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A Survey of Bioenergy Research in Forest Service Research and Development

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Abstract Forest biomass represents 25–30 % of the annual biomass available in the USA for conversion into bio-based fuels, bio-based chemicals, and bioproducts in general. The USDA Forest Service Research and Development (R&D) has been focused on producing products from forest biomass since its inception in 1905, with direct combustion, solid sawn lumber, pulp and paper, ethanol as fuel, and silvichemicals all among the mission areas of product research and development. The renewed national interest in biomass conversion to fuels and chemicals is supportive of the most critical need of USDA Forest Service R&D, uses for small-diameter trees and other forest biomass that needs to be removed in the fuel mitigation–fire suppression and forest restoration work of the USDA Forest Service. This paper will summarize the recent USDA Forest Service research on direct combustion, fuel pellets, and conversion of forest biomass to ethanol, both as stand-alone biorefinery processes and as an addition to the traditional wood pulping process.

Keywords Woody biomass · Forest service · Bioenergy · Biorefinery · Prehydrolysis · Gasification · Co-firing

Introduction

Efforts of USDA Forest Service in Research and Development (FS R&D) date to 1905 with a broad mission to improve the scientific understanding of forest ecosystems and management of the nation's forests. Forest products research was started 5 years later with narrower missions of improving utilization by increasing the yield of usable products, finding valuable uses for wood species that are not valued for existing products, and reducing wood failure in use both from a structural/engineering sense and damage due to insects and fungal decay. There has been a decade-long trend in timber utilization from large trees with considerable clear lumber to smaller trees and *engineered lumber*. I-beam-type floor joists and oriented strand board are successful examples. Where these trends have reduced logging pressure on mature forests and assisted the USDA Forest Service and US industry in preserving valued forest areas, they have not provided much assistance in the USDA Forest Service's most critical current need, a product utilizing small-diameter trees and the other low-value forest biomass that needs to be removed to reduce fire risk in overgrown forests. Typical forest management contracts to mitigate fire risks cost the USDA Forest Service and by default, the US taxpayer $500 to $1500 per acre treated. The USDA Forest Service forest products research is working to develop products of sufficient value and sufficient potential demand to pay for forest operations—the logging and transportation costs—and zero out the management activity cost. This situation already exists east of the Mississippi River where the paper industry has utilized 6–12-in.-diameter stems for decades and prefers the lower-cost wood size and wood species that are not valued for dimension lumber products. The routine demand for pulpwood has helped reduce fire risk and fire severity throughout much of the east of the USA. Unfortunately, the paper industry

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never expanded into much of the Rocky Mountain States and West Coast, largely due to the lack of major rivers that could provide the needed process water and sufficient dilution to minimize the impact of wastewater. With the international paper industry moving aggressively into tropical areas where trees attain pulpwood size in 6–10 years and where labor costs are often considerably lower, an industry expansion into the mountain west and Pacific Southwest is unlikely. An alternative product or products to utilize small-diameter trees is needed. Biomass conversion to fuels and chemicals has long been an attractive possibility. It remains, however, an economically challenging goal. For example, a ton of wood converted to paper has a value of $250–$500 but less than $200 as ethanol. In engineering evaluations on cost of ethanol production, the Department of Energy (DOE) often estimates the purchase cost for biomass at less than the harvest and transportation costs for wood.

This paper will review research on augmenting coal use in utilities with woody biomass, wood gasification for gas reforming and other applications, wood prehydrolysis as a means to add a fuel ethanol product stream to traditional papermaking, and pretreatment of woody biomass with sulfurous acid (H_2SO_3) to improve the yield of sugars and fermentation products in a biorefinery.

Prehydrolysis Pulping

Prehydrolysis has been used as a pretreatment in pulping to prepare high-cellulose pulps for production of rayon and cellulose acetate for half a century. A recent project was sponsored by the DOE with paper industry participation organized by the Agenda 2020 Technology Alliance [1]. The overall goals of the project were to evaluate the full range of potential prehydrolysis options when working with hardwoods, softwoods, and thermomechanical pulps and that of potential paper products ranging from bleached paper, corrugated containers, and newsprint. The principal deliverables of the study were kinetic models to estimate both prehydrolysis yield and pulping process performance for softwoods and hardwoods. This was fitted into a mass and energy balance spreadsheet to estimate chemical and energy needs in a pulp mill and chemical recovery process. The mass and energy balance model was attached to an economic analysis that utilized the chemical pretreatment results to estimate the impact on costs and product values in the mill. The model was tunable to match details of a particular company and mill site and was subsequently used by most of the supporting companies to evaluate potential for use at their company mills. The project also included research at the College of Environmental Science and Forestry in Syracuse, State University of New York (hardwood pulping, Thomas Amidon as lead); North Carolina State University (softwood pulping, Hasan Jameel as lead); Auburn University (yield enhancing additives, Harold Cullinan as lead), and the University of Maine (hardwood pulping with near-neutral buffers, Adriaan van Heinengan as lead). The Georgia Institute of Technology (Mathew Realff) participated in the mass and energy balance modeling which also received engineering support from American Process Inc. (Vesa Pylkkanen). Fermentation work on wood prehydrolyzates was also carried out at the National Renewable Energy Laboratory, Purdue University, and the USDA Forest Service, Forest Products Laboratory (FPL). The specific concern with regard to fermentation was that prehydrolysis of wood provides a sugar stream rich in five carbon sugars and specialized organisms were needed to recover value from xylose as well as glucose and other fermentable six-carbon sugars. Prehydrolysis experiments of softwoods for bleached pulp and thermomechanical pulp were carried out at FPL, and this section will summarize this research. The FPL was also the technical lead on the mass and energy balance and economic models and analysis.

Prehydrolysis Pulping of Loblolly Pine

Loblolly pine wood consists of 40–45 % cellulose, 20–25 % hemicellulose, and about 30 % lignin. In traditional kraft pulping to produce paper, approximately 85 % of the lignin is removed to provide a pulp ready for bleaching. Unbleached products like the paperboards used in corrugated containers often use pulps with considerably more residual lignin and higher pulp yield. For linerboard used as the inner and outer surface plies of corrugated containers, approximately 60 % of starting lignin is removed. The yield of cellulose is about 90 % in linerboard grades and 85 % for bleachable grades. Hemicellulose retention is about 70 % at the higher yield and 63 % in bleached grades. After bleaching, the high brightness pulp has less than 1 % lignin and is typically about 75 % cellulose and 25 % hemicellulose. The goal of the pretreatment project was to remove sugars from the wood chips before pulping and search for conditions that selectively removed sugars that would otherwise dissolve in the pulping process. Accomplishing this would preserve yield, pulp (paper) being the highest value product of the mill, but reduce the amount of dissolved wood substance recovered as heat and electricity in the kraft chemical recovery process.

The project at FPL evaluated woodchip pretreatments over a range of conditions and with different acids: sulfuric, sulfurous, oxalic, and acetic acids as well as sodium bisulfate [1]. Sulfuric acid is obviously a strong acid and produced prehydrolysis conditions with a final pH below 1. Bisulfate, sulfurous acid, and oxalic acid are weak acids providing a final pH in the range 1.0–2.5. Acetic acid buffers the process pH near 4. In addition, sodium carbonate was evaluated providing final pH in the range of 6.8–8.5.

Pretreatments were carried out in a 20-L batch digester using oven-dry basis (OD) 500-g samples of southern pine wood chips. The pretreated woodchips were separated into four batches, and three batches of OD 120 g each were loaded into 1-L autoclaves for kraft pulping. The three samples were dosed with different levels of pulping chemicals, and the three autoclaves were sealed and pulped at once. After treatment, samples were mixed in a British disintegrator and screened on a laboratory flat screen to remove fiber bundles and undercooked wood. Samples were tested for total yield, screened yield, kappa number (residual lignin content), and pulp viscosity, which is a measure of cellulose degradation during the pretreatment and pulping.

In general, evaluating yield relative to the residual lignin content, all acids tested provided similar outcomes with approximately 50 % of the wood removed in pretreatment ending up as additional yield loss after pulping (Fig. 1). Furthermore, none of the acids demonstrate significantly better selectivity and only the neutral bicarbonate treatment provides for a minimal loss in pulp yield. Unfortunately, bicarbonate does not provide a significant yield of sugars for a fermentation system.

The retention of sugars during conventional processing for pulp (high lignin and low lignin) and with an oxalic acid pretreatment combined with kraft pulping to high and low residual lignin targets is provided in Fig. 2. Pretreatment of woodchips with oxalic acid reduces the arabinogalactan by as much as 80 %, but over 60 % of the galactoglucomannan survives. Pulping (high lignin and low lignin) reduced the galactoglucomannan by 70 % but the arabinogalactan by only about 60 %. In contrast, methylglucuranoxylan is relatively resistant to both treatments with about 70 % retention [1]. The outcome of combined prehydrolysis with kraft pulping reduces both galactoglucomannan and arabinogalactan to less than 25 % of the starting amounts, and the combined effect on methylglucuranoxylan is almost 70 % loss where one would expect about 50 % retention if the treatments were simply additive. For this series of experiments, the control case pulping yields were 59 % pulping to a linerboard residual lignin content (high L case) and 43 % pulping to a bleachable grade lignin content (low L case). The yield after treatment with oxalic acid was 88 %. This resulted in a 51 % pulp yield relative to starting wood for the high lignin content pulp (loss of 8 points) and a 39 % yield from starting wood for the bleachable grade case (loss of 4 points).

Although the yield loss target was not met, the outcomes of the experimental work were not exclusively negative. It was found that the mild pretreatments accelerated the pulping process allowing for a small but measureable reduction in either the amount of pulping chemicals required or the retention time of the pulping process. Furthermore, the amount of waste pulping liquor solids that need to be recovered and burned for fuel value and the inorganic chemicals that need to be regenerated to produce fresh pulping chemicals are all reduced. This is significant because the chemical recovery process is one of the two largest capital expenses in a kraft pulp and paper mill, and mills are often run to where this is the production constraint. In a recovery process-limited mill, reducing the percent solids and heat value of the waste liquor sent to the recovery process allows increased pulp (paper) production which is nearly always a high value outcome for a mill.

Testing of the papers produced from the prehydrolyzed pulps presented an additional challenge for incorporating this process into a paper mill. Hemicellulose has been known for several decades as contributing to the bonding between the

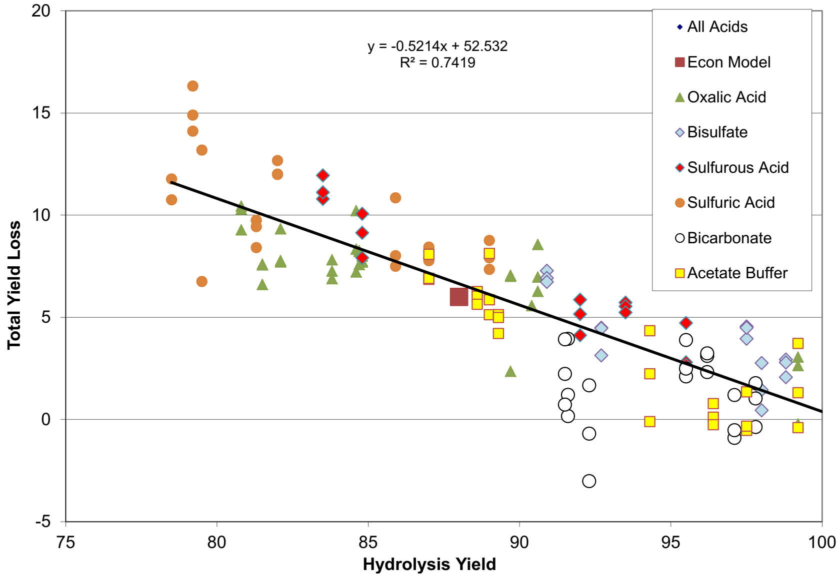
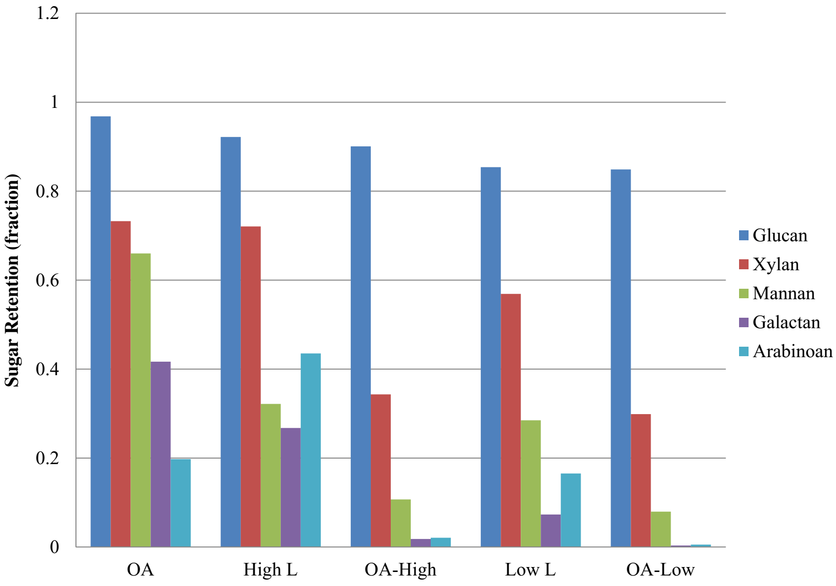


Fig. 1 Impact of hydrolysis on yield after pulping [1]

Fig. 2 Yield of individual sugars in the residual wood or pulp after oxalic acid (*OA*) pretreatment and pulping. Values are fraction remaining relative to the starting wood [1]



fibers in paper, the hydrogen bonds that form between fibers when the paper is dried. The lower hemicellulose content of the prehydrolysis pulps reduced this bonding. The tear index and tensile index of paper handsheets made from the control and a prehydrolyzed pulp are shown in Fig. 3. When graphed against the tensile index, tear often goes through a maximum as observed for the oxalic acid-treated pulps. Wood pulp is treated by beating the fibers with disk refiners or other types of attrition mills before forming the paper. The beating unravels segments of the cell wall to provide string-like fibrils and fine material that fills in gaps between fibers and increases the amount of interfiber bonding in the paper. The tensile index of paper typically increases linearly with interfiber bonding, but when the strength of the bonds exceeds the strength of the fibers, the tear index begins to decrease. With the pulp produced using the oxalic acid chip pretreatment (Fig. 3), the maximum tear index of 14 mN/m^2/g is achieved between 50 and 60 Nm/g for the tensile index [1]. The maximum tear index obtained using the control pulp is achieved at about the same tensile index but is 20 % higher. Furthermore, the maximum tensile index achieved with the pulp produced from oxalic acid-pretreated woodchips is just 80 % of the strength attained with the control. Based on the shape of the curve for the oxalic acid-pretreated case, it is unlikely to achieve the strength of the control even with extensive beating to further increase bonding. What is not shown in the graph is that it also took five times more beating—refiner energy—to achieve the same level of bonding in the pulp produced using the woodchip pretreatment.

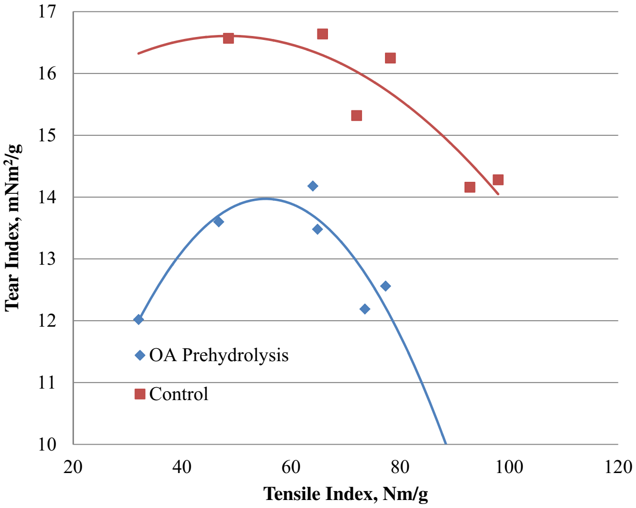


Fig. 3 Tear index relative to tensile index. The result demonstrates the loss of bonding strength and fiber strength in the oxalic acid (*OA*)-pretreated pulp [1]

Although the decrease in maximum tear index indicates weaker pulp fibers, far more significant is the loss of bonding in the pulps with lower hemicellulose content. Interfiber bonding can be improved by adding starch or other bonding aids, but that is an additional expense. Furthermore, it makes little sense to try to collect and ferment the mixture of sugars in hemicellulose and then use starch, which is readily saccharified to glucose, to recover the paper strength lost with the woodchip hydrolysis pretreatment. In addition to the cost issues associated with the lost bonding, the net loss in pulp fiber strength rules out some paper grades and generates an additional cost item in other grades. For example, the common bleached paper used in copiers and printers is typically made with 70 % or more as hardwood pulp, and the balance from softwood pulp. The softwood pulp is added to achieve the strength properties needed by the paper. Since softwood pulp is more expensive to produce, this blend needs to be managed to control costs. If either the hardwood or softwood components are weaker, more softwood pulp is needed to maintain paper strength.

It was the increased production scenario that seemed to be of most interest to paper companies. Unfortunately, the lost fuel value and the lost yield have to be made up. For sites where wood costs or energy costs are high, the net outcome is lower overall value for the mill. Paper companies are notoriously secretive about their operations, but with that caveat, none of the companies informed FPL that they had implemented prehydrolysis in their mills. The principal issue is in several cases where the process appeared to be cost-effective, the capital costs of the pretreatment system were large enough to reduce the estimated return on investment and discourage company investments.

Prehydrolysis Thermomechanical Pulping

The value proposition for prehydrolysis pretreatment as part of a thermomechanical pulping (TMP) process is quite different from kraft pulping. Thermomechanical pulping is a strictly mechanical grinding mechanism using disk refiners or attrition disks. The pulp yield is very high, 93 %, and losses are generally in very small particles and wood extractives, rather than as soluble sugars or lignin. A woodchip prehydrolysis process to collect sugars for fermentation has to suffer a loss of pulp yield, but the amount of electrical energy required to mechanically grind wood into a pulp is considerable, and the process was targeted at reducing this energy need [1, 2]. There had been over a decade of research and development at FPL on this process, starting with fungal treatments of woodchips and, eventually, when realizing that the oxalate was one of the critical chemicals secreted by the fungi, oxalic acid pretreatments. It was also known that treatment with sulfurous acid, or more accurately, sodium sulfite, provided for stronger pulps and a reduction in the refining energy, at least at higher sodium sulfite charges [3]. The goals for this task were to evaluate how much sugar could be collected in the pretreatment and whether the refining energy savings were sufficient to manage the cost of additional wood or a decrease in paper production in the mill. A second goal was to determine if lower-cost acids could provide the same benefit as the oxalic acid pretreatment. Already known was that pretreating the woodchips with many common mineral acids provided a significant decrease in refining energy but caused a loss in pulp brightness that required expensive bleaching to recover. It was not known if sulfurous acid or sodium bisulfate, which both provide a buffered pH similar to oxalic acid, would also reduce this acid hydrolysis darkening. In the preliminary experiments, the mineral acid alternatives did not control the acid-induced brightness loss of softwoods. But it did contribute to improved brightness when treating and refining the aspen. The task became focused on optimizing the sugar yield, pulp yield, and refining energy of the oxalic acid pretreatment process, but several treatments with sulfurous acid and mixtures of oxalic and sulfurous acid were tested. The earlier work had already demonstrated that there was little value in more severe treatments just to reduce refining energy, but with the added value of fermentable sugars, more extensive prehydrolysis could provide a better cost/value optimum, particularly when considering the cost of concentrating the filtrate.

The experimental work was carried out in a Sunds Defibrator CD-300, two-stage, continuous chemithermomechanical pulping pilot plant [2]. The plug screw feeder, PREX impregnator, and preheater, standard in this pilot plant, were ideal for conducting the prehydrolysis treatment. A unique plug screw discharger was used to seal pressure in the preheater and recovered part of the processing filtrate. A variety of wood supplies were tested including a mixture of white and black spruce, red pine, and a mixture of trembling and big tooth aspens. The pilot plant was operated at a feed rate of 1.2 kg of wood chips (dry weight) per min, and all pretreatments were carried out at 130 °C with 10-min retention time.

The Sunds Defibrator pilot plant mimics full-scale pulp mill equipment quite accurately. The initial plug screw feeder receives presteamed wood chips and compresses them to approximately 25 % of initial volume to provide the steam seal for the preheater. Shredded and compressed wood chips leave the plug screw immersed in the pretreatment solution where they expand, absorbing approximately 1 L of pretreatment solution per kg of dry weight chips. A pair of vertical augers conveys the shredded wood out of the impregnator chamber, with the liquid level in the chamber used to control the amount of chemical absorbed. The preheater provides up to 45-min retention time with pulp scraped off the bottom by a rotating bar into a recessed discharge auger. The plug screw discharger has a 4:1 compression ratio similar to the plug screw feeder. The discharge auger meters the pretreated wood into the plug screw discharger which compresses the wood into a plug that serves as the discharge steam seal for the preheater. For these experiments, the chemical flow to the PREX system was 2–3 L per min, which meant that the impregnation chamber overflows with the excess liquor and the chips remained immersed in liquid in the preheater. The excess liquor was readily recovered in the plug screw discharge filtrate, providing about 75 % recovery of the pretreatment filtrate. The shredded wood from some reactions was collected directly for testing and experimental refining. In others, the discharger was connected to the CD-300 pressurized refiner. The final step, also called second-stage refining, was carried out in an atmospheric 12-in. Sprout Waldron refiner.

In mechanical pulping, the extent of refining is generally measured with a drainage measurement referred to as freeness. A low freeness value indicates a slower drainage rate which is correlated with a higher overall surface area of the pulp and higher strength of the resulting paper. Pulp from the first-stage refiner was split into 1 kg batches which were refined in the second stage at different plate clearances, producing a range of freeness values. Energy comparisons are for data fit with a linear regression and interpolated to a 150 mL freeness value. This is a typical target for thermomechanical pulp grades.

Of the species tested, spruce achieved a 44 % reduction in specific energy consumption (SEC) with a 0.5 % charge of oxalic acid on dry weight wood basis (Fig. 4) [1]. Red pine did not respond as well to the oxalic acid pretreatment but achieved 33 % savings in SEC at a 0.8 % oxalic acid charge. The response of aspen to the oxalate pretreatment was significantly different in that it was almost linear even to high charges of oxalic acid. The largest savings in energy observed with aspen was 40 % achieved with a 1.5 % charge of oxalic acid on wood. Also significant to the analysis are pulp yield and brightness. The brightness of spruce TMP was not impacted by oxalic acid charges below about 0.15 % on wood but decreased 5 points for higher OA charges. Red pine brightness was not affected until the oxalic acid charge exceeded 0.4 % on wood and aspen showed a 3-point loss at the lowest oxalic acid charge, 0.08 % on wood. Neither spruce nor pine benefited significantly from treatments with sulfurous acid, but aspen brightness was improved using a combination of oxalic and sulfurous acid [1, 2].

The two softwoods do not have a significant yield loss at oxalic acid treatment levels below about 0.25 % on wood and a yield loss of 2–2.5 points at about 0.4 % oxalic acid charged to wood. Aspen behaves differently again, showing a near-linear loss relative to oxalic acid charge [1]. The yield loss was insignificant at the lowest charge evaluated (0.08 % oxalic acid on wood), but at twice the charge (0.17 %), a loss of 1.5 points was obtained. The yield results are shown in Fig. 5.

In mechanical pulps, the energy savings and yield loss are ordinary economic factors with linear costs. Brightness is more significant in that the primary products produced with mechanical pulps—newsprint and low-cost printing papers—are predicated on the brightness that can be obtained from the pulping process and a simple bleaching process using sodium dithionite ($Na_2S_2O_4$, also called sodium hydrosulfite). Chelate-stabilized and buffered dithionite can provide 7–10 points in brightness, but any charge greater than about 1 % dithionite on wood pulp is wasted. The 2-point loss in brightness puts mills beyond the point where they can maintain the brightness needed with dithionite and requires the mill to bleach with hydrogen peroxide. Peroxide bleaching requires specialized equipment and a cocktail of chemicals just to stabilize the peroxide from decomposition. The additional capital and operating cost of the peroxide bleaching process is a significant cost barrier. This limits the treatment to about 0.25 % oxalic acid on pulp and the energy savings to 35 % for spruce and 17 % on red pine.

The brightness loss with aspen and linear energy savings as opposed to the asymptotic energy savings makes use of oxalic acid to treat aspen economically untenable. Since sulfurous acid had improved brightness when used for treating aspen, it was used in the evaluations of this wood species. Mixtures up to 1 % oxalic acid and 1 % sulfurous acid provided pulps with 5 points higher brightness than the aspen controls and specific energy savings of 17–25 %.

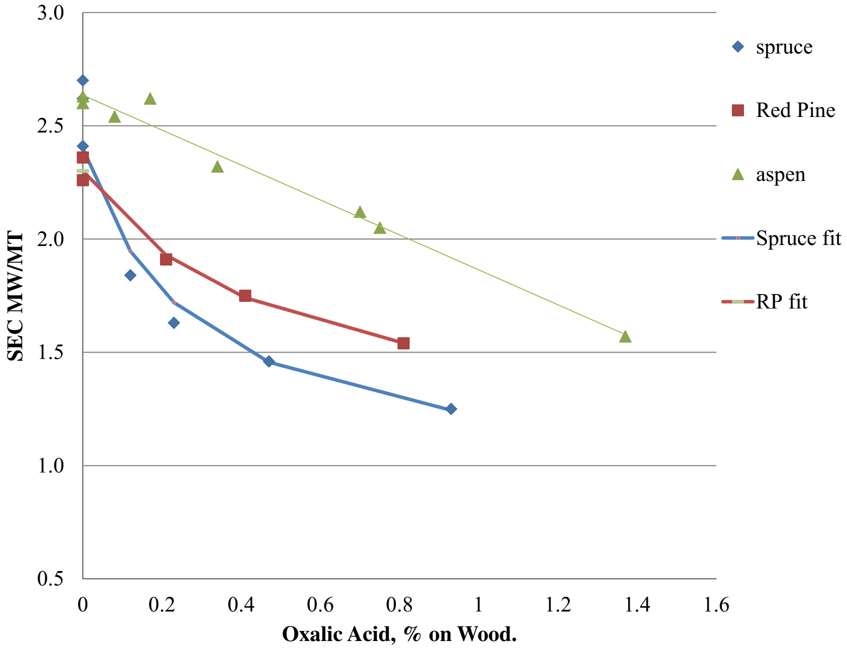


Fig. 4 Oxalic acid pretreatments reduce specific energy consumption (*SEC* in megawatts per metric ton) in refining for all three species, but mild treatments are much more effective on the softwood samples

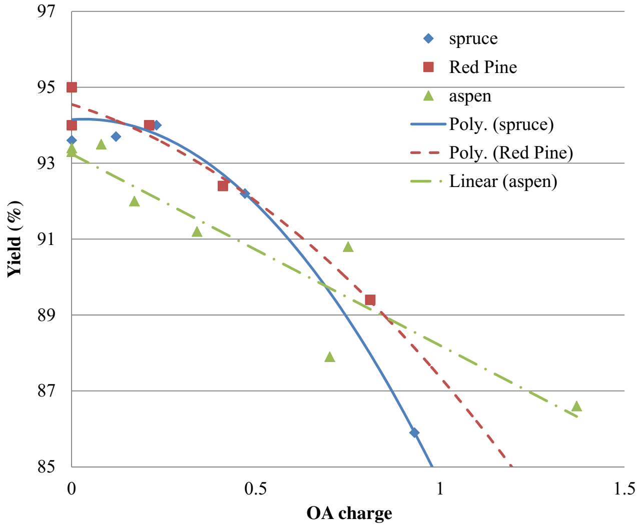


Fig. 5 Impact of oxalic acid pretreatment on pulp yield. The two softwoods appear to have almost no yield loss until the oxalic acid charge exceeds 0.25 % on wood

As with the chemical pulping work, the thermomechanical pulping effort was modeled using a spreadsheet mass and an energy balance model coupled to an economic model [4]. None of the scenarios evaluated produce enough sugar to warrant recovery, taking pretreatment of wood for thermomechanical pulping out of the bioenergy business [1]. However, electrical energy savings were sufficient to show positive returns on invested capital of around 11 % for all three wood samples [1, 4]. Unfortunately, this rate of return is below the target set by most paper companies for investments. Furthermore, the sensitivity analysis on significant cost and process efficiency variables suggested a 15 % or greater risk that the process would not be cost-effective. As with the evaluation of prehydrolysis for chemical pulping, none of the paper companies involved in the value prior to pulping project chose to pursue this process.

Woody Biomass Pretreatments with the Sulfonated Pretreatment to Overcome Recalcitrance of Lignocellulose Process

Of biomass options, wood tends to be difficult to chemically pretreat and saccharify, and softwoods are particularly difficult. Forest residuals, the most likely woody feedstock for biorefineries, can include bark and leaves or needles and a very wide range of particle sizes. All of these attributes make woody biomass feedstocks difficult to process in a saccharification–fermentation process. When used on woody biomass, most pretreatment methods end up with low sugar yields and, correspondingly low fermentation product yields, and efforts to improve saccharification often end up forming fermentation inhibitors. Sulfurous acid has been used as a wood treatment chemical for a century, primarily as the acid sulfite pulping process that was the dominant method for preparing wood pulps until 1940. For biorefining, SO_2/H_2SO_3 had been tested for production of sugars by acid hydrolysis [5, 6] and as a pretreatment for enzyme saccharification [7, 8]. Using a steam explosion-based pretreatment process on Radiata pine, Mamers and Menz reported yields of 489–587 kg of reducing sugars with sulfur dioxide included in the pretreatment [7]. Significant in this research was the recognition that the method was particularly effective for treating softwoods.

Sulfonated pretreatment to overcome recalcitrance of lignocellulose (SPORL) is an optimized sulfurous acid bisulfite treatment designed to maximize the fermentation yield from wood and, primarily, softwoods [9, 10]. The sulfurous acid bisulfite buffer is used to control and optimize the pretreatment pH. Ethanol yields in the range of 260–320 L per ton of biomass have been achieved using the sulfonated pretreatment and genetically engineered yeasts capable of fermenting mannose and xylose as well as glucose [11]. Yield is just one component of process economics. SPORL helps not only in managing softwoods, but separate steps to remove the pretreatment filtrate and detoxify the mixture are not needed [12]. The sulfonated lignin also works as a dispersant in enzyme treatment, helping to increase enzyme activity [13]. Fermentation results for SPORL-pretreated Douglas fir slash are provided in Fig. 6. These experiments used a quasi-simultaneous saccharification and fermentation with carefully controlled and optimized pH to increase ethanol production. With 20 % initial loading of solids, the yeasts were able to produce over 5 % ethanol content beer.

As one of several options evaluated by the Northwest Advanced Renewables Alliance (NARA) for production of aviation fuel [14], SPORL was selected as the pretreatment for the 1000 gal scale-up that is currently in process.

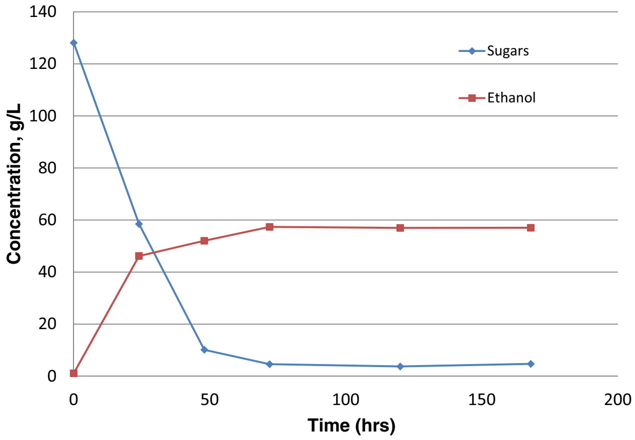


Fig. 6 Ethanol yield for SPORL-treated Douglas fir forest residues. Sugar concentration is the sum of glucose, mannose, and xylose (Gu et al., Ind. Biotech., accepted for publication)

Gasification of Woody Biomass

The role that woody biomass has played in meeting this nation's energy demands has been traditionally associated with combustion. In addition to its use as a thermal feedstock, there has been a continuing shift towards woody biomass serving as a thermochemical feedstock in which thermal decomposition products, pyrolysis oil, and/or producer gas serve as an intermediate for producing a liquid transportation fuel. It is projected that this dual utilization of woody biomass as both a thermal and thermochemical feedstock will result in doubling of woody biomass harvesting to meet demands by 2040 [15].

One of the drawbacks of woody biomass as a feedstock is the lack of homogeneity as a result of factors such as processing; composition of the biomass including bark, leaves, and needles; the composition of the wood such as lignin, cellulose, hemicellulose, extractives, and ash; and wood species mix. The result is a myriad of physical, chemical, and thermal properties of woody biomass that can affect conversion processes. The use of thermochemical processes help to minimize the changes in the woody biomass feedstocks. A majority of new and planned woody biomass energy facilities are thermochemical conversion facilities that produce some form of liquid transportation fuel in which a synthesis gas serves as the intermediate.

This section summarizes research conducted on a pilot-scale downdraft gasification unit and focuses on the effect of the woody biomass feedstocks on the producer gas and subsequent conversion to liquid transportation fuels.

Gasification experiments were performed on a Biomax 25 downdraft gasifier produced by the Community Power Corporation of Littleton, Colorado. The gasification unit has a controlled-air chamber with temperature profiles controlled using a series of five air injection rings throughout the length of the gasification chamber. Temperatures within the gasification chamber are typically between 850 and 900 °C. The producer gas exiting the chamber is cooled from approximately 500 to 120 °C and then passes through one of four filter bags. The cooled, filtered producer gas can be routed to any of three end processes: compressed for conversion to liquid transportation fuel, fed to an internal combustion engine turning a 25-kWh generator, or flared in the atmosphere. Producer gas composition is monitored for oxygen, carbon monoxide, carbon dioxide, hydrogen, and methane using an in-line Nova 7900P5 infrared gas analyzer. Flow rate ranges from 40 to 70 standard m^3 per h (scmh) with the most common flow rate of 55 scmh. For a detailed description of the gasifier and its operating parameters, see Elder and Groom [16].

There are numerous processing variables that affect producer gas composition such as flow rate, residence time, and particle size [17–19]. This research focused on the influence of wood variables and temperature profile, along with Fischer–Tropsch conversion to hydrocarbons

The effects of the operating conditions of biomass gasification are reflected in the temperature profile of the gasifier and the subsequent producer gas composition [20]. Multiple combustion-related reactions occur simultaneously in gasification, and controlling the balance of the reactions is compounded by the change in bulk density, variation in the biomass charring, changes in chip bed permeability, and changes in rates due to consumption and bed defects including bridging by the chips and subsequent collapse. The average carbon monoxide concentration of the producer gas for three consecutive runs is provided in Fig. 7. The raw data (Fig. 7a) shows the variability of the runs. The major source of variation in the CO concentration is due to the inability to completely control the temperature in the five levels of the reactor. The variability also made it more difficult to compare producer gas from different gasification experiments. The CO output was correlated to the operating parameters using multiple regression, and this was then used to normalize the producer gas concentration to a standard temperature profile for the reactor. The normalized data provided a better way to evaluate the influence of changes. Figure 7b shows the resultant carbon monoxide percentage after normalizing the temperature profile. The residual standard deviation dropped from 0.52 to 0.16, allowing a more discriminating comparison of processing changes.

The Biomax was then used to evaluate mixed southern yellow pine and mixed hardwoods as a feedstock [16]. Although the different feedstocks affected the processing parameters, the composition and energy content of the producer gas were within a standard deviation of each other. Species effects, although typically minor, can be attributable in part to the composition of the wood [21]. Extractive content has been shown to affect the producer gas composition. Elder et al. evaluated the effect of extractives on producer gas using two sources of slash pine (*Pinus elliottii*) [22]. The effect of elevated extractive levels on percent of carbon monoxide for the two samples is shown in Fig. 8. The slash pine with a higher level of extractives resulted in a producer gas higher in carbon monoxide.

A by-product of biomass gasification is a solid residual char that is rich in inorganic constituents. The char collected in the gasifier bag filter was analyzed and reported in a series of papers [23–26]. Not surprisingly, the char was similar to composition of wood ash from boilers and wood stoves, apart from 52 % of the material being unburned carbon. As with other sources of wood ash, calcium was the most common inorganic element.

The residual char from the gasifier was evaluated as a soil amendment by Pan and Eberhardt [27] and Jeong et al. [28]. Pan and Eberhardt found that the alkaline pH of the residual char (9.5) along with high concentrations of calcium,

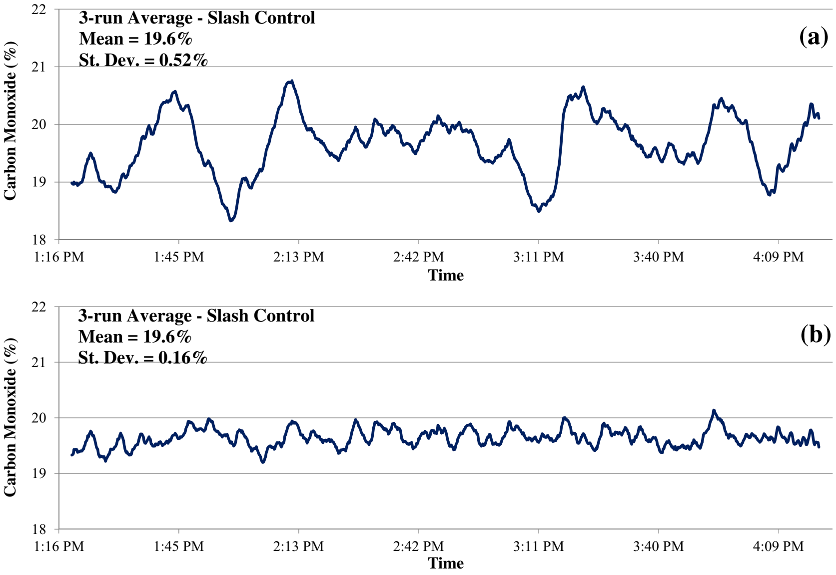


Fig. 7 Percentage of carbon monoxide in producer gas during a 3-h gasification run (three-run average) of slash pine (*Pinus elliottii*) wood chips with **a** raw data and **b** data normalized for a constant temperature profile

potassium, and magnesium was suitable as both a liming agent and a fertilizer [27]. In addition, the concentrations of most metals were lower than the guidelines for ecological soil screening levels. It was also noted that toxic metals were generally less bioavailable, thus increasing the potential applicability of residual char as a soil remediate. Jeong et al. evaluated the effectiveness of woody biomass residual char as an adsorption–desorption medium and for transport of tylosin, a macrolide class of veterinary antibiotics [28]. The results showed that biochar amendments enhance the retention and reduce the transport of tylosin in soils.

The producer gas in a downdraft gasifier is high in carbon monoxide and hydrogen, allowing for conversion to liquid transportation fuels using the Fisher–Tropsch process. Sharma et al. reported on converting synthesis gas prepared from southern yellow pine into C_5+ hydrocarbons via the Fischer–Tropsch (F-T) process [29]. The producer gas from the gasification step was compressed and cleaned in a series of sorbents to produce the following feed to the F-T reactor: 2.78 % CH_4, 11 % CO_2, 15.4 % H_2, 21.3 % CO, and balance N_2. Results show that catalysts promoted with Zn and Al provide a higher extent of reduction and carburization in CO and a higher amount of carbides and CO adsorption as compared to catalysts promoted with Si. This resulted in higher activity and selectivity to C_5+ hydrocarbons than the catalyst promoted with silica. Subsequently, Mai et al. evaluated the effect of catalyst preparation methods on the conversion of synthesis gas by iron-based F-T catalysts [30]. Two iron-based catalysts were prepared using two methods: co-precipitation and

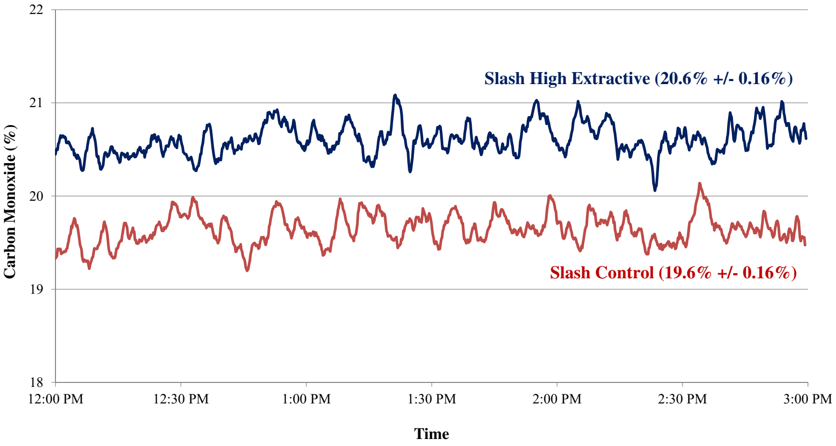


Fig. 8 Average concentration of carbon monoxide in producer gas during 3-h gasification runs (three-run average). Samples are a high-extractive slash pine (*Pinus elliottii*) and control slash pine wood chips. Data were normalized to a constant temperature profile

impregnation. Results showed that the co-precipitated catalyst had higher reduction and carburization, leading to higher carbon conversion and C_5+ selectivity than the impregnated catalyst.

In another project also looking at small gasifiers, Anderson et al. evaluated products from a small commercial biomass gasifier and a small commercial pyrolysis unit, both sized to manage wood wastes from sites like a sawmill or veneer plant [31]. The Biochar Systems, Inc. (BSI) pyrolysis unit had an operating capacity of 225 kg/h of biomass. The unit operated with two zones, a 700–750 °C reactor with controlled oxygen atmosphere, and 1-min retention time followed by a 10–15-min reactor held at 400–450 °C under anaerobic conditions. The second reactor was swept with a carrier gas that results in a dilute gas product with just 15–25 % as a typical gasification product. The gasifier was a 700 kg/h prototype system provided by Tucker Engineering Associates (TEA). This was an anaerobic chamber heated to 1040 °C and with a residence time of about 1.5 min. For this project, the residual solid material from the first pass through the reactor was fed back to the reactor to simulate a longer 3-min retention time. This process does not use a carrier gas and results in a higher concentration gas product. Sixty to seventy percent of the TEA gas product was hydrogen, carbon monoxide, and small hydrocarbons C_1–C_5; these molecules accounted for just 15–25 % of the gas stream from the BSI system. It should be noted that the BSI system used the aerobic zone to heat the wood and required no external process heat where the TEA system was heated by natural gas. The bulk of the study was focused on the biochar which was evaluated both as a coal substitute and as a raw material for activated carbon.

The work with the Biomax 25 was all carried out with wood chips as the feed. But gasifiers can accept a mixture of energy sources, and Brar et al. considered co-gasification of coal and biomass for utility sizes ranging from 5 to 100 kW [32]. Small gasifiers, in particular, have shown promise for rural economic development, with several commercial manufacturers working to address this need. Some noted advantages of including biomass in the feedstock (versus coal alone) are as follows: an increase in H_2 content in the producer gas, a reduction of sulfur and mercury in both the producer gas and char, and an increase in the energy content of the gas. Although the small gasifier systems are primarily designed for biomass, they can operate using as much as 30 % coal. The use of both wood and coal in small systems increases fuel flexibility and can reduce fuel costs. New technical and non-technical challenges were encountered when co-feeding wood chips and coal to gasification systems. For example, because coal and biomass have different chemical compositions, densities, and material handling properties, it was harder to maintain gas production rates and gas composition uniformity. This can be compounded by the inherently different gasification rates of coal and biomass. An overall conclusion of this research was that co-gasification of coal and biomass has advantages that can lead to near-term opportunities in the energy sector.

Co-firing Wood in Coal-Fired Utilities

Many large coal plants are located within forested regions of the USA and often near national forests. Because transportation of biomass is expensive relative to its value as energy, the proximity of these coal-fired utilities to available woody biomass offers an opportunity for co-combusting these materials for energy generation. Over the past decade, co-firing research in the USDA Forest Service has addressed several important themes. Most of these studies have addressed technical, social, or economic barriers to co-firing. These include co-firing location, woody biomass resource potential, and acceptance by coal plant managers. Other work has addressed regional themes for co-firing, focused mostly on the Northeastern USA and Rocky Mountain Region. At least one study has addressed the national status of co-firing facilities, highlighting successful efforts. Smaller power plants (typically using grate systems) and larger power plants (mostly using pulverized systems) have both been evaluated. The USDA Forest Service involvement in co-firing research involving woody biomass and coal is likely to remain an important research focus as energy security and climate change remain to be high national priorities. Ultimately, these research findings will translate into practices that coal plants around the USA can implement for environmental and economic benefits.

Economic factors influencing co-firing in the Northern USA were evaluated by Aguilar et al. [33] and Goerndt et al. [34]. They included factors such as fuel prices and renewable energy mandates in developing an econometric model for what influences local decisions to co-fire wood. The evaluated factors included utility plant location, the number of coal-fired power plants in a county, and availability of wood mill residues. The location of existing coal-fired power plants and technical feasibility were highly significant variables for estimating the probability a plant would co-fire wood. A key finding of this research was the need for flexible design in power plants to accommodate fuel feeding, fuel handling, and transportation systems suitable for both biomass and coal feedstocks at various ratios. This research also found that the future development of co-firing is likely to be centered in the US Great Lakes region, due to the proximity of coal plants to wood product facilities. A surprising policy-related finding of this research was that state-level renewable energy portfolio standards have not statistically influenced the utility adoption of co-firing.

Feedstock availability is a critical component that influences decisions to co-fire woody biomass by electrical utilities [35]. Many factors influence the availability and costs, including ecological and policy constraints, ongoing harvesting operations making low-cost slash available, and delivery issues including distances and reliability. The woody biomass evaluated in this study included logging residues, small-diameter trees, and integrated harvesting residues. The evaluation considered concentric transportation radii that were assessed at the county level. Delivered fuel costs were determined for each power plant in the study. Under most scenarios, woody biomass feedstocks could replace up to 30 % of coal-generating capacity. However, if adjacent coal plants were competing for the same "wood basket," then co-firing potential was reduced to about 10 %.

In a similar study, Goerndt et al. considered the availability of woody biomass as a co-firing feedstock in 20 northern states [36]. They first estimated net annual woody biomass growth for each state, based on USDA Forest Service inventory data. If all woody biomass available was used for electric generation, it could displace close to 19 % of coal-based electrical generation or 11 % of total electric energy generation. They concluded that in some cases, a coal-fired plant could replace 10 % of the coal feed if it could collect just 30 % of the net annual woody biomass growth within a 34-km radius of the plant. By extending the radius to 45 km, the plant could offset up to 20 % of the coal required by the plant. It was recognized that in practice, biomass supply zones are not nice concentric circles. The irregular spatial distribution of coal-fired power plants and potential overlap of biomass supply zones all reduce the amount of biomass conveniently available for co-firing. When also considering social, economic, and technical limitations, the near-term capacity to replace coal-fired electric generation with woody biomass in this region was estimated at less than 5 %.

In the studies mentioned earlier, biomass availability and resources issues were evaluated as primary drivers for co-firing woody biomass [33–36]. The authors determined that there was a lack of understanding on how co-firing impacted power plant operations and on manager perceptions of biomass co-firing [37]. This research considered input from coal power plant managers to assess the most important conditions influencing past and current co-firing decisions and to explore future prospects. Transportation issues and biomass cost were identified as being most important to managers, whereas environmental regulations were considered somewhat less significant (yet recognized as potentially being important under future air quality regulations).

There can be considerable wood residue or wood waste generated in both forest management activities like thinning to reduce fire risks or to improve growth rates, slash from harvest operations, and sawdust, slabs, and cores from sawmills and veneer plants. Loeffler and Anderson evaluated total emissions for various wood utilization strategies [38]. They modeled emissions from co-firing bituminous coal with forest biomass from forest restoration treatments in Southwestern Colorado. Emission contributions from five different component processes were considered: coal mining, power plant processes, forest biomass processes, boiler emissions, and forest biomass disposal. For each process, CO_2, CH_4, SO_x, NO_x, and particulate (PM10) emissions were evaluated. The primary objective was to compare emissions from co-firing versus open burning of harvesting residues in the forest. Co-firing rates of 0, 5, 10, 15, and 20 % biomass by energy value were considered. At maximum co-firing rates, 189,240 tons of CO_2 was avoided at a single power facility (versus burning coal only). When harvest residues were disposed with open burning, an additional 144,200 tons of CO_2 was generated. Emissions of methane are almost entirely avoided with co-firing. This research extended past work by providing a methodology for assessing emission tradeoffs that incorporate the operational aspects of managing forest treatment residues.

A key consideration for co-firing woody biomass with coal is particle size reduction of the biomass, particularly in boilers using pulverized fuel systems. Wood particles must be reduced in size to well below that of sawdust, a task beyond the capability of conventional wood processing equipment found at most sawmills. A study carried out by Mitchell and Rummer evaluated in-wood processing options for co-firing at a pulverized coal facility in Alabama [39]. Their feedstock was unmerchantable wood from timber harvests in the Talladega National Forest in the Southeastern USA. They focused on in-wood equipment, such as horizontal grinders, capable of reducing wood particle size for compatibility with coal plant fuel handling systems. They found that wood particles must be "clean and sharp" to prevent plugging at the coal plant. They also determined that woody biomass is more easily reduced in size by a cutting action rather than a shearing action, especially when co-firing with pulverized coal systems. A specially equipped horizontal grinder was identified as being a choice of suitable equipment to produce particles with these properties.

Nicholls et al. considered the use of woody biomass from forest management activities near Fairbanks, Alaska, as a co-firing feedstock [40]. In Fairbanks, the coal plants are grate systems capable of handling chip-size particles and burning close to a total of 600,000 tons coal per year. The biomass source in this study was biomass removed as part of defensible space treatments aimed at reducing fire risk to structures. Important issues that must be addressed to enable co-firing include wood chip uniformity and quality, fuel mixing procedures, transportation, wood chip processing costs, infrastructure requirements, and long-term biomass supply. Although the Fairbanks North Star Borough is well positioned to use biomass for co-firing at coal burning facilities, long-term co-firing operations would require expansion of biomass sources beyond defensible space-related harvesting alone. These could potentially include a range of woody materials including forest harvesting residues, sawmill residues, and municipal wastes.

Nicholls and Zerbe evaluated the current status of biomass co-firing in North America at more than 40 facilities known to have conducted tests [41]. They identified current trends and success stories, types of biomass used, coal plant size, and primary co-firing regions. A key barrier to co-firing at higher rates (typically greater than 5 % of energy value from wood) can be the capital investment needed for new fuel handling equipment. In some cases, entire coal plants have been repowered to use wood as the only fuel. Typically, these plants are 50 MW in size or smaller. Recently, Nicholls, Huang, and Wright completed two test burns at a 23 MW coal-fired power plant in Fairbanks, Alaska. The first trial was conducted over 2 days and consisted of burning approximately 20 tons of high-quality aspen chips at levels of 5 and 15 % in one of the three burners. In the second trial, close to 40 tons of low-value hog fuel from a wood pellet mill was burned, also at 5 and 15 % energy value. Both tests demonstrated the feasibility of co-firing at up to 15 % without adversely affecting plant operation (publications in progress).

Future co-firing applications could include increased use of torrefied wood. Torrefied wood is a higher-value product that can be transported more economically than traditional wood chips due to its higher energy density [42]. Torrefied wood is closer to the fuel density of coal and handles much like coal, a drop-in biomass replacement for coal. Mitchell and Elder provided an overview of torrefied wood, with a focus on co-firing applications and also applications where coal could be replaced by torrefied wood. Torrefied wood can reduce or eliminate many of the fuel handling problems associated with wood chips, while also reducing SO_2, NO_x, and net greenhouse gas emissions of CO_2. It does, however, require a separate partial combustion process to torrefy the wood, and this cost needs to be factored into the analysis of where this process works economically.

Conclusion

Woody biomass use for energy applications remains a high priority research area within the product research portfolio of the USDA Forest Service R&D. The ultimate research and development objective in this case is to provide applications with sufficient value to mitigate costs for forest management activities, generally thinning of overgrown forests to reduce fire risks or provide defensible space around structures. Where markets and sufficient product values exist, the wood value can cover some or, in ideal cases, all the costs of the forest operation and transportation. The product value helps to stretch the fuel treatment and forest restoration budget and extend treatments to more at-risk forestlands. A significant problem in fuel products is the low value of fuels relative to other uses for timber such as lumber, panel products, and paper. Whereas these higher-value products pay stumpage fees in addition to harvesting and transportation costs, fuel uses usually cannot and often depend on the logging slash or saw mill residuals provided by higher-value uses. This is clearly one of the findings of the wood/coal co-firing research carried out by Aguilar et al. [33] and Goerndt et al. [34–36]. Co-firing is practiced primarily where there is an active forest product industry that can provide logging residuals and wood processing wastes at costs competitive with coal. The pulp and paper research referred to as value prior to pulping was also affected by the value of fuels relative to the higher-value paper products. Wood had far greater product value as paper, and the yield loss from prehydrolysis of the woodchips prior to pulping has greater cost than the value of the fermentation–fuel product that could be produced. Where there were other advantages of prehydrolyzing woodchips before pulping, these advantages were not sufficient to overcome the investment and risk costs of installing the prehydrolysis and fermentation processes.

Large-scale commercial success in utilizing waste wood for transportation fuels and other energy products is going to require improvements across the entire supply chain: harvesting, transportation, and product conversion. Many of the projects that the USDA Forest Service needs to do in order to restore forests to a more natural state require the removal of currently unmerchantable wood. These projects result in considerable expense to the USDA Forest Service. The use of biomass for energy products does not require large trees and is not sensitive to species. These are good applications for the unmerchantable biomass the USDA Forest Service needs to remove, and provide a value chain that can offset some of the biomass harvest and removal costs. The ultimate goal is for the woody biomass that needs to be removed for effective forest management to have sufficient value to pay all costs. Partial success that cannot pay all costs still extend the fire-risk mitigation dollars and allow for more acres to receive needed treatments. Part of the burden for restoration of the national forests shifts from taxpayers to a valued use. Woody biomass has a much smaller greenhouse gas footprint and does not contain toxic metals. These are both major concerns of coal use. As utilities begin to address these concerns, woody biomass use to provide energy is sure to increase.

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