hemicellulose	n/a	0.49	n/a
	Corn Fiber	Batch	0.39–0.413	93–102
		Fed Batch	0.35–0.395	118
E. coli FBR5	Corn Stover	n/a	0.46	n/a
	Rice Hull	Batch	0.43	64
Zymomonas mobilis 8b	Corn Stover	Batch	0.42	n/a
Pichia stipitis	Wheat Straw	n/a	0.41	n/a
P. stipitis CBS 5773	Spent SulfiteLiquor	Continuous	0.35	n/a
Saccharomyces cerevisiae 424A (LNF- ST)	Corn Fiber	Batch	0.36	48
	Corn Stover	Batch	0.45	55
S. cerevisiae TMB3006	Spruce	Fed Batch	0.37	n/a
S. cerevisiae TMB3400	Spruce	Fed Batch	0.43	n/a
	Corn Stover	SSF, Batch	0.33	96
		SSF, Fed Batch	0.3	96

Source: Reference 63

Table 6. Suggested research priorities for lignocellulosic ethanol research

Overall	Pilot and precommercial demonstrations to assess efficiency and reduce risk
Feedstock	Reduced costs by improved crop yields, pest resistance and cropping systems; Evaluation of the use of dedicated energy crops; Genetic modification of herbaceous plants to improve their carbohydrate content; Economic utilization of different and alternative wastes such as MSW
Pretreatment	Reduction of milling power; Optimization of steam explosion and dilute acid pretreatment; Development of LHW, AFEX and alkaline hydrolysis; Reduced formation of inhibitors; Recycling of concentrated acids
Hydrolysis	Increase in activity, thermal stability and cellulose-specific binding of cellulases; Reduction of cellulase production costs; Cellulase production by solid-state fermentation; Recycling of cellulases; Improvement of acid hydrolysis of MSW
Fermentation	Increase in conversion of glucose and pentoses to ethanol; Continuous fermentation with high cell density, increased yields and productivity; Recombinant strains with increased stability and efficiency for assimilating hexoses and pentoses, and for working at higher temperatures; Development of strains more tolerant to inhibitors; Increase of ethanol tolerance in pentose-fermenting microorganisms

Source: Reference 12

Anaerobic Digestion

Wood has typically been viewed as resistant to anaerobic digestion. Herbaceous biomass resources have been shown to undergo anaerobic digestion more rapidly than hardwoods (67) and their digestibility is improved with pretreatment (68). The low moisture content, lignin content, and particle size make wood more resistant to anaerobic digestion without extensive pretreatment. At the molecular level, lignin resistance is likely due to its high molecular weight and the inability of anaerobic microbes to induce depolymerization (69). Nevertheless, a number of woody feedstocks and wood species have been tested in anaerobic digesters (70). Hybrid poplar and sycamore generate higher levels of methane than other species examined (75).

The paper and pulp industry uses anaerobic digestion to treat wastewater and effluents (71- 74). However, kraft effluent containing compounds with molecular weights of greater than 1,000 daltons cannot be suitably treated with the anaerobic systems commonly used in the industry (72). Additionally, some mill effluents contain compounds toxic to anaerobic microbes (75). Table 7 summarizes the impacts of several pulping operations on anaerobic digestion processes.

Table 7. Characteristics of different pulping operation waste streams suitable for anaerobic digestion

Wastewater source	COD (mg COD/ liter)	Organic composition (% of COD)	Anaerobic degradability (% of COD)	Potential inhibitors for anaerobic treatment
Wet Debarking	1300-4100	Tannins 30-55, carbohydrates 30-40, monomeric phenols 10-20, resin acids 5	44-78	Tannins, resin acids
TMP	1000-5600	Carbohydrates 25-40, lignin 16-49, extractives20, acids < 10	60-87	Resin acids
CTMP	2500-13000	Polysaccharides 10-15, lignin, 30-40, organic acids 35-40	40-60	Resin acids, fatty acids, sulfur, DTPA
NSSC Spent liquor	40000	nr	nr	Tannins
NSSC Condensate	7000	Acetic acid 70	nr	Sulfur, ammonia
KEC	1000-33600	Methanol 60-90	83-92	Sulfur, resin acids, fatty acids, volatile terpenes
SEC	7500-50000	Acetic acid 33-60, methanol 10-25, fatty acids < 10	50-90	Sulfur, organic sulfur
ChlorineBleaching	900-2000	Chlorinated lignin polymers 65-75, methanol 1-27, carbohydrates 1-5, VFA 3	30-50	Chlorinated phenols, resin acids
Sulfite Spent Liquor	120000-220000	Lignosulfates 50-60, carbohydrates 15-25	nr	nr

Source: Reference 71

Citations

1. Huber, G. W.; Iborra, S.; Corma, A. Synthesis of Transportation Fuels from Biomass: Chemistry, Catalysts, and Engineering. Chem. Rev. 2006, 106: 4044-4098.
2. Bridgwater, A. V.; Toft, A. J.; Brammer, J. G. A techno-economic comparison of power production by biomass fast pyrolysis with gasification and combustion. Renew. Sustain. Energy Rev, 2002. 6: 181-248.
3. Bridgwater, A. V. Renewable fuels and chemicals by thermal processing of biomass. Chem. Eng. J., 2003. 91: 87-102.
4. Gray, K.A., L.S. Zhao, and M. Emptage, Bioethanol. Current Opinion in Chemical Biology, 2006. 10(2): 141-146.
5. Hahn-Hagerdal, B.; Galbe, M.; Gorwa-Grauslund, M. F.; Liden, G.; Zacchi, G. Bio-ethanol - the fuel of tomorrow from the residues of today. Trends in Biotechnology, 2006. 24(12): 549-556.
6. Lynd, L.R., Overview and evaluation of fuel ethanol from cellulosic biomass: Technology, economics, the environment, and policy. Annual Review of Energy and the Environment, 1996. 21: 403-465.

7. Lynd, L. R.; Cushman, J. H.; Nichols, R. J.; Wyman, C. E. Fuel Ethanol from Cellulosic Biomass. Science, 1991. 251(4999): 1318-1323.

8. Mielenz, J.R., Ethanol production from biomass: technology and commercialization status. Current Opinion in Microbiology, 2001. 4(3): 324-329.

9. Wheals, A. E.; Basso, L. C.; Alves, D. M. G.; Amorim, H. V. Fuel ethanol after 25 years. Trends in Biotechnology, 1999. 17(12): 482-487.

10. Wyman, C.E., Biomass ethanol: Technical progress, opportunities, and commercial challenges. Annual Review of Energy and the Environment, 1999. 24: 189-226.

11. Wyman, C.E., What is (and is not) vital to advancing cellulosic ethanol. Trends in Biotechnology, 2007. 25(4): 153-157.

12. Sanchez, O. J.; Cardona, C. A. Trends in biotechnological production of fuel ethanol from different feedstocks. Bioresource Technology, 2008. 99(13): p. 5270-5295.

13. Hammerschlag, R., Ethanol's energy return on investment: A survey of the literature 1990 - Present. Environmental Science & Technology, 2006. 40(6): p. 1744-1750.

14. Van Loo, S.; Koppejan, J. The Handbook of Biomass Combustion and Cofiring. Earthscan, London, 2008. 442 pp.

15. Nussbaumer, T.; Neuenschwander, P.; Hasler, P.; Jenni, A. Buhler, R. Technical and economic assessment of the technologies for the conversion of wood to heat, electricity and synthetic fuels. 1998, Biomass for Energy and Industry, 10th European Conference and Technology Exhibition, June 8-11, 1998, Wurzburg, Germany. 4 pp.

16. Bain, R.L.; Amos, W.A.; Downing, M.; Perlack, R.L. *Highlights of Biopower Technical Assessment: State of the Industry and the Technology*. 2003, US Dept. of Energy National Renewable Energy Laboratory TP-510-33502. 47 pp.

17. Energy Information Administration. *Impacts of a 25-Percent Renewable Electricity Standard as Proposed in the American Clean Energy and Security Act Discussion Draft.* 2009, US Dept. of Energy Energy Information Administration Office of Integrated Analysis and Forecasting, Washington, DC. 50 pp.

18. National Renewable Energy Laboratory. Biomass Cofiring in Coal-Fired Boilers. 2004, US Dept. of Energy Energy Efficiency and Renewable Energy Program, Golden, CO. 36 pp.

19. Cao, Y.; Zhou, H.; Fan, J.; Zhao, T.; Hack, P.; Chan, C.; Pan, W. *Mercury Emissions during Cofiring of Sub-bituminous Coal and Biomass (Chicken Waste, Wood, Coffee Residue, and Tobacco Stalk) in a Laboratory-Scale Fluidized Bed Combustor*. 2008, Environ. Sci. Technol. 42: 9378–9384.

20. McKendry, P., Energy production from biomass (part 3): gasification technologies. Bioresource Technology, 2002. 83(1): 55-63.

21. Bridgwater, A.V. The Technical and Economic-Feasibility of Biomass Gasification for Power-Generation. Fuel, 1995. 74(5): p. 631-653.

22. Tijmensen, M. J. A.; Faaij, A. P. C.; Hamelinck, C. N.; van Hardeveld, M. R. M. Exploration of the possibilities for production of Fischer Tropsch liquids and power via biomass gasification. Biomass & Bioenergy, 2002. 23(2): 129-152.

23. Wang, L.; Weller, C. L.; Jones, D. D.; Hanna, M. A. Contemporary issues in thermal gasification of biomass and its application to electricity and fuel production. Biomass & Bioenergy, 2008. 32(7): 573-581.

24. Prins, M.J., K.J. Ptasinski, and F. Janssen, More efficient biomass gasification via torrefaction. Energy, 2006. 31(15): 3458-3470.

25. Prins, M.J.; Ptasinski, K.J.; Janssen, F.J.J.G. From coal to biomass gasification: Comparison of thermodynamic efficiency. Energy, 2007. 32(7): 1248-1259.

26. Milne, T. A.; Evans, R. J.; Abatzoglou, N. Biomass Gasifier "Tars": Their Nature, Formation and Conversion, National Renewable Energy Laboratory, NREL/TP-570-25357, 1998.

27. Devi, L.; Ptasinski, K. J.; Janssen, F. A review of the primary measures for tar elimination in biomass gasification processes. Biomass & Bioenergy, 2003. 24(2): 125-140.

28. Han, J.; Kim, H. The reduction and control technology of tar during biomass gasification/pyrolysis: An overview. Renewable & Sustainable Energy Reviews, 2008. 12(2): 397-416.

29. Sutton, D.; Kelleher, B.; Ross, J. R. H. Review of literature on catalysts for biomass gasification. Fuel Processing Technology, 2001. 73(3): 155-173.

30. van Heesch, B.; Pemen, G.; Yan, K. P.; van Paasen, S. V. B.; Ptasinski, K. J.; Huijbrechts, P. Pulsed corona tar cracker. Transactions on Plasma Science, 2000. 28(5): 1571-1575.

31. Matsumura, Y.; Minowa, T.; Potic, B.; Kersten, S. R. A.; Prins, W.; van Swaaij, W. P. M.; van de Beld, B.; Elliott, D. C.; Neuenschwander, G. G.; Kruse, A.; Antal, M. J. Biomass gasification in near- and super-critical water: Status and prospects. Biomass & Bioenergy, 2005. 29 (4): 269-292.

32. Calzavara, Y.; Joussot-Dubien, C.; Boissonnet, G.; Sarrade, S. Evaluation of biomass gasification in supercritical water process for hydrogen production. Energy Conversion and Management, 2005. 46(4): 615-631.

33. Mohan, D.; Pittman, C. U.; Steele, P. H. Pyrolysis of wood/biomass for bio-oil: A critical review. Energy & Fuels, 2006. 20(3): 848-889.

34. Bridgwater, A. V. Principles and practice of biomass fast pyrolysis processes for liquids. Journal of Analytical and Applied Pyrolysis 1999. 51(1-2): 3-22.

35. Czernik, S.; Bridgwater, A. V. Overview of applications of biomass fast pyrolysis oil. Energy & Fuels, 2004. 18(2): 590-598.

36. Bridgwater, A. V.; Peacocke, G. V. C. Fast pyrolysis processes for biomass. Renewable & Sustainable Energy Reviews, 2000. 4(1): 1-73.

37. Scott, D. S.; Majerski, P.; Piskorz, J.; Radlein, D. J. A second look at fast pyrolysis of biomass - the RTI process. Journal of Analytical and Applied Pyrolysis, 1999. 51(1-2): 23-37.

38. Maschio, G.; Koufopanos, C.; Lucchesi, A. Pyrolysis, a Promising Route for Biomass Utilization. Bioresource Technology, 1992. 42(3): 219-231.

39. Ni, M.; Leung, D. Y. C.; Leung, M. K. H.; Sumathy, K. An overview of hydrogen production from biomass. Fuel Processing Technology, 2006. 87(5): 461-472.

40. Oasmaa, A.; Czernik, S. Fuel oil quality of biomass pyrolysis oils - State of the art for the end user. Energy & Fuels, 1999. 13(4): 914-921.

41. Soltes, E. J.; Elder, T. J. Pyrolysis, in Organic Chemicals from Biomass, I.S. Goldstein, Editor. 1981, CRC Press: Boca Raton.

42. Sipila, K.; Kuoppala, E.; Fagernas, L.; Oasmaa, A. Characterization of biomass-based flash pyrolysis oils. Biomass & Bioenergy, 1998. 14 (2): 103-113.

43. Effendi, A.; Gerhauser, H.; Bridgwater, A. V. Production of renewable phenolic resins by thermochemical conversion of biomass: A review. Renewable & Sustainable Energy Reviews, 2008. 12(8): 2092-2116.

44. Czernik, S.; French, R.; Feik, C.; Chornet, E. Hydrogen by catalytic steam reforming of liquid byproducts from biomass thermoconversion processes. Industrial & Engineering Chemistry Research, 2002. 41(17): 4209-4215.

45. Wang, D.; Czernik, S.; Montane, D.; Mann, M.; Chornet, E. Biomass to hydrogen via fast pyrolysis and catalytic steam reforming of the pyrolysis oil or its fractions. Industrial & Engineering Chemistry Research, 1997. 36(5): 1507-1518.

46. Rioche, C.; Kulkarni, S.; Meunier, F. C.; Breen, J. P.; Burch, R. Steam reforming of model compounds and fast pyrolysis bio-oil on supported noble metal catalysts. Applied Catalysis B-Environmental, 2005. 61(1-2): 130-139.

47. Wang, D. N.; Czernik, S.; Chornet, E. Production of hydrogen from biomass by catalytic steam reforming of fast pyrolysis oils. Energy & Fuels, 1998. 12(1): 19-24.

48. Zhang, S. P.; Yan, Y. J.; Li, T. C.; Ren, Z. W. Upgrading of liquid fuel from the pyrolysis of biomass. Bioresource Technology, 2005. 96(5): 545-550.

49. Adam, J.; Antonakou, E.; Lappas, A.; Stocker, M.; Nilsen, M. H.; Bouzga, A.; Hustad, J. E.; Oye, G. In situ catalytic upgrading of biomass derived fast pyrolysis vapours in a fixed bed reactor using mesoporous materials. Microporous and Mesoporous Materials, 2006. 96 (1-3): 93-101.

50. Carlson, T. R.; Tompsett, G. A.; Conner, W. C.; Huber, G. W. Aromatic Production from Catalytic Fast Pyrolysis of Biomass-Derived Feedstocks. Topics in Catalysis, 2009. 52(3): 241-252.

51. Uslu, A.; Faaij, A. P. C.; Bergman, P. C. A. Pre-treatment technologies, and their effect on international bioenergy supply chain logistics. Techno-economic evaluation of torrefaction, fast pyrolysis and pelletisation. Energy, 2008. 33(8): 1206-1223.

52. Bergman, P. C. A.; Boersma, A. R.; Kiel, J. H. A.; Prins, M. J.; Ptasinski, K. J.; Janssen, F. J. J. G. In Second world biomass conference; Van Swaaij, W. P. M., Fjällström, T., Helm, P., Grassi, A., Eds.; ETAFlorence and WIP-Munich: Rome, Italy, 2004. P. 679–82.

53. Zwart, R. W. R.; Boerrigter, H.; van der Drift, A. The impact of biomass pretreatment on the feasibility of overseas biomass conversion to Fischer-Tropsch products. Energy & Fuels, 2006. 20(5): 2192-2197.

54. Solomon, B. D.; Barnes, J. R.; Halvorsen, K. E. Grain and cellulosic ethanol: History, economics, and energy policy. Biomass & Bioenergy, 2007. 31(6): 416-425.

55. Galbe, M.; Zacchi, G. A review of the production of ethanol from softwood. Applied Microbiology and Biotechnology, 2002. 59(6): 618-628.

56. Araque, E.; Parra, C.; Freer, J.; Contreras, D.; Rodriguez, J.; Mendonca, R.; Baeza, J. Evaluation of organosolv pretreatment for the conversion of Pinus radiata D. Don to ethanol. Enzyme and Microbial Technology, 2008. 43(2): 214-219.

57. Marzialetti, T.; Olarte, M. B. V.; Sievers, C.; Hoskins, T. J. C.; Agrawal, P. K.; Jones, C. W. Dilute acid hydrolysis of Loblolly pine: A comprehensive approach. Industrial & Engineering Chemistry Research, 2008. 47(19): 7131-7140.

58. De Bari, I.; Nanna, F.; Braccio, G. SO2-catalyzed steam Fractionation of aspen chips for bioethanol production: Optimization of the catalyst impregnation. Industrial & Engineering Chemistry Research, 2007. 46(23): 7711-7720.

59. Teramoto, Y.; Tanaka, N.; Lee, S. H.; Endo, T. Pretreatment of eucalyptus wood chips for enzymatic saccharification using combined sulfuric acid-free ethanol cooking and ball milling. Biotechnology and Bioengineering, 2008. 99(1): 75-85.

60. Pan, X. J.; Gilkes, N.; Kadla, J.; Pye, K.; Saka, S.; Gregg, D.; Ehara, K.; Xie, D.; Lam, D.; Saddler, J. Bioconversion of hybrid poplar to ethanol and co-products using an organosolv fractionation process: Optimization of process yields. Biotechnology and Bioengineering, 2006. 94(5): 851-861.

61. Sassner, P.; Martensson, C. G.; Galbe, M.; Zacchi, G. Steam pretreatment of H2SO4-impregnated Salix for the production of bioethanol. Bioresource Technology, 2008. 99(1): 137-145.

62. Ewanick, S. M.; Bura, R.; Saddler, J. N. Acid-catalyzed steam pretreatment of lodgepole pine and subsequent enzymatic hydrolysis and fermentation to ethanol. Biotechnology and Bioengineering, 2007. 98(4): 737-746.

63. Olsson, L.; HahnHagerdal, B. Fermentation of lignocellulosic hydrolysates for ethanol production. Enzyme and Microbial Technology, 1996. 18(5): 312-331.

64. Wingren, A.; Galbe, M.; Zacchi, G. Techno-economic evaluation of producing ethanol from softwood: Comparison of SSF and SHF and identification of bottlenecks. Biotechnology Progress, 2003. 19(4): 1109-1117.

65. Sassner, P.; Galbe, M.; Zacchi, G. Techno-economic evaluation of bioethanol production from three different lignocellulosic materials. Biomass & Bioenergy, 2008. 32(5): 422-430.

66. Lynd, L. R.; van Zyl, W. H.; McBride, J. E.; Laser, M. Consolidated bioprocessing of cellulosic biomass: an update. Current Opinion in Biotechnology, 2005. 16(5): 577-583.

67. Benner, R.; Maccubbin, A. E.; Hodson, R. E. Anaerobic Biodegradation of the Lignin and Polysaccharide Components of Lignocellulose and Synthetic Lignin by Sediment Microflora. Applied and Environmental Microbiology, 1984. 47(5): 998-1004.

68. Fernandes, T. V.; Bos, G. J. K.; Zeeman, G.; Sanders, J. P. M.; van Lier, J. B. Effects of thermo-chemical pre-treatment on anaerobic biodegradability and hydrolysis of lignocellulosic biomass. Bioresource Technology, 2009. 100(9): 2575-2579.

69. Zeikus, J. G.; Wellstein, A. L.; Kirk, T. K. Molecular-Basis for the Biodegradative Recalcitrance of Lignin in Anaerobic Environments. Fems Microbiology Letters, 1982. 15(3): 193-197.

70. Turick, C. E.; Peck, M. W.; Chynoweth, D. P.; Jerger, D. E.; White, E. H.; Zsuffa, L.; Kenney, W. A. Methane Fermentation of Woody Biomass. Bioresource Technology, 1991. 37(2): 141-147.

71. Rintala, J. A.; Puhakka, J. A. Anaerobic Treatment in Pulp and Paper-Mill Waste Management - a Review. Bioresource Technology, 1994. 47(1): 1-18.

72. Vidal, G.; Videla, S.; Diez, M. C. Molecular weight distribution of Pinus radiata kraft mill wastewater treated by anaerobic digestion. Bioresource Technology, 2001. 77(2): 183-191.

73. Thompson, G.; Swain, J.; Kay, M.; Forster, C. F. The treatment of pulp and paper mill effluent: a review. Bioresource Technology, 2001. 77 (3): 275-286.

74. Rajeshwari, K. V.; Balakrishnan, M.; Kansal, A.; Lata, K.; Kishore, V. V. N. State-of-the-art of anaerobic digestion technology for industrial wastewater treatment. Renewable & Sustainable Energy Reviews, 2000. 4(2): 135-156.

75. Vidal, G.; Diez, M. C. Methanogenic toxicity and continuous anaerobic treatment of wood processing effluents. Journal of Environmental Management, 2005. 74(4): 317-325.

76. Gunaseelan, V. N. Anaerobic digestion of biomass for methane production: A review. Biomass & Bioenergy, 1997. 13(1-2): 83-114.

77. Gilesnan, R. Personal Communication. Natural Resources Canada, 2010.

Market Impacts of Broad-scale Woody Biomass Utilization

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Public Policies Impacting Wood as an Energy Source

The abundance, accessibility, and cost of wood relative to other fuels with similar BTU values, have traditionally been the primary drivers of wood energy use in North America. But recent concerns over energy security and the environmental and greenhouse gas impacts of fossil fuel use are spurring interest in using renewable energy sources including biomass. Legislation, both in Canada and the U.S., has been passed or is in discussion, and includes a variety of mechanisms (mandates, tax incentives, or incentive payment programs) to spur the use of biomass for energy.

The U.S. Energy Independence and Security Act (EISA) of 2007 expanded the historical focus of renewable biofuels policies from corn-based ethanol to include higher quantities of cellulose-based fuels. EISA mandates production of 36 billion gallons of renewable fuels (21 billion gallons from non-corn sources; 16 billion gallons from cellulose sources) by 2022. If the entire cellulose-derived fuels were made from woody biomass, 320 million cubic meters would be needed annually (1). EISA restricts eligible woody materials to include residues such as slash from logging activities or storms; separated yard wastes; pre-commercial thinning operations; and fuel treatment materials near areas occupied by people or from public infrastructure areas. Planted trees can only be collected from actively managed tree plantations on non-federal lands. Efforts are underway to expand the definition of eligible woody biomass, particularly to include material from federal lands. EISA also established a $1.04 per gallon tax incentive/subsidy for cellulosic biofuels and reduced corn ethanol credits by $0.06 per gallon to $0.45.

The 2007 U.S. Farm Bill created a new research program to address forest biomass supply chain issues. The bill also established the Biomass Crop Assistance Program (BCAP) which shares the cost of establishment and provides cost matches (to aid with transportation and logistics) of up to $45/ton to producers who have contracts with user facilities. BCAP provides incentives to farmers and forest landowners to supply eligible biomass materials to qualifying facilities, and can reduce the cost of raw materials to the facility. As of January 2010, the initial BCAP Notice of Funding Availability ended and new draft guidelines were published in the Federal Register. Final guidelines are expected in mid to late 2010 following public comments and revision.

Currently, thirty-three states mandate renewable energy goals, and an additional five states have voluntary goals. The goals are designed to encourage renewable energy industry development, to promote renewable energy use, and to encourage decentralized, domestic energy production. Typically, electricity producing entities are required to produce a fixed portion (ranging from 8 to 40% depending on state) of their total production from renewable sources (biomass, wind, solar, hydro, etc.). Policies vary by state and change regularly. An updated summary of current policies can be found at **http://apps1.eere.energy.gov/states/maps/renewable_portfolio_states.cfm**.

Similarly, Canada has developed an alternative energy growth program aimed at expanding renewable power, fuels, and heat. The federal government has set goals to reduce the country's greenhouse gas emissions by 60-70% below 2006 levels by 2050 and to produce 90% of its electricity from non-emitting sources by 2020. Both goals create significant demand for biomass feedstocks. The development of energy programs to support these goals is supported through tax incentives, including an Accelerated Capital Cost Allowance deduction and the Canadian Renewable and Conservation expense deduction. There is also a Sustainable Technology Development Fund and a Clean Energy Fund that provides grants, loans, and other financing for renewable energy technology and facility development. The programs have options for next-generation biofuels, biopower, and others.

Canada's ecoENERGY program is constructed to provide a variety of incentives for bioenergy. The ecoEnergy for Renewable Power program provides incentives (1 cent per kilowatt hour for power, for example) for the development of industrial facilities, conversion of existing ones, and general expansion of the renewable energy sector, including fuels other than woody biomass. In the ecoEnergy for Biofuels program, the government has signed twenty one agreements representing a total commitment of $965million ($765million for ethanol and $200 million for biodiesel projects) with a potential production of 1.6 billion liters by 2012. Though focused on first-generation agricultural biomass derived fuels, the program is expected to benefit second-generation cellulosic-based fuels as well.

Specifically focused on forestry and woody biomass, Natural Resources Canada will be starting a program in 2010 aimed at advancing clean energy technologies in the forestry sector. The $100 million Next Generation Renewable Power Initiative will support the development and commercial implementation of wood-fueled renewable power technologies.

At the provincial level, several programs and legislative mandates have been put into place. Alberta has instituted a Bioenergy Infrastructure Development Grant Program that provides funding for industrial bioenergy production, transmission and environmental sustainability infrastructure. British Columbia has mandated that it will be electricity self-sufficient by 2016, including a mandate that all new electricity generation will have zero net greenhouse gas emissions. It has also set a 5% renewable fuels goal as well. Ontario passed the Green Energy and Green Economy Act of 2009 that creates programs to encourage renewable energy programs, sets renewable energy standards, and provides financial incentives for renewable energy production. Its programs include a feed-in tariff, grid connection rights, and smart grid improvements for its electricity generation sector. Ontario Power Generation is also working to convert four of its coal-powered electricity generation facilities to woody biomass by 2014. Other provincial programs include New Brunswick's embedded generation tariff program for renewable electricity and the Northwest Territories' Alternative Energy Technologies Program that provides funding and incentives for renewable energy.

The combination of federal, state, and provincial energy mandates, incentives, and funding mechanisms provide a strong outlook for wood-based energy production in the future. These and other programs will have significant impacts on demand of wood for energy and the availability of wood-based energy and products. Public policy is a key method to advancing wood to energy in both nations.

Impacts of Increased Woody Biomass Utilization

The use of wood for energy is increasing. There are 110 identified wood pellet facilities in the U.S. and Canada (2), and wood pellet use in the U.S. increased from 3 million tons in 2000 to 9 million tons in 2007 (3). European renewable energy credits of $80 to $100 per ton are increasing pellet demand, and use is projected to increase from the current level of 6 million tons annually to 20 million tons annually by 2020 (4). Electricity production, in the U.S., increased by approximately 3000 megawatthours from 1997 to 2007 (5). Use of wood to produce ethanol is a potential emerging market. The technology to convert wood to liquid fuels is not as well developed as those for pellets and electricity, but could become a significant market. For example, if wood was the only lignocellulosic feedstock used to meet the EISA renewable fuels standard, an estimated 348 million cubic meters of wood (75% of 2005 U.S. harvest) would be needed annually (1). No commercial scale wood-to-ethanol facilities are currently in operation, but several demonstration and commercial scale facilities have been announced or have begun construction (Renewable Fuels Association, **www.ethanolrfa.org**).

As wood-based bioenergy markets increase, competition for woody materials between existing fiber uses and developing bioenergy uses could arise. Though traditionally two separate markets, roundwood and fuelwood uses are becoming less distinct as roundwood can now be used in growing energy markets. The increased demand for wood for bioenergy use could increase raw material costs for traditional fiber industries, putting additional pressure on industries already hard hit by the current economic climate. The impacts on sawn lumber mills, panel industries, and pulp mills will likely differ as a result of shifting market and policy conditions. The uncertainty surrounding the bioenergy industry, caused in part by changing policies that increase the difficulty to make long-term investment decisions, is viewed as a major concern (6-10).

A recent study evaluated the impacts of global biofuels production on fuelwood production, wood prices, industrial production, and forestland from 2006 to 2060 for two scenarios (growth of the global biofuels industry by 2.7 times the current rate and growth of the global biofuels industry by 5.5 times the current rate) (11). The study related impacts of these scenarios to specific nations and continents. Under a 2.7 fold increase in global biofuels production, fuelwood production was estimated to increase from 4.8% annually in the U.S. and 8.3% annually in Canada. Under a 5.5 fold increase scenario, fuelwood production was estimated to increase from 5.2% annually in the U.S. and 10.8% annually in Canada. Industrial roundwood (for sawlogs, pulp, and panels) prices are estimated to remain at current levels through 2030 and increase thereafter. Fuelwood prices are projected to increase throughout the time period of the analysis, increasing from current prices of less than \$50/m^3 to \$80/m^3 (2.7 fold increase scenario) or \$100/m^3 (5.5 fold increase scenario) in 2030 and continuing to increase through 2060. The study also projected that the industrial roundwood and fuelwood cost curves would converge by 2025 and continue an identical price increase from that time forward. Though traditionally two separate markets, with the current economic climate and the increased emphasis on wood for energy, the line between roundwood and fuelwood is no longer clearly defined with materials generally classified as roundwood being used for energy production in some cases.

Through all this projected change, industrial pulp manufacturing is projected to remain constant in North America, primarily due to the increased use of recycled paper as a feedstock.

In Austria, biofuels mandates are estimated to triple fuelwood consumption in as little as 10 years, and increase pine pulpwood and fuelwood prices by as much as 43% and 53% respectively by 2020 (12). Norwegian pulpwood prices are estimated to increase by more than 30% as a result of bioenergy mandates (13). Two other studies estimate that forestry and sawn lumber mills will benefit by bioenergy policies, while the pulp and panel industries will be most negatively affected (26,27) These industries operate on low profit margins and increased fiber prices caused by competing interests for the same fuel/feedstock could have significant disruptive influence.

Forest2Market (2008) (4), using a dynamic timber supply model, analyzed the potential impact of developing bioenergy uses (combined heat and power, wood pellet, and cellulosic ethanol) on wood resources in the southern U.S. Assuming that wood is the only feedstock used to meet the cellulosic renewable fuels standard for the southern U.S., wood consumption and raw wood prices are projected to be 60% and 20%

higher respectively in 2020 than would occur without bioenergy production. Wood for energy uses in the southern U.S. is estimated to increase from 200,000 short tons annually in 2007 to 18.5 million short tons in 2020. The majority of this wood will come from softwood pulpwood and chips (increasing from 89 to 96 million short tons per year by 2020), while hardwood supplies decline over the same time period. Softwood supply increases are due to the establishment of 5 million new plantation acres by 2020. Residual chip availability remains steady at nearly 59 million short tons per year. The analysis indicates that while the forest products industry will remain the primary user of wood in 2020 (78% of total demand), biomass electricity and cellulosic ethanol will each require nearly 8% of the total wood produced in 2020 based on projected projects and demand. Wood pellet production will consume 4% of the wood produced. Average pine pulpwood prices are projected to increase 7% (to $31/delivered green ton) and hardwood pulp increases 4% (to $34/delivered green ton) by 2020. The increase in wood energy demands combined with increased demand for wood for oriented strandboard production, negatively impact the pulp and paper industry. Pellet markets are projected to become saturated by 2011, resulting in declining prices thereafter. This, combined with a projected 15% increase in the costs over the next 5 years, will put substantial pressure on the pellet industry. CHP growth is generally limited to district-scale heating systems.

Opportunities for Existing Industry: Integration of Biomass Conversion Technologies

The emergence of new biomass industries creates anxiety among the existing wood industries regarding wood price and availability. While it is easy to focus on the negative impacts of expanding bioenergy use, the development of these industries might also provide an opportunity for fiber industries to refocus their operations. Indeed, some analysts feel that the basic industry models of the past are dead and that, to survive, the forest products industry will have to adjust, explore new opportunities, and take risks (14).

The new bioenergy markets present opportunities for forest managers to increase their return on traditional forest harvesting operations by offering new markets for materials not traditionally used (15). Sawmills can expand their operations to include pelleting, or to handle small diameter trees harvested as part of forest health operations (15). Dedicated short-rotation woody crop plantations could become a larger component of the woody biomass supply, which could reduce the competition for resources while still providing a regular source of woody materials (15). The economic downturn has sharply reduced wood product manufacturing capacity and many of the older facilities are unlikely to reopen as the housing market returns. Alternative uses of these facilities, to take advantage of the existing capital investment and supply logistics, are being evaluated, including using these facilities as sites for biomass staging operations (e.g., drying, size reduction, and other preprocessing steps).

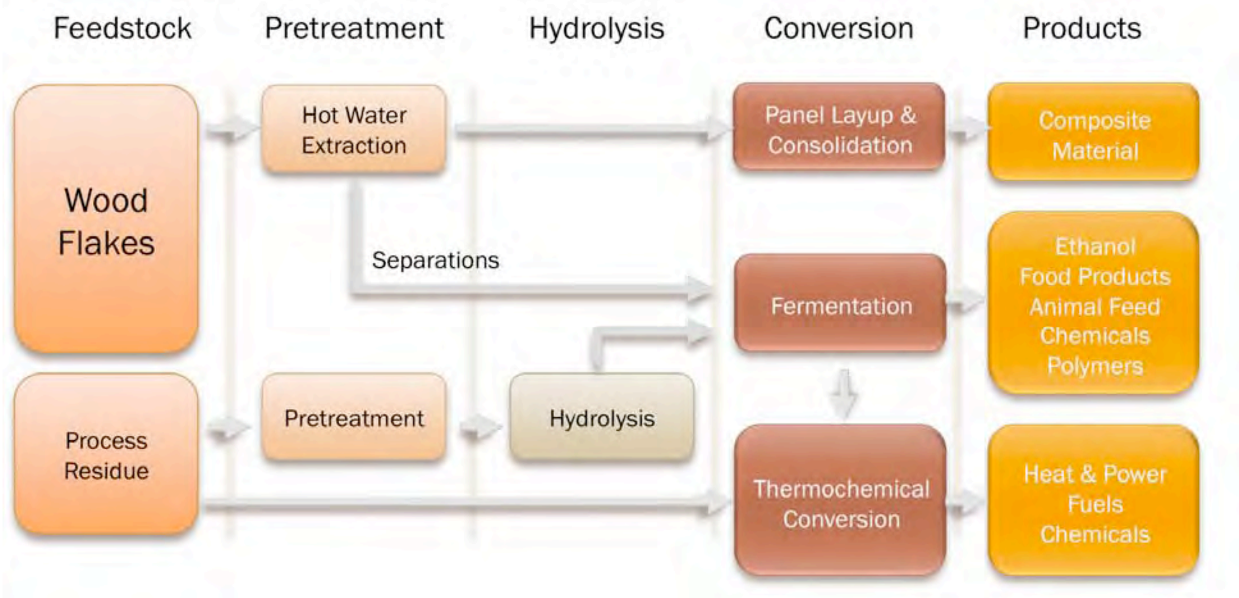
Production of liquid fuels from woody biomass creates an opportunity to more efficiently utilize raw materials by integrating new process technologies with existing manufacturing operations. The forest biorefinery concept has been pioneered by the pulp and paper sector. Often described as an integrated biorefinery (producing paper, energy, and other products), the industry has more recently advanced the concept of ‘value prior to pulping’ as a means to diversify their product portfolio. In this approach, some of the hemicellulose is removed prior to pulping and used to produce fuels or other chemicals via biochemical processes. While this approach also reduces the energy cost of pulping, and improves the strength properties of the primary product (i.e., paper), other performance attributes appear to suffer. With more than 15 million tons of capacity lost since 2000, this innovation offers significant opportunities for improved efficiency and enhanced competitiveness. Considerable effort is ongoing to address the problems that have become apparent in the development process.

Due to the anticipated benefits of integrating paper and fuels production, interest to extend the approach to other segments of the forest industry is occurring. Value prior to combustion is one system that has been investigated. Despite a reduction in feedstock BTU's, the potential to isolate a sugar stream for liquid fuels production may provide other benefits.

Preliminary research (at a bench scale) suggests similar benefits for oriented strandboard (OSB) manufacture as for pulp and paper manufacture (University of Tennessee; University of Maine). Figure 1 illustrates the process. Removal of some of the hemicelluloses prior to composite production confers several benefits including:

- Improved strength and stiffness of the composite panel. Composite strength nearly doubled after extracting 20 percent (weight) of the wood strands.
- Improved dimensional stability of the composite panel. Moisture absorption was cut in half, substantially improving dimensional stability.
- Improved mold resistance of the composite panel.

Figure 1. Value prior to processing schematic for oriented strandboard manufacture.



The magnitude of the improvement in composite performance properties may allow use of new woody materials and entry into new markets. For example, inferior quality logs and sub-optimal strands can be separated and used for bioenergy purposes within the OSB facility. Extraction of wood strands prior to manufacturing, which reduces hygroscopicity, reduces the energy needed for drying, and thus reduces costs and the carbon footprint of the industry. The elimination of the sugars and extractives reduces emissions during the drying and pressing operations. Implementation of this process scheme is certainly more complicated for this industry segment since the necessary capital equipment is not in place, but the significant benefits imparted to the panel product have kept interest high.

The "value prior to processing" approach offers substantial benefits to fiber manufacturers, but relies on the corresponding development of biochemical technologies to convert the sugar steams to fuels and chemicals. Alternatively, forest industry manufacturers can convert residues to fuels and chemical intermediates using thermochemical technologies such as gasification and pyrolysis. Although less developed, they can accommodate a range of biomass feedstocks, as well as offering the promise of drop-in fuels (fuels that do not require significant distribution or engine system modifications).

Integrating fiber and energy operations in existing facilities will not be easy. Energy company and pulp mill executives were surveyed regarding their goals and objectives (14). Forest products executives emphasized paper production, customer-relations management, and pulp production as their primary focus areas. Energy production was not considered a major goal. Personnel were worried about securing sustainable feedstock supplies at reasonable costs. Energy company executives emphasized energy production, risk management and the management of customer relations as their primary focus areas. They expressed enthusiasm for using wood as an energy feedstock. Participants from both industries, however, recognize that the future will be substantially different from the past, as both industries become increasingly intertwined.

Sustainability

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Ecological sustainability is critical to a long-term expansion of the wood to energy industry.

The sustainability of wood bioenergy uses will be judged based on economic, ecological, and social criteria (16).

Economic sustainability includes consideration of both supply and demand issues. Adequate feedstock supplies are needed to encourage investment. Feedstock supplies are critical when determining facility location. Technologies must fit the biomass at the chosen location, and technologies with the flexibility to use multiple feedstocks (e.g., softwood, hardwoods residues, hog fuel) at the same facility are increasingly viewed as important to success (16). Harvesting, collection, and transportation costs are important components of sustainable woody biomass supply. Small diameter trees and less desirable classes of wood present harvesting challenges (17), but technology improvements and developing markets are making these practices more economic. Supply chain components (e.g., people, equipment, contracts) require significant investments of time and money and require sustained demand to establish and maintain.

Ecological sustainability includes consideration of the impacts of woody biomass production and removal from forests and plantations. A key consideration is whether annual forest growth exceeds removal (16), which has traditionally been the case in Canada and the U.S. The impact of woody biomass removal on soil nutrient quality, soils protection/stabilization, soil compaction, and stand regeneration (18, 19) must be considered. The use of small diameter trees currently being harvested for forest health reasons and for which no markets currently exist, can provide woody materials without affecting existing uses and potentially improve the ability of forest managers to practice sound management techniques. Sustainability criteria will differ based on the feedstock source. Forest-based residues may impact soil quality and wildlife habitat more significantly than short-rotation crops. Similarly, the plant diversity of forests may provide increased benefits over homogenous plantations. When evaluating the sustainability of the feedstock, careful analysis of the source of the materials must be undertaken. New facilities require due diligence and investors and developers should conduct a detailed feedstock availability study, in addition to business feasibility and finance planning, prior to committing to a location (17).

Tools to improve and monitor ecological sustainability include state and regional sustainable forest harvest guidelines (17) and forest certification programs. Groups such as the Council for Sustainable Biomass Production (2009), the Roundtable on Sustainable Biofuels (2009), and the Forest Guild (2008) have established best management practices to harvest biomass for energy. The guides provide wood contractors with information about skidding, road and landing construction, and biomass removal practices that maintain the environment. Existing forest certification programs (e.g., Sustainable Forestry Initiative, Forest Stewardship Council, and the American Tree Farm System) can be used to independently verify that sound production practices have been used. Traditional wood industries have used these guidelines and certification programs for many years, with positive results.

Social sustainability may be the most difficult criteria to describe and quantify. Public policy can drive a biomass-powered industry or stop it in its tracks. Public education regarding wood production and consumption is needed to permit society to make informed personal and political choices. An understanding of landowner attitudes, goals, and objectives toward wood and bioenergy production are needed for industrial wood users and suppliers to develop good working relations and ensure sustainable feedstock supplies (16).

The evaluation of the sustainability of wood to energy must be made on a case by case basis. Factors ranging from feedstock source (with both ecological and social impacts) to the economics of the feedstock production, collection, and conversion process, along with others, will differ significantly between locations and situations.

Citations

1. Sedjo, R.A. and Sohngen, B. The implications of increased use of wood for biofuels production. 2009, Resources for the Future Issue Brief #09-04. 13 pp.
2. Spelter, H. and Toth, D. North America's Wood Pellet Sector. USDA Forest Service Forest Products Laboratory, 2009. Research Paper FPL-RP-656. 21 pp.
3. Wild, M. The Pellets Market in Europe status 2008 targets for the future new approaches. European Pellets Roadmap up to 2020 Workshop, June 26, 2008, 2008. Accessed December 1, 2009.
4. Forest2Market. US South Forest Biomass Outlook and Price Forecast. Forest 2 Market Inc., 2008. 90 pp.
5. Energy Information Administration. Net Generation by Other Renewables: Total (All Sectors). US Dept. of Energy Energy Information Administration, 2010. Available at: http://www.eia.doe.gov/cneaf/electricity/epm/table1_1_a.html
6. Milbrandt, A. A Geographic Perspective on the Current Biomass Resource Availability in the United States. U.S. Department of Energy, National Renewable Energy Laboratory, 2005. http://www.nrel.gov/docs/fy06osti/39181.pdf

7. Skog, K.E.; Rummer, R.; Jenkins, B.; Parker, N; Tittmann, P.; Hart, Q.; Nelson, R.; Gray, E.; Schmidt, A.; Patton-Mallory, M.; Gordon, G. A Strategic Assessment of Biofuels Development in the Western States In: McWilliams, Will; Moisen, Gretchen; Czaplewski, Ray, comps. 2008 Forest Inventory and Analysis (FIA) Symposium; October 21-23, 2008: Park City, UT. Proc. RMRS-P-56CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, 2009. 1 CD.
8. Richter Jr, D.B., Jenkins, D.H., Karakash, J.T., Knight, J., McCreery, L.R., and Nemestothy, K.P. Wood Energy in America. Science, 2009. 232: 1432-1433. Energy Information Administration. Impacts of a 25-Percent Renewable Electricity Standard as Proposed in the American Clean Energy and Security Act Discussion Draft. US Dept. of Energy Energy Information Administration Office of Integrated Analysis and Forecasting, Washington, DC, 2009. 50 pp.
9. Becker, D.R., Larson, D., and Lowell, E.C. Financial considerations of policy options to enhance biomass utilization for reducing wildfire hazards. Forest Policy and Economics, 2009. 11(8): 628-635.
10. Raunikar, R.; Buongiorno, J.; Turner, J.A.; and Zhu, S. Global outlook for wood and forests with the bioenergy demand implied by scenarios of the Intergovernmental Panel on Climate Change. Forest Policy and Economics, 2010. 12: 48–56.
11. Schwarzbauer, P. and Stern, T. Energy vs. material: Economic impacts of a “wood-for-energy scenario” on the forest-based sector in Austria — A simulation approach. Forest Policy and Economics, 2010. 12: 31–38.
12. Trømborg, E. and Solberg, B. Forest sector impacts of the increased use of wood in energy production in Norway. Forest Policy and Economics, 2010. 12: 39–47.
13. Patari, S. Industry- and company-level factors influencing the development of the forest energy business — insights from a Delphi Study. Technological Forecasting & Social Change, 2010. 77: 94–109.
14. Berndes, G.; Hoogwijk, M.; and van den Broekc, R. The contribution of biomass in the future global energy supply: a review of 17 studies. Biomass and Bioenergy, 2003. 25: 1-28.
15. Damery, d.; Benjamin, J.; Kelty, M.; and Liliholm, R.J. Developing a sustainable forest biomass industry: case of the US northeast In: Brebbia, C.A. and Tiezzi, E (eds) Ecosystems and Sustainable Development VII. Wessex Institute of Technology Press, Southhampton, 2009. PP. 141-152.
16. Caputo, J. Sustainable forest biomass: promoting renewable energy and forest stewardship. Environmental and Energy Study Institute Policy Paper, 2009. 23 pp.
17. Kelty, M.J; D'Amato, A.W.; and Barten, P.K. Silvicultural and ecological considerations of forest biomass harvesting in Massachusetts. University of Massachusetts Department of Natural Resources Conservation, Amherst, 2008. 65 pp.
18. Hacker, J.J., Effects of Logging Residue Removal on Forest Sites: A Literature Review. Resource Analytics for West Central Wisconsin Regional Planning Commission, 2008. 29 pp.

Conclusion

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The utilization of wood for energy will be critical to the development of bioenergy in the US and Canada.

Woody biomass is, and will, continue to be an important part of biomass-based energy in the U.S. and Canada. Many factors will play a significant role in determining the future of wood-to-energy industries, including economic conditions, price of competing energy sources (e.g., fossil fuels), public policy, and technology improvements. It is worth noting that the opportunities to take advantage of new process technologies for converting woody biomass to liquid fuels and chemicals are, at this point, uncertain. It is clear, however, that integrating the wood products industry into emerging markets will create refinements in the efficient use of the resource through fractionation. This should ultimately enhance competitiveness of the existing industry through innovation and creative solutions to current challenges. Federal and state/provincial environmental, climate, and energy policies will have a major impact on the development of wood-to-energy industries. Uncertainty with respect to how these policies may change and/or be implemented significantly affects wood-to-energy investment decisions.

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