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Project Title: Indirect Liquefaction of Wood Waste for Remote Power Generation Fuel

Contract Number: RD3-66 Milestone Number: 8 Report Date: March 23, 2012

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Congressional District: Not Applicable

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MILESTONE 8 AND FINAL PROJECT REPORT

Project funding was provided by customers of Xcel Energy through a grant from the Renewable Development Fund and the U.S. Department of Energy.

Executive Summary

Minnesota produces 300,000 tons/year of waste from its forestry operations that are not used in any existing or proposed facility. Through the process of indirect liquefaction, this wood waste could be converted into liquid fuels that could be used in remote, off-grid sites to power fuel cells to produce electricity. Using distributed power generation at off-grid sites saves Xcel Energy ratepayers from having to pay for transmission lines to be built to the sites. In addition, the wood-to-fuel technology provides a non-fossil energy-based, nearly carbon dioxide neutral method to fuel backup generators, even in areas that are served by the grid, saving Xcel Energy ratepayers the cost of maintaining large backup power production systems. In addition, with this technology, Xcel Energy ratepayers may be able to take advantage of future carbon credits or avoid carbon taxes applied to fossil energy-based power production.

The University of North Dakota Energy & Environmental Research Center (EERC) has developed and tested at laboratory and bench scale much of the technology necessary for distributed indirect liquefaction systems. The goal of the RD3-66 project was to demonstrate the performance of this technology in a mobile system at one-quarter commercial scale, or 100 lb wood/hr. However, the EERC was able to match the RD3-66 funding with funds obtained from the U.S. Department of Energy (DOE). With the additional funding, the EERC designed and built a demonstration-sized mobile indirect liquefaction system (MILS) twice as large as that

envisioned in the original Renewable Development Fund (RDF) proposal, greatly surpassing the original project goal. It also achieved project objectives by operating the system and determining best construction and operating practices, overall system productivity, and what design changes will be needed in order to make the concept more commercially viable as described below.

The system uses a gasifier to convert the wood waste into synthesis gas, which is cleaned and compressed and flows to a gas-to-liquids (GTL) reactor to convert the gas to a liquid. In this program, we focused on the production of methanol because it can be easily transported and reformed at an off-grid site into hydrogen which can be used to power fuel cells to efficiently make electricity. The gasifier constructed was specially designed by the EERC to handle wet wood waste, thereby saving the need to separately dry the wood before gasification, as most commercial gasification units require. The system was designed to gasify up to 200 lb of wet wood per hour, but operating experience indicates that it can go as high as 300 lb/hr.

The methanol production rate was approximately 10 to 20 gallons per ton of biomass for both wood types tested. This production rate was approximately half of what was predicted for this gas composition because the syngas flow rate was only about half of what was needed because of an undersized syngas blower and water freezing in the gas cleanup system. Another program objective was to test the methanol “as is” after filtration in a fuel cell reformer for 113 hours by IdaTech LLC of Bend, Oregon. IdaTech’s tests showed carbon deposit formation in the fuel cell vaporizer, indicating that the vaporizer will need to be cleaned more often than when high-purity methanol is used. Alternatively, the methanol produced by the MILS system can be made more pure either by better syngas scrubbing or fractional condensation of the gas leaving the GTL reactor.

Although the methanol production rate was lower than originally anticipated, computer modeling, which was validated by the testing, indicates that if we insulate the gasifier to increase the temperature of the bed and upgrade the blower and insulate the gas-cleaning equipment, then methanol production should increase to 50 gallons/ton of wood. The modeling indicates that, with additional modifications, production could be increased to as much as 150 gallons/ton of wood.

Assuming that the modifications to the system are made to allow production of 100 gallons of methanol per ton of wood, then the 300,000 tons of unused forest residue produced each year in Minnesota could be converted to approximately 30 million gallons of methanol. A fuel cell uses approximately 1 gallon of methanol to create 5 kWh of electricity, so 30 million gallons of methanol could be used to create 150,000 MWh of electricity per year by a fuel cell in remote locations. However, an economic analysis indicates that the modified system will need a throughput of approximately 400 lb/hr, which could be done on two trailers instead of one, in order to lower the cost of the methanol to produce electricity at a cost similar to that of a diesel generator, assuming a fuel cell cost of $2000/kW.

Technical Progress

System Design and Construction:

Design: The original concept for the technology built and tested in this project was to have a system that could be easily transported to a site where a nonpermanent source of wood waste was available and convert that wood waste into liquid fuel that could be used to create electric power at another site that did not have grid power available or needed backup power. It was also originally thought that some sort of carbon tax could be taken advantage of in this scenario to offset some of the higher costs associated with small-scale production. To keep operational costs to a minimum, the system was designed to operate with as little labor as possible. Figure 1 is a schematic that illustrates the overall concept of the MILS. Wood chips are fed into the top of the gasifier in batches of approximately 100 lb every ½ hour. In the gasifier, the wood is heated in the presence of a limited amount of air to convert the wood into a gas, known as synthesis gas, or syngas, composed of carbon monoxide (CO), carbon dioxide (CO_2), hydrogen (H_2), water vapor (H_2O), tars, and a small amount of hydrogen disulfide (H_2S). The incompletely converted wood, known as char, and ash are augured out of the bottom of the furnace. The syngas passes through a wet scrubber where it is sprayed with water to remove entrained ash and tars, then passes through a bed of activated carbon to remove remaining volatile tars and H_2S. The gas then passes through a particle filter to remove remaining fine particulate matter. The air is pulled into the gasifier, and the syngas from the gasifier, using a large fan known as a blower.

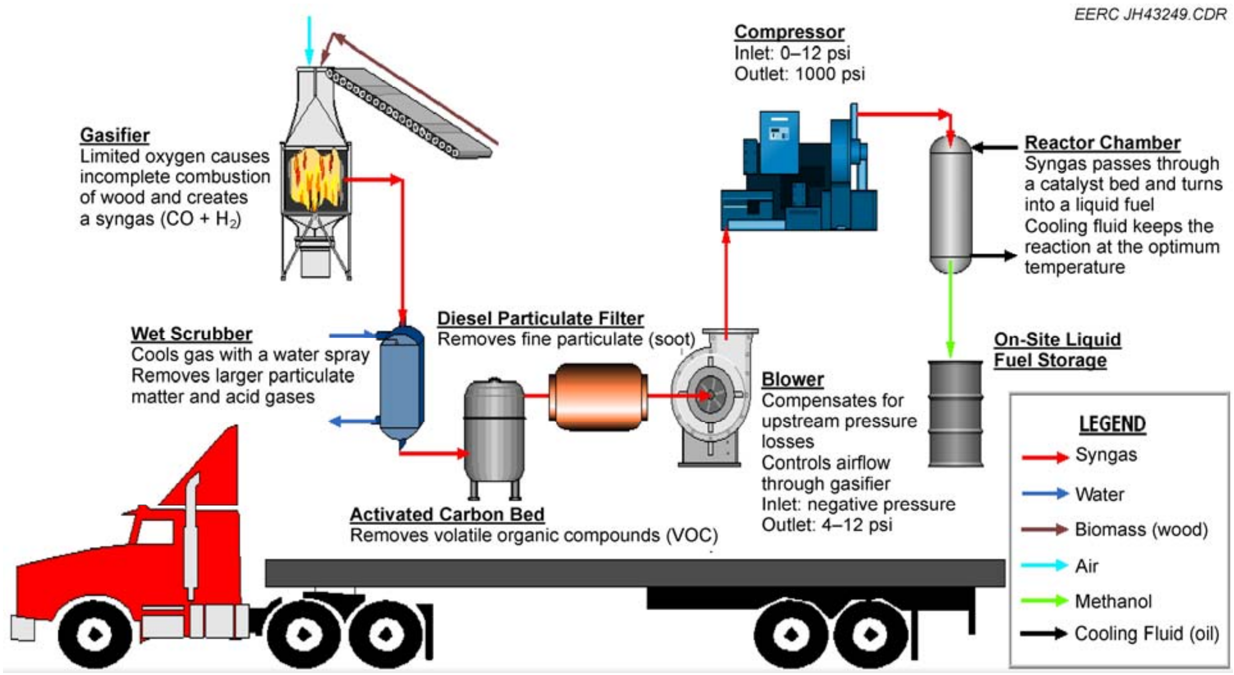

Figure 1. Schematic illustrating the overall concept of the MILS.

After the particle filter, the gas is pushed by the blower into the compressor which pressurizes it to 900 psi and then passes into the GTL reactor where it is heated to 225°C and converted by a catalyst into a liquid that is predominantly methanol. The methanol is condensed at the outlet of the reactor, and the remaining gas is sent to a flare in which it is burned, along with any surplus gas that is not compressed.

Figure 2 shows the general 3-D design of the MILS. The sizing of the gasifier, heat exchangers, and gas cleanup components is such that the system extends beyond the trailer roof height and so requires assembly in the field.

The control area is at the front of the trailer, shown by the enclosed box on the upper trailer. A photo of the MILS system is shown in Figure 3.

Sensors and Controls: The programming language for controlling the indirect liquefaction system is Labview. This language has been used in both academic and industrial control applications. The EERC has prior knowledge and experience using Labview for control applications.

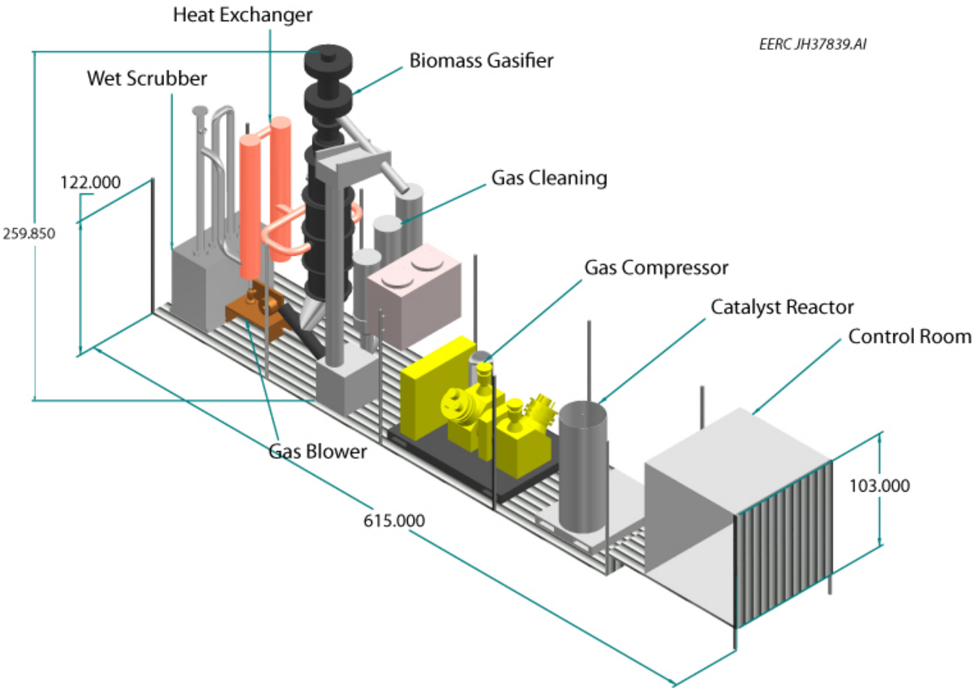

Figure 2. 3-D drawing of the trailer-mounted gasification system. The trailer roof has been removed for this depiction only. Lengths are in inches.

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Figure 3. The completed MILS system. The GTL reactor and control room are behind the trailer curtain.

The indirect liquefaction control system can be broken into two parts: a real-time controller (RTC) and a human–machine interface (HMI). The RTC utilizes a real-time operating system (RTOS) which is more robust for control systems than a general OS. Fail-safe logic and alarms are located on the RTC and are inaccessible to the user to prevent tampering. The RTC sorts the various input and output controls and device communications and allows the system to be programmed for part-time automatic operation, although in the system testing work done under the project, all controls were performed manually.

Although the RTC is present in the system, the control of the system is performed through the HMI, which allows an operator to monitor and control the system. This includes device control, data logging, real-time data trending, and system status and alarms. Noncritical system logic is located on this device.

The MILS gasifier and gas-cleanup system are shown in Figure 4. Figure 5 shows the conveyor that brings the wood chips to the top of the gasifier.

The gasifier was designed to handle approximately 200 pounds of wet wood an hour, but we believe, based on initial operation, that over 300 pounds of wet wood could be handled by the gasifier an hour.

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Figure 4. The MILS gasifier and gas-cleanup system.

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Figure 5. The conveyor used to carry the wood chips to the top of the gasifier.

System Operation:

Fuels Tested: The bases of the fuel selection were its availability and its near-zero or negative cost. The feedstocks selected were, therefore, two different softwoods representing widely available wood species of great commercial interest. Figure 6 shows the two fuels used in the experiments: a) chipped green poplar wood waste and b) city wood waste, primarily chipped ash trees. The green poplar wood waste was purchased from Dukek Logging, obtained from a site near Regal, Minnesota, and chipped ash trees were provided by Dwight's Tree Service of Grand Forks, North Dakota. The second fuel can be considered a negative-cost fuel based on its cost associated with disposal after it is chipped. Dwight Tree Services is required to transport chipped wood waste for its disposal. Fuel transportation to the EERC was relatively easy, and free delivery was a primary motivator.

Both wood species were simultaneously chipped and truck-filled. After the receipt of biomass, it was filled in a plastic super sack weighing in the range of 750–850 pounds per bag. During the experiments, the fuel bags were hung with the help of a forklift and directly dispensed on the belt of the conveyor feeding system. In order to determine the weight of the fuel injected in the gasifier, the bags were suspended on an electronic balance fixed on the arms of a forklift.

The biomass moisture contents were first measured in 1-pound samples and found to have varied from 27% to 38%. Considering this variation to be too large, further analysis was conducted using larger samples containing about 5 lb each. Based on the measurements, it was determined that the green poplar wood waste moisture content ranged from 27% to 55% with an average of 41%. The chipped ash tree moisture content ranged between 38% and 43%, with an average of 41%. It was, therefore, concluded that the moisture content in both fuels is similar, although the

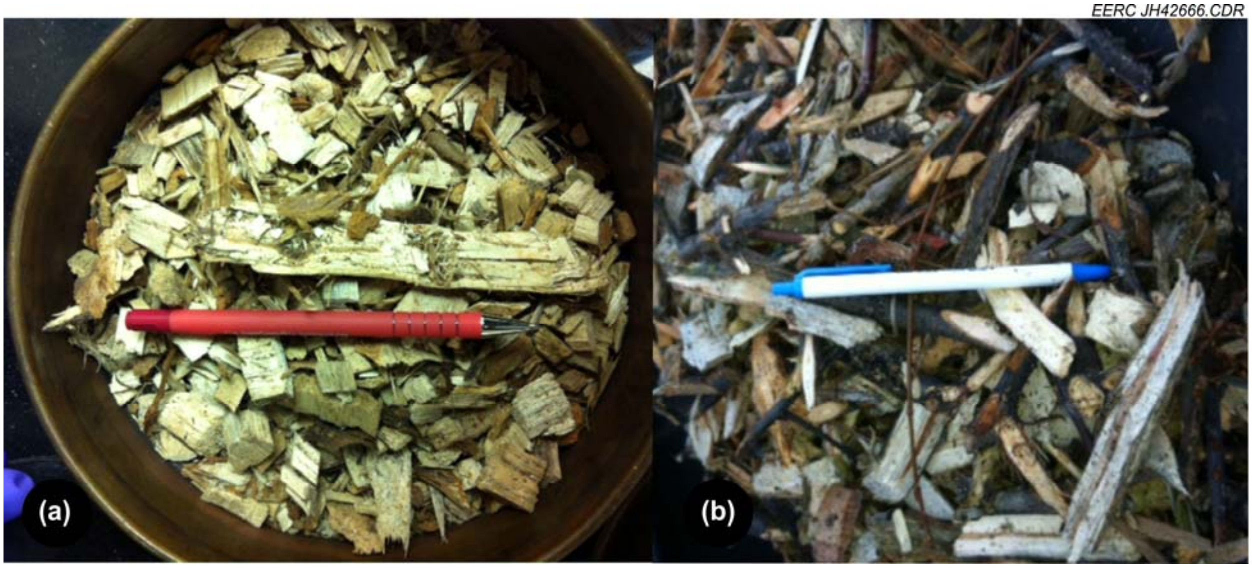

Figure 6. Biomass used in the experiments: a) chipped green poplar wood waste and b) city wood waste, primarily chipped ash.

ash tree chips had a narrow range compared to the poplar wood chips. The moisture content is far too high for use in most commercial gasifier designs that can only handle partially dried wood (15% or less). However, the MILS gasifier is specially designed to handle wood with this level of moisture and maintain a required temperature profile such that clean syngas can be produced and a higher fraction of moisture can be converted to syngas. Feeding of the fuel was successful except for occasional bridging in the feed convergent section upstream of the gasifier lock hopper because of longer sticks or branches.

Gasifier Operation: The gasifier can achieve a high turndown ratio once the designed operating temperature profile in the gasifier is achieved. During this steady-state operating condition, the gasifier has capabilities of maintaining desired syngas composition irrespective of the fuel composition such that the effect of variation of the feedstock composition has near-zero impact on the methanol production for that specific syngas composition. As stated above, the moisture content of the biomass was much higher than can be handled by other gasifier designs. It was also highly variable between the two fuels, but the variation in the moisture content or biomass species had no measureable effect on the syngas composition.

System tests were conducted to understand the effects of different feed rates and the ability of the gasifier to adjust to the varying operating conditions. During these tests, wet wood was injected at rates ranging between 150 and 165 lb/h. A total of 3300 pounds of wet wood was consumed during the initial operating period. In addition to wood chips, about 310 pounds of wood charcoal was also consumed during the initial start-up. It was observed that the gasifier could generate combustible gas within 25 minutes after forced bed ignition during winter conditions (−4°C). Thereafter, it can be autoignited within 17 minutes if the gasifier operation is initiated within 90 hours of its previous operation. With an overnight shutdown (12–16 hours), combustible syngas can be generated within 4 minutes of starting the air feed. Figures 7 and 8 show the gasifier bed, wall, and pre- and postscrubber syngas temperature–time history measured during bed and flare ignition after both 90 hours and overnight shutdown.

The average syngas production rate was observed to have ranged between 80 and 95 scfm. In all system tests, air temperatures were below freezing. Because of the cold weather, the heat-transfer fluid had solidified, and the reactor had to be externally heated to thaw the fluid. To prevent freezing, the oil pump and heater were continuously operated. The methanol catalyst was activated under flowing hydrogen and nitrogen at concentrations of 10% and 90%, respectively. The reactor temperature was ramped up to 250°C for catalyst activation.

The rate of production of methanol is dependent on the composition of the syngas, particularly the concentration of hydrogen. Higher hydrogen concentration in the syngas is preferred since it is the feedstock to the CO and CO_2 hydrogenation reactions. The hydrogen content of the fuel and the effective utilization of the biomass moisture in the gasifier bed contribute to the increase in hydrogen concentration in the syngas. These conversion reactions are more favored at higher bed temperatures. The gasifier operation at a designed (higher) temperature condition becomes critical, particularly in the case of wet biomass gasification. The moisture can be utilized in the

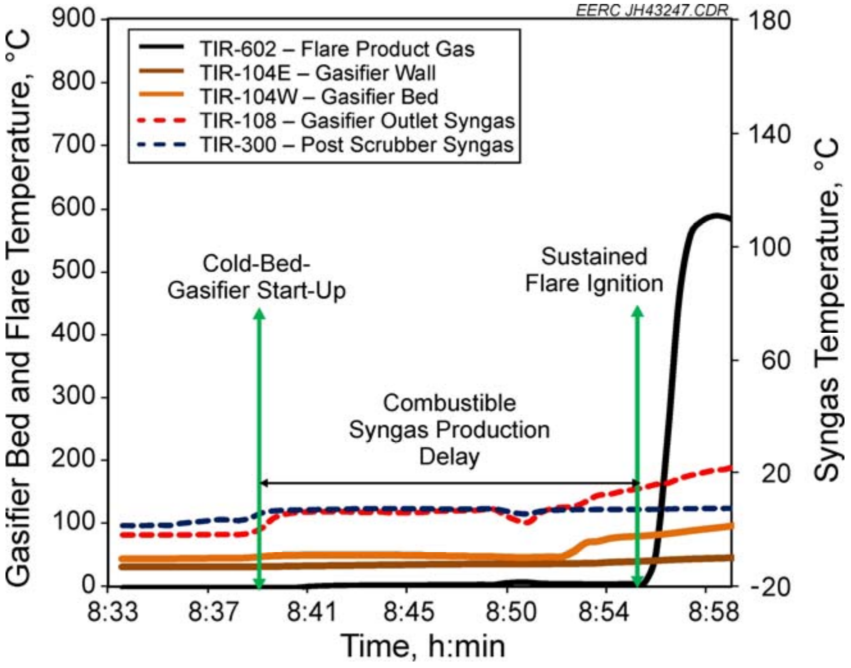

Figure 7. Gasifier bed, wall, pre- and postscrubber syngas temperature–time history measured during bed and flare autoignition achieved after 90 hours of system shutdown.

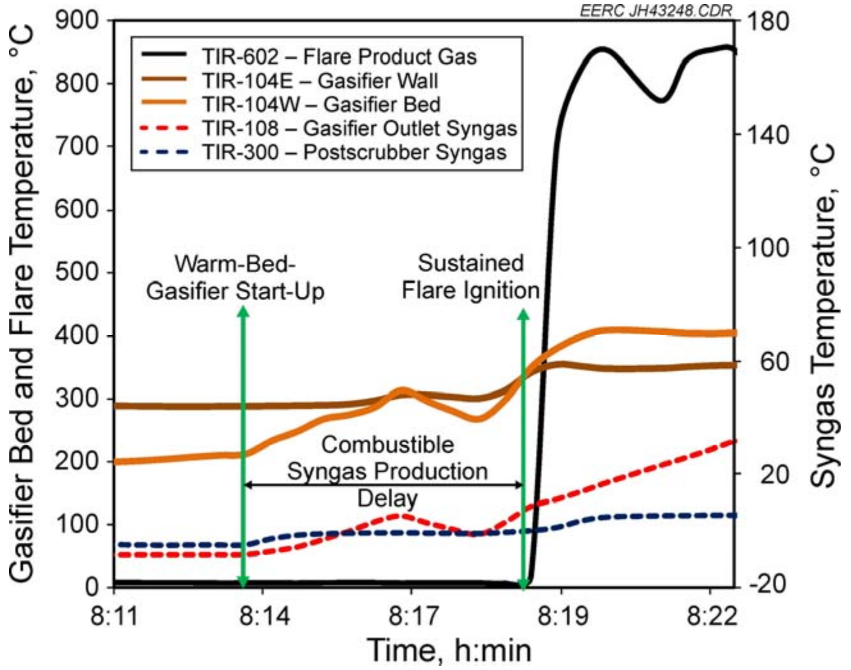

Figure 8. Gasifier bed, wall, and pre- and postscrubber syngas temperature–time history measured during bed and flare ignition achieved after an overnight system shutdown.

reactor effectively at higher operating temperatures where the reactor wall heat losses become significant. In a self-sustained gasification process, the desired bed temperature is achieved through partial oxidation of fuel and effective utilization of heat while adiabatic reactor conditions are maintained as closely as possible.

Figure 8 depicts the gasifier bed, wall, and pre- and postscrubber syngas temperature–time history measured during a typical bed and flare ignition. As can be seen, the gasifier bed temperature slowly increases after the injection of air marked at the point of gasifier start-up. This start-up is initiated after 14 hours of bed cooling achieved after previous-day methanol production operation. The refractory wall temperature was close to 300°C at the time of start-up; however, the gasifier core temperature was expected to be higher. As can be seen, combustible syngas production, marked by "sustained flare ignition" was achieved within 5 minutes of the gasifier start-up. Soon after the ignition of the gasifier bed, the bed and wall temperature increases. The rate of temperature increase is dependent on the heat generation and heat loss rate. The heat generated is a result of partial oxidation of the fuel and other overlapping exothermic gasification reactions, while the heat loss occurs primarily in the heating of the feedstock from room or atmospheric temperature to the gasification temperature and endothermic devolatilization as well as gasification reactions. Heat loss from the reactor wall becomes a determining factor particularly if the gasifier is not insulated adequately. The capability of the blower to attain the designed operating flow rate also plays a critical role in maintaining the required exothermic heat profile through oxidation reactions. Table 1 shows the syngas composition measured at the time of flare ignition and after about an hour of gasifier operation. As can be seen, the increase in H_2 concentration and decrease in CO_2, CH_4, and higher hydrocarbons is owing to increasing bed temperature. At this point in time, the gasifier bed temperature increased by about 350°C while the refractory wall temperature increased by 150°C. The blower speed was maintained at 20 Hz for another hour, and it was observed that the gasifier wall temperature increase rate had significantly reduced owing to the wall heat losses. It was concluded that the gasifier insulation was inadequate. Continuation of the experiment at full blower speed revealed the designed oxidizer/fuel throughput condition necessary for establishing the desired exothermic heat profile and corresponding syngas composition could not be achieved. While the blower was required to develop a flow rate of 160 cfm at 10 psig, it developed only 79 acfm, or 131 scfm, most likely because of an undersized motor. The temperature profile determined at this operating condition was not adequate to produce the desired concentration of hydrogen and carbon monoxide, although the H_2/CO concentration obtained was greater than 1 as necessary for methanol production. Based on the observed slow increase in the bed temperature at full-speed blower operation, it was estimated that the planned single-shift operations will be, timewise, inadequate to attain the desired temperature profile, and the syngas composition, particularly higher H_2 and CO concentration and low CO_2 concentration, would be difficult to achieve.

During the initial test campaign, the peak wood throughput attained was 264 lb/h at a peak syngas production rate of 131 scfm during a methanol production test. This flow rate was less than the expected 160 scfm because of an underperforming syngas blower. The suction pressure

Table 1. Syngas Composition at the Time of Ignition and after 1 hour

	Syngas Composition, vol%	
	At Flare Ignition	After 1 hour
CO	10.26	10.29
H_2O	0.22	0.25
H_2	15.21	18.37
O_2	1.11	1.12
N_2	49.45	50.88
CO_2	17.87	16.72
CH_4	2.84	1.32
C_xH_y	3.04	1.05

required was about 75 inches of water column, while the delivery pressure developed by the blower was 10.5 psig. In later tests at lower ambient temperature (all tests were performed below freezing temperatures), the pressure drop across the gas cleanup packed bed increased substantially because syngas water vapor froze in the bed matrix. The highest pressure drop experienced was during the coldest phase of the experiment when the measured ambient air temperature was −15°C. The total pressure drop that the blower had to overcome was 169 inches of water column. This condition resulted in reduction of the syngas flow rate to as low as 83 scfm at the maximum blower speed (instead of 131 scfm observed during operation at higher ambient temperature). Experiments under such conditions were suspended because of stalling of the syngas compressor as a result of attainment of lowest flow and inlet pressure limits. Insulating the packed bed should alleviate this problem in the future. A total of 5900 lb of biomass was consumed during testing.

Methanol Production: For the methanol production tests, syngas was fed to the methanol reactor at a flow rate of 75 scfm. A typical syngas composition would be CO 15%, H_2 15%, CO_2 17%, N_2 50%, and hydrocarbons 3%. During a typical run, the concentrations of each of the gas species varied by several percentages up and down because of fuel variability and the fact that the fuel is fed in batches, not continuously. The composition of the gas produced by both of the wood types tested was within this amount of variability, indicating no measurable difference in syngas composition produced by these two wood types. However, the fuels tested were both softwoods. It is expected that syngas compositions may vary more if hardwoods or coniferous woods were used.

The methanol reactor was operated at 210°C and 900 psi. The methanol production rate was approximately 10 to 20 gallons per ton of biomass for both fuels. This production rate was approximately half of what was predicted for this gas composition because the syngas flow rate produced by the blower was only about half of what was predicted. In addition, a sample of pressurized syngas was also collected in a gas cylinder for testing the production of Fischer–Tropsch (FT) fuels using a laboratory reactor.

Although the methanol production rate was low, modeling with Aspen Plus software indicates that if we can insulate the gasifier better to increase the temperature of the bed to what we have achieved on the pilot scale and if we upgrade the blower to get the full 160 scfm flow rate of syngas, then methanol production should increase to 50 gallons/ton of wood. In fact, after surveying other methods of increasing production rates, including talking with product manufacturers, Aspen Plus modeling indicates that production rates can be increased considerably more. The modeling indicates that if a second gas-to-liquids reactor were added to the system, then production rates could be increased to 85 gallons per ton of wood. If, instead, we add gas separation membranes of the type used at oil refineries, then production could be increased to 100 gallons per ton of wood. If, in addition to the gas separation membranes, we also add a water–gas shift reactor to the system, then production could be increased to as much as 150 gallons/ton of wood.

Long-term, steady-state operation of the methanol reactor has been hindered by a couple of operational issues. Occasional air leaks upstream of the reactor increased the concentration of oxygen in the syngas to 1%–2%. The oxygen vigorously reacted with the catalyst and syngas at the entrance of the methanol reactor, which caused unacceptably high temperature increases and forced reactor shutdowns. The air leaks were identified and repaired. The syngas compressor had difficulty providing consistent feed to the reactor as well because of low suction pressure faults. The root cause of the faults is an undersized blower, which pulls air through the gasifier and pressurizes the gas to the compressor. As a short-term solution to prevent the compressor from faulting, the low suction pressure limit was reduced from 5 to 1 psi.

The liquid produced by the system is of relatively high purity for a GTL process. Tests show that it is 89% methanol and contains approximately 6% water, 4% simple oxygenated organic compounds such as ethanol or dimethyl ether, and 1% aromatic compounds such as benzene and toluene. These numbers vary only about 1 actual percent between different samples, which is within the experimental error of the measuring devices. The constancy of the liquid composition is largely a factor of the catalyst used, which is very specific for methanol. Because the catalyst is so specific and because the syngases produced from the two types of wood fed were so similar, all of the methanol produced was combined in one barrel, and separate methanol samples produced from the separate types of wood feed were not analyzed.

Additional analyses showed that the liquid also contains some inorganics, including approximately 10 ppm iron and several ppm copper, which may or may not hinder fuel cell operation by creating an ash layer on the reformer catalyst and creating a light ash within a combustor system. The iron and copper are believed to come from the catalyst used to create the methanol and should drop in concentration with long-term use of the system. When the product comes out of the GTL reactor, it is clear. But after several hours, it begins to turn a yellowish color, and a precipitate forms, as seen in Figure 9, probably because of oxidation of the iron and condensation of waxes. Therefore, the liquid was filtered before it was sent to IdaTech for testing in its fuel cell reformer. Figure 10 shows the methanol after filtering. The filtering process was effective at removing the precipitate and reduced the iron and copper concentrations to below 0.5 ppm, the lower detection limit of the analytical equipment.

Methanol Testing by IdaTech: Fifteen gallons of the clarified methanol product was sent to IdaTech LLC of Bend, Oregon, for testing to determine if the methanol product could be used

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Figure 9. The liquid methanol-based product before filtering.

EERC JH43251.CDR

Figure 10. The liquid methanol-based product after filtering.

"as is" in a fuel cell system. IdaTech's full report is included with this report as Appendix B. To no one's surprise, the raw methanol produced in the MILS did not meet the stringent specifications used for fuel purchases. In particular, IdaTech found that the dissolved solids were too high, and it prefers not to have aromatic compounds such as benzene and toluene present because those chemicals may not be chemically compatible with fuel cell system parts. However, IdaTech agreed to test the fuel in a reforming system of the type used to convert the methanol fuel back into synthesis gas containing carbon monoxide and hydrogen, which is the first step in how IdaTech's system converts methanol into electricity.

The IdaTech testing ran for 113 hours. At the end of the tests, it found that deposits had formed in the vaporizer section of the reformer. Figure 11 shows iron pellets used in the vaporizer after the test with the MILS methanol versus after a test with commercial methanol. Scanning electron microscopy showed that the deposits were primarily made of carbon, with some potassium and sodium present as well. The carbon deposits likely formed from a very small amount of tar that made it to through the GTL reactor. These deposits could ultimately plug the vaporizer in a system operating for extended periods. To deal with the deposits, either the steel shot in the fuel cell vaporizer will need to be replaced and regenerated periodically, or the methanol will need to be purified. The best way to purify the methanol is either to clean the syngas better before it enters the GTL reactor, primarily with more extensive water scrubbing, or to condense the gas leaving the GTL reactor in a stepped temperature fashion.

FT Catalyst Testing: In addition to the methanol production tests with the large reactor, we also tested the possibility of using the syngas for production of FT liquids. FT liquids consist of long-chain hydrocarbons that can be readily converted into diesel or jet fuel. They are made using a compressor and reactor similar to what is used to make the methanol from the syngas, except that a different catalyst is used.

To perform these tests, a gas cylinder full of syngas, collected during a MILS gasifier run, was passed through a laboratory-scale reactor that had been built previously during a separate EERC

Figure 11. Close-up of the steel shot used in the methanol vaporizer showing deposits formed from carbon and potassium. The left picture is from the vaporizer testing the MILS methanol, and the right picture is from tests with commercial methanol.

project. Unfortunately, the FT catalyst was negatively affected by the MILS syngas, largely deactivating it. The reason for the negative result is still being investigated. Initial beliefs are that the relatively high carbon dioxide content of the syngas in relation to the relatively low hydrogen content of the gas may have led to hydrothermal deactivation of the catalyst. If the hydrogen content of the gas stream is increased as described above, this problem would be alleviated. Another option would be to use a different catalyst material.

Economics of the Technology:

An economic analysis was performed in order to understand the feasibility of the conceptual MILS to succeed commercially and to determine factors critical for its success. Based on EERC experience pertaining to the impact of system size on the economics, the study includes a base case methanol production rate of 100 gal/ton of woody biomass (system size 1×) and a larger system (system size 2×) producing twice the hourly production rate of methanol while maintaining the same conversion rate of 100 gal/ton.

Assumptions: The cost to produce methanol comprises direct operating costs and capital costs. The analysis was conducted to separately compare and highlight the impact of a debt-free plant versus a debt-loaded plant evaluating the base case methanol production rate of 12 gal/hr for system size 1× or the targeted nominal production of 100 gal/ton of green woody biomass (moisture up to 40%). These throughputs are double for system size 2× considered in the analysis. In additional EERC modeling, used in the RDF proposal, it was assumed that a system that could handle a feed rate of 400 lb/hr (feed moisture 20% to 30%) could be built on a single semitrailer. However, after laboratory testing, it was determined that a much higher gas pressure was required in the GTL reactor and that a compressor producing the needed pressure has a larger footprint than originally estimated. In light of testing, the largest GTL system that can be put on a single trailer is one sized to handle the syngas flow from gasifying only 200 lb/hr (to accommodate a higher feed rate for higher than 30% moisture biomass), which is the size of the system built under this program. Of course, if a second trailer were used for the GTL system, then a system size 2× with double throughput could be employed.

It is assumed in the analysis that the biomass is available at zero cost as waste products of forestry processing. The system requires electricity for its operation. The direct operating cost of purchasing the electricity from the grid can pose a significant impact on process economics. Considering the gasifier’s unique feature of achieving high turndown ratios, it is possible to produce a supplementary quantity of syngas which, along with the residual combustible gases removed from the methanol reactor, could be fired in a modified natural gas-burning electric generator to produce electricity for the MILS. Therefore, the analysis includes two separate scenarios: the first one includes purchased electricity from the grid at a higher operating cost, while the second scenario includes production of electricity at an additional capital cost involved in procuring the generator which is fueled with the excess synthesis gas. Because of the zero fuel cost assumption, the impact on direct operating cost as a result of almost doubling the biomass consumption is also assumed to be zero.

The equipment and the corresponding capital costs for 1× and 2× systems are shown in Table 2. For the base system 1x, the costs are estimated based on the incurred actual cost of building the experimental system, including the material as well as estimated labor costs involved in the individual system fabrication and assembly. We also assume that a hydrogen separation membrane is employed and system insulation and a larger blower are used so that the methanol production rate reaches 100 gal/ton of 22% moisture wood. The 2× system costs are approximated based on the 1× system cost multiplied by simple multiplicative factors that were estimated based on prior experience. For example, the cost of the gasifier for a 2× system will be 1.5 times the 1× system.

The capital cost presented is based on the experience gained through the MILS program and includes a price escalation of 10% in order to attain a realistic, up-to-date number. The labor cost was estimated based on the extent of fabrication and system assembly. A guideline from the established practice of an established fabrication vendor was utilized for estimating the labor cost. The estimations utilized in arriving at the labor cost for fabricating and assembling the complete MILS are presented in Table 3. The total capital cost shown in Table 2 is the cost of the experimental system built by the EERC. There is a scope of cost optimization if multiple systems are built; however, the present analysis utilizes the current cost in the anticipation that the cost optimization will be utilized in further improvements of the system in order to increase methanol yield, and to include onboard electricity generation.

Table 2. Capital Equipment Costs for MILS, $

System Size	**1×**	**2×**
Gasifier	271,733.62	407,600.42
Gas Cleanup	60,775.01	91,162.52
Feed System	49,280.00	68,992.00
Methanol Reactor	86,604.07	129,906.11
Electrical and Instruments	118,866.13	166,412.58
Hydrogen Separation Membrane	50,000.00	75,000.00
Compressor	226,283.87	407,310.96
Trailer	35,967.40	64,741.32
Miscellaneous Piping and Fitting	7,437.66	11,156.49
Total Cost	906,947.76	1,422,282.41
Optional Engine Generator, 100 kWe	100,000.00	180,000.00
Total Cost (with engine generator)	1,006,947.76	1,602,282.41

Table 3. Labor Cost Estimation for Building Capital Equipment for MILS

Labor Effort	Percent Material Cost, %
Partial Fabrication and Partial Assembly	50
Partial Fabrication and Assembly	30
Partial Assembly	15
Transportation and Minor Assembly	12

General assumptions for plant operation include availability of 85% and unattended operation. Unattended operation assumes a person is not continuously monitoring the process; rather, the process operates automatically and provides alarms for upset conditions (plugged filters, etc.), assuming that the system is used at a facility that has labor performing other duties but available for short times to address the upset issues. General maintenance is based on 6% of plant capital and includes labor, which is about a percentage higher than that recommended by Baasel (Baasel,W.D. *Preliminary Chemical Engineering Plant Design*, 2nd Edition; Van Nostrand Reinhold, NY, 1990). The higher cost is due to considerations given to the complexity of the system and that a nominal system monitoring of about 2 hours a shift by a skilled operator would be required. Catalyst life is assumed to be 5 years, and costs were averaged from commercial suppliers that provided the catalyst for the demonstration experiment at $35.00/kg. Plant auxiliary power can be provided from waste energy consumed in a generator or electric grid power. The grid cost assumed was $0.07/kWh, primarily utilized to operate the syngas compressor, blower, and electric motors for the pump and screw auger. The sulfur and trace tar removal occurs in the preparatory scrubber systems, requiring replacement and zero disposal costs. Use is 3600 lb/yr at $3.50/lb.

Results: Operating costs for system size 1× and 2× are provided in Table 4. These costs are based on operations after repayment of capital and starting cost loans. Based on the modeling results, the best performance of the methanol reactor can be obtained by incorporating proprietary syngas recycling and low-cost gas separation systems included in the capital cost. The cost of methanol production is based on the best-case production rate of 12 gal/hour, or approximately 100 gal/ton. The lowest production cost based on this production rate is $1.40 in the case of the first scenario, but only $0.83/gallon in the case of the second scenario involving generation of electricity from the syngas. At the time of the RDF proposal, EERC calculations indicated that production costs could be as low as $0.79/gallon. This cost was estimated on the methanol production rate of a biomass throughput of 400 lb/h. The current cost estimation is based on a system sized for a biomass throughput of 200 lb/h and, correspondingly, a lower syngas production rate. Although the size and cost of the compressor are reduced, the capital and related operational costs for syngas production equipment are not significantly reduced as would be expected, owing to the reduction in the biomass throughput, particularly with respect to the capital costs associated with the gasifier, syngas cleanup, and methanol reactor. In addition, the cost of electricity consumption, based on the current experimental determination, is found to be about 18% higher than the previous estimations based on theoretical calculations for a 400-lb/h biomass throughput system. Also, because of system maintenance experienced, the estimated general maintenance cost is about a percent (of the capital cost) higher than the earlier assumption. The methanol production cost is, therefore, higher because of the reduction in production rate without any major reduction in capital and associated operating costs. The lowest production cost for system size 2×, based on the production rate of 24 gal/hour, is $1.27/gallon in the case of the first scenario, but only $0.72/gallon in the case of the second scenario involving generation of electricity from the syngas. As can be seen, the production cost for system size 2× is lower than the 1× system.

Although the first scenario is relatively simple compared to the second scenario, recent developments in syngas-to-electricity production at the EERC since the time of the original

Table 4. Operating Cost after Loan Repayment

	System Size 1×		System Size 2×	
	Electricity Purchased	Electricity Produced	Electricity Purchased	Electricity Produced
General Maintenance and Partial Labor	$54,417	$60,417	$85,337	$96,137
Catalyst Replacement	$840	$840	$1,680	$1,680
Electric Power Consumption	$57,334	$0	$114,668	$0
Activated Carbon – Syngas Polishing	$12,600	$12,600	$25,200	$25,200
MeOH Production, gal	89,352	89,352	178,704	171,258
Total Operating	$125,191	$73,857	$226,885	$123,017
Cost of Production	$1.40	$0.83	$1.27	$0.72

proposal have led to the possibility of attaining an electricity self-sufficient MILS, thus lowering the production cost to essentially the same as that provided in the proposal.

The production cost of the electricity self-sustained system is attractively low by about 41% and 46% for system size 1× and 2×, respectively; the impact of additional capital cost on the increased cost of financing on both system sizes is presented in Table 5. First, the economics are compared by assuming the investor would finance over a 5- or 10-year period at 6.5% and desire debt-free operation after the fifth or tenth year. Therefore, the operating cost in the debt-loaded years includes financing of capital at 6.5%. Table 5 compares two methanol production scenarios for system size 1× and 2×. The data indicate that long-term financing with electricity generation can favor reducing the methanol production cost by up to 15% and 19% for system size 1× and 2×, respectively; however, the benefit is comparatively low for short-term financing (8% and 11% for system size 1× and 2×, respectively). Under such circumstances, the site-

Table 5. Operating Cost Including Loan Repayment for System Size 1× and 2×

	System Size 1×		System Size 2×	
	Electricity Purchased	Electricity Produced	Electricity Purchased	Electricity Produced
Debt Loading, 10 yr	$126,161	$140,071	$197,846	$222,885
Debt Loading, 5 yr	$218,243	$242,306	$342,250	$385,564
Direct Operating	$125,191	$73,857	$226,885	$123,017
Total Operating, 10 yr	$251,352	$213,928	$424,731	$345,902
Total Operating, 5 yr	$343,434	$316,163	$569,136	$508,581
MeOH Production, gal/h	12.0	12.0	24.0	24.0
MeOH Production, gal	85,629	85,629	178,704	178,704
Cost per Gallon Debt-Loaded, first 10 yr	$2.94	$2.50	$2.38	$1.94
Cost per Gallon Debt-Loaded, first 5 yr	$4.01	$3.69	$3.18	$2.85
Cost per Gallon Debt-Free	$1.46	$0.86	$1.27	$0.69
Long-Term – 20 yr Breakeven	$2.42	$1.93	$1.99	$1.50

specific cost of electricity and its availability become deciding factors between Scenarios 1 and 2. The breakeven cost of production over a 20-year life is $2.42/gal and $1.93/gal for these scenarios for system size 1× and $1.99/gal and $1.50/gal for system size 2×. These costs can be reduced as a combined effect of system cost and throughput optimization and increases in the methanol production rate. The major improvement would be in reducing the electricity requirement of the system by adopting system innovations. For comparison purposes, IdaTech currently pays $2.66/gallon for a fuel cell-grade methanol–water mixture. However, it is very highly purified. A methanol seller in Florida called to ask about the technology. He makes long-term delivery contracts for methanol at a cost of around $1.50/gallon. Therefore, to become competitive, the mobile technology needs to reduce its capital cost, benefit from a green subsidy, or perhaps go even larger in size.

Cost of Electricity Generation Utilizing Biomethanol in a Distributed System:

Considering that the methanol produced in the MILS will be primarily utilized for distributed electricity generation in a standby generator for applications in remote locations such as remote health centers or communication power sources, the following cost analysis is aimed at determining the MILS size as a factor in determining unit electricity production cost. Since the methanol-based fuel cell generators are expected to replace diesel generators, the cost of producing electricity in the diesel generator is also estimated for the sake of comparison. The generator system size is estimated based on the maximum methanol production rate for 2× systems which is equivalent to a continuous electricity production load of 120 kW (considering currently available fuel cell generation efficiency of 30% and a 24-gal/h methanol production rate). The 1× system methanol production is at a 12-gal/h rate; however, for simplicity sake, the electricity generator size is assumed to be 120 kW, the same as that of 2× system, and the generator will be operated intermittently at full load or continuously at half load, without any impact on fuel cell efficiency. The cost of methanol production for a 10-year debt-loaded system calculated at 6.5% interest rate is considered in calculating the methanol cost expressed in MMBtu, as shown in Table 6. The MMBtu cost of diesel is based on the current (March 2012) retail cost of $4.09. The equipment costs considered for diesel and fuel cell generators are $250/kW and $2000/kW, respectively. The cost for the fuel cell generator is an estimate made by the EERC and is not confirmed by IdaTech. It is assumed that these are commercial systems with a low annual maintenance cost of $5000/year. The system availability of 85% is considered for all of these systems. As seen in Table 6, methanol production has a lower cost, as in the case of system size 2× reducing unit production cost by 20%, and is within 5% of a diesel-fueled system. It is, therefore, concluded that methanol produced in a 2× system can compete commercially with diesel-fueled distributed generation if the fuel cell cost is $2000/kW. However, if the fuel cell cost is higher, then other cost reducers such as carbon credits will be necessary to make the MILS–fuel cell concept for distributed power generation more commercially viable.

Table 6. Cost Comparison of Distributed Electricity Generation Using Diesel Fuel Bought at Retail Price of in Minnesota and Methanol Produced in System Size 1× and 2×

Fuel Type	Diesel	MeOH	
System Size		1×	2×
Fuel Cost, \$/MMBtu	\$29.50	\$44.00	\$34.20
Capital Cost, kW	\$250	\$2,000	\$2,000
Generator Size, kWe	120	120	120
Total Capital, generator	\$30,000	\$240,000	\$240,000
Yearly Maintenance	\$5000	\$5000	\$5000
Availability	85%	85%	85%
Efficiency	25%	30%	30%
Annual kWh	893,520	893,520	893,520
Interest Rate	6.5%	6.5%	6.5%
Loan Period, yr	10	10	10
Annual Loan Payment	\$4173	\$33,385	\$33,385
Annual Gas Use	\$359,851	\$447,272	\$347,653
MMBtu	12,198	10,165	10,165
Total Annual Cost	\$369,024	\$485,657	\$386,038
Cost of Electricity, \$/kWh	**\$0.413**	**\$0.544**	**\$0.432**

Wood Resources in Minnesota:

Ratepayers will benefit from the conversion of wood waste into liquid fuels by being saved the cost of building transmission lines to sites needing electricity but which are far from available transmission lines and by not needing the construction of backup generators by Xcel Energy in the case of systems where grid power is available. In addition, jobs can be created to make further use of the state’s forest resources for the production of electric power at sites removed from the forest resources where the methanol is produced. The initial business model for the MILS concept focuses on legacy piles of wood waste available at forestry product-processing sites which would be essentially free to the processor. This is the concept for the economics of the technology presented in the previous section. However, it was decided to also survey the total forestry resources available in Minnesota for future economic analyses (beyond the scope of this project) applied to all forestry products that could be produced in Minnesota.

To determine the level of total forestry resources available in Minnesota, an analysis of the resource availability was performed by William Berguson of the University of Minnesota, Duluth, which was funded under RD3-66. His report, attached as Appendix A, shows that Minnesota’s wood products industry contributes approximately \$6.9 billion to the state’s economy. While a portion of the forest products industry is not entirely dependent on local resources for raw material, the majority of northern Minnesota’s forest products industry is dependent on wood produced through harvesting of stands located within Minnesota or neighboring states and provinces of Canada.

In the past, wood for fuel has been used primarily for residential heating, with very little wood purchased solely for industrial energy applications. Up to this point, wood wastes produced in industrial processes such as bark, sawdust, edgings, and planer shavings have been used to produce energy, but the use of wood exclusively for energy has not been widespread. Recently, prices of petroleum-derived energy sources such as heating oil and natural gas have risen to the point where wood might be considered an economically viable alternative to fossil fuels. A comparison of the price of fossil fuels and woody biomass shows that wood chips, and in some cases roundwood, may be considered a viable replacement to higher-priced fossil fuels such as natural gas.

The capacity of the state's forest resource to provide timber supply to the forest products industry in a sustainable manner has been a subject of intense study. Minnesota is a nationally recognized leader in this area through the process of the Generic Environmental Impact Statement on Forestry (GEIS), which evaluated forest resources in the context of environmental impacts, including long-term soil productivity, water quality, and wildlife populations. After evaluation of several harvest levels and associated impacts, GEIS identified a level of 5.5 million cords as a sustainable long-term harvest level. This harvest level was also stated as a goal of the Governor's Task Force on the Competitiveness of the Forest Products Industry. A recent follow-up study to GEIS indicates a high level of implementation of recommendations to mitigate environmental impacts. Given a sustainable harvest level of 5.5 million cords and current usage by the forest product industry of 2.9 million cords, an estimated 2.6 million cords of roundwood could be available in the future to produce energy or forest products.

In addition to roundwood harvests, forest harvest residues, specifically tops and limbs, could supply feedstock for energy production. An evaluation of the proportion of harvest residues shows that approximately 800,000 dry tons of harvest residues is currently produced, resulting from a harvest level of 2.9 million cords of pulpwood and sawtimber. Using the same ratio of harvest residues to roundwood shows that a harvest level of 5.5 million cords would produce approximately 1.5 million dry tons of harvest residue biomass. Current and proposed facilities could demand 500,000 dry tons annually, leaving about 300,000 tons of forest harvest residues available at the present time at current harvest levels. Assuming a conservative methanol production rate of 100 gallons per dry ton, this means that approximately 30 million gallons of methanol could be created from these residues. A fuel cell uses approximately 1 gallon of methanol to create 5 kWh of electricity, so 30 million gallons of methanol could be used to create 150,000 MWh of electricity by fuel cell in remote locations. Additional biomass could be obtained through a variety of sources, including thinning of Red Pine plantations. Thinning of Red Pine could contribute an additional 225,000 dry tons annually above current levels which could be used to create just over 110,000 MWh of electricity.

While likely the most expensive option, hybrid poplar plantations grown on agricultural lands have the potential to supply large quantities of woody biomass. Analysis of the economics of production in these systems shows that the delivered price of biomass would have to be from $70.00 per dry ton in the case of replacement of land currently growing wheat to a high of $181 per dry ton if grown on highly productive corn-growing land. Obviously, the choice of location and land type is critical to the end product price of biomass grown in dedicated energy crop systems such as hybrid poplar. Based on this analysis, the dominant cost in dedicated biomass energy production systems is the opportunity cost of growing alternate crops and not the cost of the biomass production system itself. This underscores the need to concentrate research in dedicated biomass crops in those areas where the economics of crop production are less profitable.

The development of this industry will depend on the prevailing price of the competing energy source and the long-term price stability of the end product. Based on current costs of wood resources, it appears that development of efficient conversion technologies could contribute to increased economic activity in rural areas of the state. While not unlimited, wood supplies currently exist to supply raw material for this emerging industry. The benefits of reduced carbon dioxide production, local jobs, and reduced imports of fossil fuels are additional benefits that should also be considered in assessments of the feasibility of alternate fuel production. Opportunities to develop new biomass energy technologies exist and biomass from natural sources as well as dedicated energy crops such as poplar, willow, switchgrass, or other species could play a significant role in the expansion of this industry in Minnesota.

Project Benefits:

- During this project, the EERC team designed, constructed, and operated a mobile system to convert biomass into methanol which could be used in a fuel cell system to produce electricity at an off-grid site, successfully moving technologies that had been developed in the laboratory to a demonstration scale.

- The gasifier used in the system is of a new design that allows the operator to fire high-moisture wood, obviating the need for drying the wood before use.

- Tests with the system were used to validate a computer model that was then used to develop new concepts for modifying the system that could increase methanol production rates to as much as 150 gallons of methanol/ton wood waste.

Project Lessons Learned:

- The team from the University of Minnesota Duluth performed a literature survey and found that approximately 300,000 tons/year of forest residue is produced but not used in Minnesota each year.

- A mobile indirect liquefaction system can be built and operated as envisioned, but setup and takedown are much more involved than anticipated, implying that time operating at a site must also be extended. The vision now is not for movement on a weekly basis, but more like monthly or seasonally.

- Higher syngas compression ratios are necessary for adequate methanol production than originally anticipated. The larger compressor required was very difficult to source as the pressure required falls outside of commercial technology common availability. This drove the price up substantially. Only one vendor was found willing to supply the system in the United States.

- The large compressor has a large footprint and power requirements, so we now believe that the biggest system that can be built on a trailer is around 200 lb of wood/hr, rather than 400 lb/hr of wood as originally anticipated.
- The engineering system model was verified with operational data, giving confidence that the models used to evaluate additional system technologies should have a high validity.
- Several modifications and technologies need to be added to the system to increase production levels. The engineering model indicates a pathway to achieving production of up to 150 gallons of methanol per ton of wood.
- Some modifications necessary to make a more pure methanol product were also identified including more effective gas scrubbing and fractional condensation of the GTL product.
- An economic analysis indicates that if grid power is used in the production of the methanol, the lowest production cost (after paying off construction loans) would be approximately $1.40/gal, whereas if extra syngas were used to power an electric generator, then the production cost would be only $0.83/gallon.

Usefulness of Project Findings:

RD3-66 has been extremely useful in testing and further developing possible indirect liquefaction technologies from those which currently have only been tested at the laboratory scale. Although initial production runs of methanol were much lower than initially anticipated, the results validated our modeling of the concept with Aspen Plus software. By validating the modeling, we can be more assured of the correctness of the model in predicting the advantages of additional system improvements such as those outlined in the previous section of this report.

Assuming that modifications to the indirect liquefaction system are made to allow production of 100 gallons of methanol per ton of wood, then 300,000 tons of unused forest residue could be converted to approximately 30 million gallons of methanol. A fuel cell uses approximately 1 gallon of methanol to create 5 kWh of electricity, so 30 million gallons of methanol could be used to create 150,000 MWh of electricity by fuel cell each year in off-grid sites around Minnesota. However, during the time line of this project, the cost of methanol produced from natural gas has dropped by 40% because of the release into the gas market of great quantities of shale gas such as from the Marcellus Shale in the northeastern United States and the Bakken Formation in North Dakota and Montana. This cost reduction of natural gas-produced methanol will be an impediment to commercialization of the MILS technology unless capital costs for the system are reduced, incentives for production from renewable resources are implemented, or a larger multiple-trailer-type system is employed. An economic analysis indicates that a system twice as large, operating on two trailers instead of one, can produce methanol for $1.27/gallon using grid power and $0.72/gallon using power produced onboard. The analysis also indicates that, assuming a 10-year capital cost repayment on a double-sized system, the methanol production cost could be low enough that the cost of power produced in a fuel cell costing $2000/kW can become competitive with electricity produced in a diesel generator.

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APPENDIX A

SURVEY OF FORESTRY RESOURCES AVAILABLE IN MINNESOTA

Background Document

Minnesota's Woody Biomass Resource
Volumes, Cost and Logistics of Procurement

EERC Wood-to-Methanol Project

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Project funding provided by customers of Xcel Energy through a grant from the Renewable Development Fund

October, 2011

Executive Summary

Recent developments in alternate energy may present new opportunities to expand the economy of northern Minnesota using wood resources. At the same time, increased wood usage in the state can affect the existing industry. The purpose of this document is to evaluate various wood resources and discuss opportunities for growth in the energy industry in the context of the existing forest products industry. Minnesota's wood products industry is an important part of the state's economy contributing approximately $6.9 billion to the state's economy. While a portion of the forest products industry is not entirely dependent on local resources for raw material, the majority of northern Minnesota's forest products industry is dependent on wood produced through harvesting of stands located within Minnesota or neighboring states and provinces of Canada.

In the past, wood for fuel has been used primarily for residential heating with very little wood purchased solely for industrial energy applications. Up to this point, wood wastes produced in industrial processes such as bark, sawdust, edgings and planer shavings have been used to produce energy but use of wood exclusively for energy has not been widespread. Recently, prices of petroleum-derived energy sources such as heating oil and natural gas have risen to the point where wood might be considered an economically viable alternative to fossil fuels. A comparison of the price of fossil fuels and woody biomass shows that wood chips, and in some cases roundwood, may be considered a viable replacement to higher priced fossil fuels such as natural gas.

The capacity of the state's forest resource to provide timber supply to the forest products industry in a sustainable manner has been a subject of intense study. Minnesota is a nationally recognized leader in this area through the process of the Generic Environmental Impact Statement on Forestry. The GEIS evaluated forest resources in the context of environmental impacts including long-term soil productivity, water quality and wildlife populations. After evaluation of several harvest levels and associated impacts, the GEIS identified a level of 5.5 million cords as a sustainable long-term harvest level. This harvest level was also stated as a goal of the Governor's Task Force on the Competitiveness of the Forest Products Industry. A recent followup study to the GEIS indicates a high level of implementation of recommendations to mitigate environmental impacts. Given a sustainable harvest level of 5.5 million cords and current usage by the forest product industry of 2.9 million cords, an estimated 2.6 million cords of roundwood could be available in the future to produce energy or forest products.

In addition to roundwood harvests, forest harvest residues, specifically tops and limbs, could supply feedstock for energy production. An evaluation of the proportion of harvest residues shows that approximately 800,000 dry tons of harvest residues are currently produced resulting from a harvest level of 2.9 million cords of pulpwood and sawtimber. Using the same ratio of harvest residues to roundwood shows that a harvest level of 5.5 million cords would produce approximately 1.5 million dry tons of harvest residue biomass. Current and proposed facilities could demand 500,000 dry tons annually, leaving about 300,000 tons of forest harvest residues available at the present time at current harvest levels. Additional biomass could be obtained through a variety of sources including thinning of Red Pine plantations. Thinning of Red Pine could contribute an additional 225,000 dry tons annually above current levels.

The ultimate delivered price of biomass feedstock is affected by many factors such as land owner, species composition, harvesting equipment used, form of the biomass product and location of the wood-using plant. Assuming a fifty mile average haul distance, the estimated delivered cost of biomass derived from Minnesota’s forest is estimated to range from $20 to $40 per green ton or $50 to $80 per dry ton.

While likely the most expensive option, hybrid poplar plantations grown on agricultural lands have the potential to supply large quantities of woody biomass. Analysis of the economics of production in these systems shows that the delivered price of biomass would have to be from $70.00 per dry ton in the case of replacement of land currently growing wheat to a high of $181 per dry ton if grown on highly-productive corn-growing land. Obviously, the choice of location and land type is critical to the end product price of biomass grown in dedicated energy crop systems such as hybrid poplar. Based on this analysis, the dominant cost in dedicated biomass energy production systems is the opportunity cost of growing alternate crops and not the cost of the biomass production system itself. This underscores the need to concentrate research in dedicated biomass crops in those areas where economics of crop production are less profitable.

The development of this industry will depend on the prevailing price of the competing energy source and the long-term price stability of the end product. Based on current costs of wood resources, it appears that development of efficient conversion technologies could contribute to increased economic activity in rural areas of the state. While not unlimited, wood supplies currently exist to supply raw material for this emerging industry. The benefits of reduced carbon dioxide production, local jobs and reduced imports of fossil fuels are additional benefits that should also be considered in assessments of the feasibility of alternate fuels production. Opportunities to develop new biomass energy technologies exist and biomass from natural sources as well as dedicated energy crops such as poplar, willow, switchgrass or other species could play a significant role in the expansion of this industry in Minnesota.

Introduction and Background

The purpose of this report is to describe Minnesota's wood resources and estimate the potential volumes that could be used to produce methanol for electrical generation on a small scale using technology that is under development at the University of North Dakota's, Energy and Environment Research Center. This technology is described in detail in other associated project reports by those working on the engineering aspects of the project.

An understanding of the raw material source is one of the most critical aspects of any biomass-based alternate energy venture due to the fact that the relative proportion of total end-product production cost attributed to raw material is typically high. Also, raw material supply is affected by uncontrollable events such as weather and inevitable changes in biological systems associated with the resource itself (e.g. aging, disease). Furthermore, the price paid for biomass material is subject to swings as the relative demand on the resource at any given time can fluctuate widely, further adding uncertainty to the economic performance of the project. This report describes some of the aspects of supply, demand and expected price for woody biomass procured from existing wood resources in Minnesota. Also, alternate production systems such dedicated energy crops on agricultural lands will be briefly described and economics of these systems discussed.

Existing Wood Using Industry

Procurement of wood for new applications such as liquefaction of wood to methanol must be understood in the context of the existing forest products industry. Minnesota's wood products industry is comprised of a variety of enterprises producing paper and pulp, oriented strandboard, fiberboard and sawn products in addition to animal bedding and other specialty products. The industry is an important part of the state's economy contributing approximately $6.9 billion to the Minnesota economy (Minnesota Forest Industries, 2007). Over 22,000 people are employed in the various facets of the forest products industry manufacturing lumber, oriented strandboard, engineered composite products as well as pulp and paper. While a portion of the forest products industry is not entirely dependent on local resources for raw material, the majority of northern Minnesota's forest products industry is dependent on wood produced through harvesting of stands located within Minnesota, and to a lesser degree, neighboring states and provinces of Canada.

Energy Prices and Wood Energy Value

Energy prices have fluctuated dramatically over the past decade with the effects of energy price increases being felt in every sector of the economy and all socioeconomic levels. Concerns over long-term supply of petroleum products and continued expansion of emerging market economies of China, India and other countries have contributed to tightening supplies worldwide. The U.S. produces only about one-third of its oil domestically and a steady petroleum supply is critical to the U.S. economy. In the past, wood for fuel has been used primarily for residential heating with very little wood purchased solely for industrial energy applications. Up to this point, wood wastes produced in industrial processes such as bark, sawdust, edgings and planer shavings have been used to produce energy but use of wood exclusively for energy has not been widespread. This has changed somewhat with the construction and modification of facilities at St. Paul District Energy and the Laurentian Energy Authority, both using biomass for energy to produce heat and power.

Recently, prices of petroleum-derived energy sources such as heating oil and natural gas have risen to the point where wood might be considered an economically viable alternative to fossil fuels, particularly in residential heating applications. Table 1 shows the average net realized price per unit of usable energy assuming various rates of conversion efficiency of common energy sources based on current prices (fall of 2011) of the fuel sources. After taking into account conversion efficiency, the cost per million British Thermal Units (mmBTUs) of wood-based energy is currently lower than heating oil and propane and similar to natural gas depending on wood form be it chips, roundwood or pellets. The price advantage of wood pellets over propane and heating oil, in particular, has been the impetus for the development of the pellet fuels industry over the past five years in the Lake States. The differential in price between heating oil or propane and wood is sufficient to encourage investment in pellet production infrastructure and commercial and residential combustion equipment to replace these higher-priced fuels. Thus, the use of wood to produce energy can be expected to increase and could become a significant part of the future economic landscape of the state.

Table 1. Comparison of common fuels and net realized price per mmBTU as of September 2011.

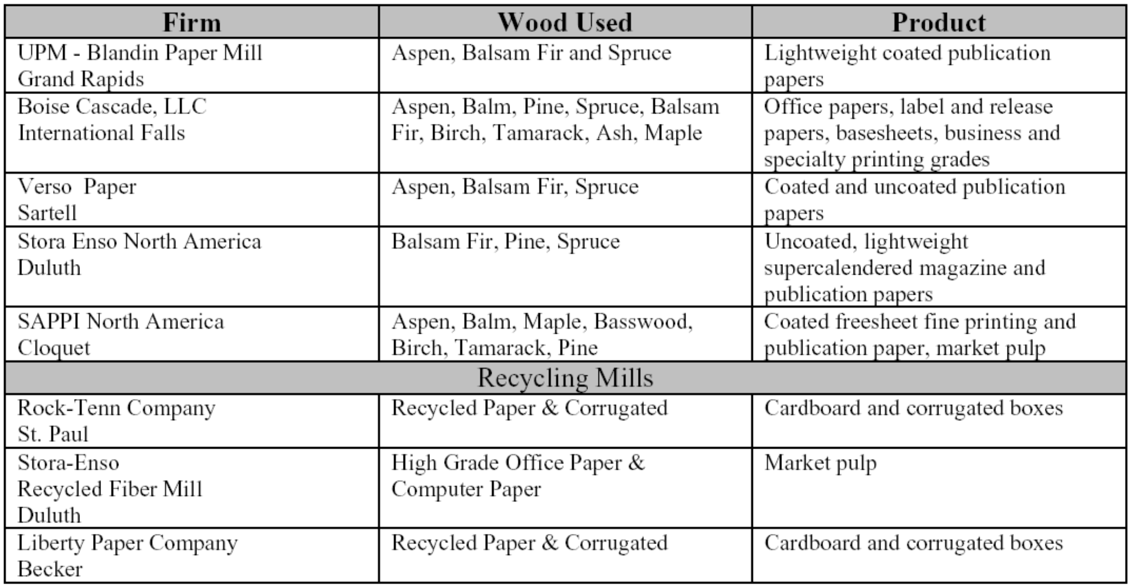
Fuel Type	$/unit	Unit	$/mmBTU	Conversion Efficiency	Net Cost ($/mmbtu)
Natural Gas	**$5.60**	**Mmbtu**	**$5.60**	**0.9**	**$6.22**
Heating Oil	**$3.89**	**Gallon**	**$29.53**	**0.85**	**$34.75**
Propane	**$2.19**	**Gallon**	**$24.33**	**0.9**	**$32.03**
Wood Pellets	**$200**	**Ton**	**$11.76**	**0.8**	**$14.70**
Round Wood	**$75.00**	**Cord**	**$3.83**	**0.6**	**$7.35**
Wood Chips	**$30.00**	**Gr. Ton**	**$3.52**	**0.6**	**$5.88**

While the above discussion does not directly relate to procurement of wood for conversion to methanol, it does provide context to better understand the potential competing uses for wood in both residential and industrial applications. Currently, markets for pellet fuels may not consume a large amount of biomass in Minnesota. However, industrial applications such as taconite kilns and paper mills may consume large amounts of biomass if the price for the alternate fuel increases. In most industrial applications in northern Minnesota, the least-cost fuel source in industrial processes is natural gas. Natural gas appears to be an abundant resource in the United States. However, energy forms are fungible and replacement of one fuel for another may take place over time. For example, migration of gasoline-powered transportation to compressed natural gas (CNG) is currently technically and potentially economically feasible. However, the development of the infrastructure to make CNG widely available in the U.S. is required. Although highly localized, the current price of a gallon-gasoline-equivalent unit of CNG in the U.S. varies from less than $1.00 to $2.50. Thus, the fact that some forms of energy may readily substitute for another (such as wood pellets for propane or CNG for gasoline) should be appreciated because of the potential to alter the demand and price of a given fuel type and its associated effect on the local price of raw material as markets shift to the next least expensive energy option. Given the wide swings in energy prices over the past decade, investments in new biomass-based industry must be done with an appreciation of the impacts of the world energy markets and how quickly those effects are felt at a local level.

Minnesota's Forest Products Industry Overview

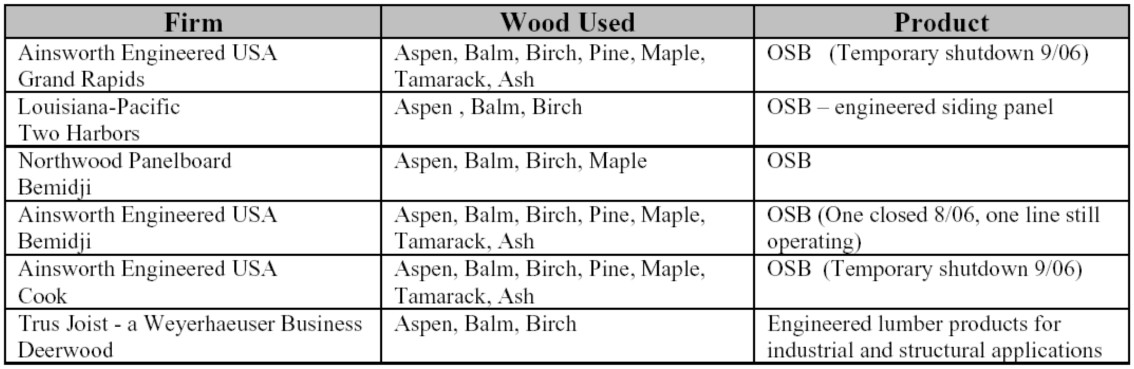
Obviously, the largest user of wood biomass in the state is the existing forest products industry. The state's forest products industry produces a range of products and is geographically dispersed with mills located across the Arrowhead and as far west as Solway, near the prairie-forest border (Minnesota Department of Natural Resources, 2006). Tables 2 and 3 show the location, type of wood used and product produced from the pulp and paper and oriented strandboard industries located in the state as of 2006.

Table 2. Minnesota's pulp and paper industry (source: MN DNR, 2006 Forest Resources)



Firm	Wood Used	Product
UPM - Blandin Paper Mill Grand Rapids	Aspen, Balsam Fir and Spruce	Lightweight coated publication papers
Boise Cascade, LLC International Falls	Aspen, Balm, Pine, Spruce, Balsam Fir, Birch, Tamarack, Ash, Maple	Office papers, label and release papers, basesheets, business and specialty printing grades
Verso Paper Sartell	Aspen, Balsam Fir, Spruce	Coated and uncoated publication papers
Stora Enso North America Duluth	Balsam Fir, Pine, Spruce	Uncoated, lightweight supercalendered magazine and publication papers
SAPPI North America Cloquet	Aspen, Balm, Maple, Basswood, Birch, Tamarack, Pine	Coated freesheet fine printing and publication paper, market pulp
Recycling Mills		
Rock-Tenn Company St. Paul	Recycled Paper & Corrugated	Cardboard and corrugated boxes
Stora-Enso Recycled Fiber Mill Duluth	High Grade Office Paper & Computer Paper	Market pulp
Liberty Paper Company Becker	Recycled Paper & Corrugated	Cardboard and corrugated boxes

Table 3. Minnesota's OSB industry (source: MN DNR, 2006 Forest Resources)

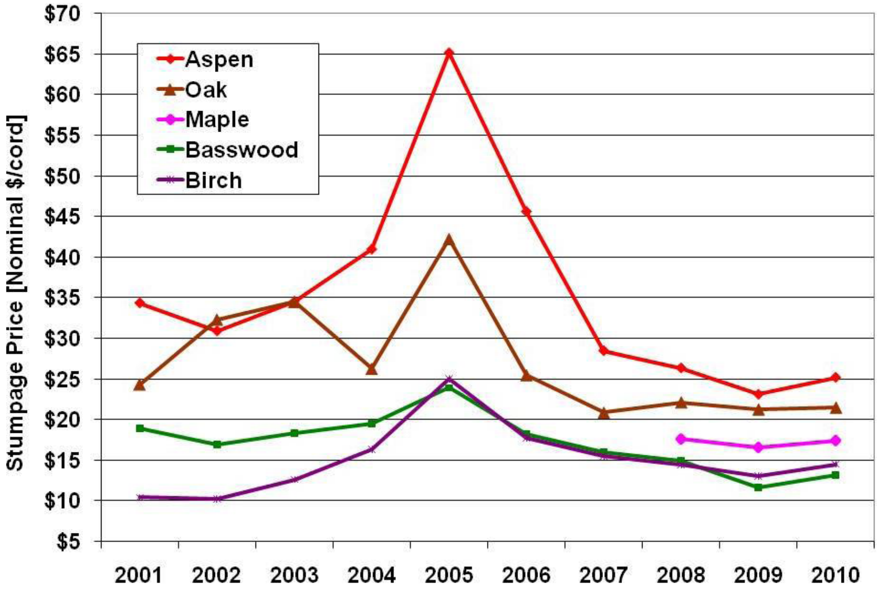


Firm	Wood Used	Product
Ainsworth Engineered USA Grand Rapids	Aspen, Balm, Birch, Pine, Maple, Tamarack, Ash	OSB (Temporary shutdown 9/06)
Louisiana-Pacific Two Harbors	Aspen , Balm, Birch	OSB – engineered siding panel
Northwood Panelboard Bemidji	Aspen, Balm, Birch, Maple	OSB
Ainsworth Engineered USA Bemidji	Aspen, Balm, Birch, Pine, Maple, Tamarack, Ash	OSB (One closed 8/06, one line still operating)
Ainsworth Engineered USA Cook	Aspen, Balm, Birch, Pine, Maple, Tamarack, Ash	OSB (Temporary shutdown 9/06)
Trus Joist - a Weyerhaeuser Business Deerwood	Aspen, Balm, Birch	Engineered lumber products for industrial and structural applications

A major shift that occurred in this industry since 2005 is the closure of the Ainsworth plants at Grand Rapids, Cook and Bemidji and the TrusJoist plant near Deerwood. Prior to these plant shutdowns, the total timber demand of Minnesota's mills was about 4.2 million cords annually (Governor's Task Force Report, 2006). However, not all of this demand was satisfied by in-state harvest and the industry was dependent to some degree on fiber imported from neighboring states and Canada. The Department of Natural Resources publishes a report of annual statewide harvest levels, prices and timber availability by species. The 2010 MNDNR publication of "Minnesota's Timber Resources" indicates that approximately 2.9 million cords are harvested in the state including pulpwood, sawtimber and fuelwood, down from a high in 2005 of 3.7 million cords, a decrease of 800,000 cords (roughly 920,000 dry tons). Of this total, roughly seventy five percent is pulpwood. As energy markets develop across the region, it is likely that imported fiber may be more difficult to obtain due to high demand for timber in areas that currently ship fiber to Minnesota. As a result, mills may be more reliant on locally produced timber in the future.

The recent history of wood prices in Minnesota is a clear demonstration of the interaction of supply and demand and potential to affect the industry. For example, average stumpage prices have ranged from a low of $30.00 to a high of $60.00 during the period 2002-2005 (Minnesota Department of Natural Resources, 2011, Figure 1). However, with the closure of the Ainsworth OSB mills and the TrusJoist plant at Deerwood, demand has fallen with the associated decrease in price. In relative terms, the price of aspen increased by 2005 by a factor of 2.5 times the previous 2002 level. However, aspen stumpage price has fallen back to below the 2002 price in 2010. If markets for forest products remain high and stable, profit margins will be sufficient to allow the industry to pay high prices for raw material and maintain competitiveness nationally and globally. However, paper and board markets have been highly variable and high wood prices in this environment have not been maintained. Consideration of any new industrial expansion in the forest products industry, be it wood products or energy, must take into account the current industry and the capacity to supply sufficient amounts of raw material at prices that allow the existing and proposed new industry to produce a profit and remain viable in the long term.

Figure 1. Historical hardwood stumpage price (source: MN DNR Price Report, 2010 Forest Resources)



Minnesota's Forest Resource

Of the total 50.8 million acres of land in Minnesota, 17.1 million acres is forested, 26 million acres is agricultural land and the remainder is urban, water and other land types such as brushland and grassland. Of the 17.1 million acres classified as forestland in the state, slightly less than one million acres are in reserved areas such as the Boundary Waters Canoe Area and not available for commercial timber harvest. The total land area potentially available for timber harvest, referred to as timberland by the FIA, is approximately 15.7 million acres (USFS, 2009 FIA Database). This land area has actually increased over the past decade by approximately one million acres due to reversion of some poorly productive agricultural lands to trees. For purposes of this report, information presented on forest resources is restricted to commercially available timberland as these lands are expected to be the predominant wood source in the future.

Compared to the Southeast and Pacific Northwest, the state's forest is characterized by diversity both in terms of species mix and ownership. Minnesota's forestlands are comprised of a wide variety of species types which occur in mixed stands as well as relatively pure-species stands. Prior to settlement, a greater proportion of the forest was in climax forest dominated by longer-living species such as white pine, the source of timber that built the cities of the Midwest. Since that time, harvest of many of these stands has led to reversion to early successional species such as aspen, birch and jack pine. Also, abandonment of land that had been cleared for agriculture has accomplished the same effect of "resetting the successional clock" to early successional species. As a result, the state's forest is a mix of species, age classes and ownership with a blend of early- and late-successional forest types.

Species Composition

Using the Minnesota Department of Natural Resources cover type classifications, Minnesota's forests are comprised of nineteen major forest types (Table 4). Aspen is by far the dominant forest cover occupying about one third of the total forested acreage or 4,849,747 acres, over four times the acreage of the next largest forest type. The criteria for assignment of land to a cover type is based on plurality of stocking of a given tree species. While aspen is a large forest cover type, aspen stands are characterized by a mix of species within these stands. Aspen fiber is highly desirable both for manufacturing of oriented strandboard as well as paper. As a result, of the total pulpwood sold in Minnesota, approximately sixty percent of the volume is aspen. Compared to other tree species, aspen stands are unique in that they regenerate naturally from root sprouts (suckering) and require no replanting and little financial input to reestablish after harvest. This makes aspen attractive both from a silvicultural management and financial point of view. The next largest forest cover types are northern hardwoods with 2,050,457 acres, black spruce with 1,335,033 acres and lowland hardwoods with 1,104,834 acres followed by a mix of other covertypes as shown below.

Table 4. Minnesota's forest cover types, acreage and proportion (USDA-FIA,2011-2010 survey).

Forest-type group	Total	Proportion
Aspen / birch group	6,139,697	38.7%
Elm / ash / cottonwood group	1,535,038	9.7%
Exotic hardwoods group	7,938	0.1%
Exotic softwoods group	8,237	0.1%
Maple / beech / birch group	1,129,688	7.1%
Nonstocked	197,083	1.2%
Oak / hickory group	2,019,185	12.7%
Oak / pine group	264,034	1.7%
Other eastern softwoods group	19,706	0.1%
Other hardwoods group	204,257	1.3%
Spruce / fir group	3,502,675	22.1%
White / red / jack pine group	833,260	5.3%
Totals:	15,860,797	

Land Ownership Patterns

In contrast to the southeastern U.S. where a large proportion of land is owned and managed by the timber industry, Minnesota's forests are owned by a broad range of entities ranging from non-industrial private landowners (NIPF) to public land management agencies such as the Minnesota Department of Natural Resources, counties and the US Forest Service (Fig. 3). NIPF lands are usually held for a multiplicity of uses including hunting, recreation as well as timber production. As a result of this diverse ownership pattern, procurement of timber for the state's mills involves a very active program working with different agencies with varying purposes for their land and policies affecting management. Some landowners, such as public agencies, are actively managing their lands for multiple benefits and timber sales are an integral part of the overall forest management program. NIPF landowners may be involved in forest management organizations such as the Minnesota Forestry Association or have assistance of professional forester but this is not always the case. Diversity in land ownership is important from a timber availability standpoint because it has a direct effect on the proportion of timber resources potentially available for harvest and the rate that timber is brought to market.

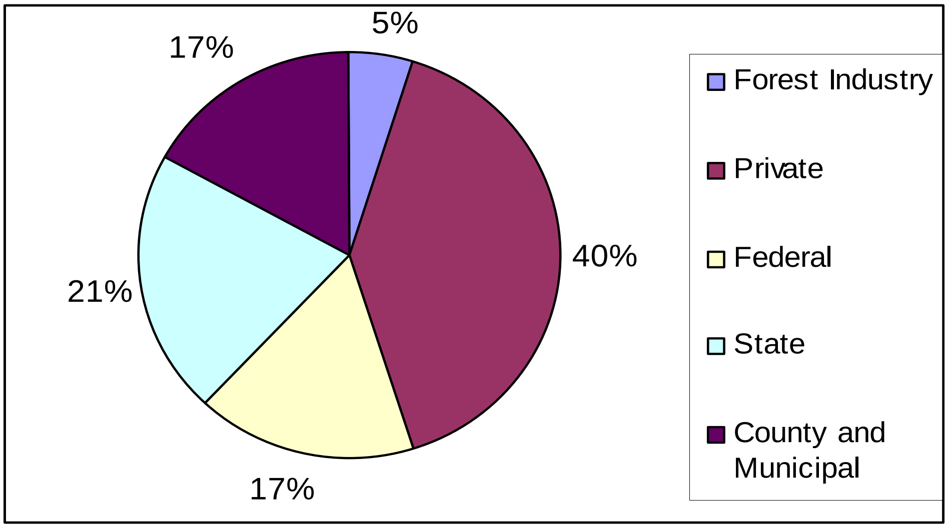


Figure 1. Ownership of forestland in Minnesota (FIA, 2010).

Land ownership affects the process by which timber is sold. Public land agencies identify stands that are ready for harvest using geographic information systems and inventory data. Once stands are identified for harvest, a forester will conduct a cruise of the stand volume using a "cruise course", a set of points within the stand where data on timber volume and species composition are collected. Using this information, the stands are put up for sale to the public, either through sealed bids or oral auction. Thus, the stumpage price will fluctuate depending on demand by mills, sometimes quite dramatically as shown above. Sale of timber volume on private lands, a significant portion of the land base, is not as formalized as sales on public lands. A landowner may be contacted by a local logger or forester and the negotiation of price is done between the landowner and the forester or logger. Thus, the process of locating stands for harvest, determining stand volume and stand value can differ depending on the land owner.

Growth and Expected Allowable Harvests

The central question related to evaluating future opportunities for development of a next-generation, wood-based energy industry is wood supply. According to the USDA-FIA Inventory (Miles and Brand, 2007), the total net annual growth of the state's forests on timberland acreage is approximately 7.0 million cords. This value includes in it the volume that is lost to mortality, estimated to be 3.8 million cords. Taken together, a combination of net growth and some portion of annual mortality represents the biological potential of available forest lands and does not take into account practices employed to accommodate other forest values such as wildlife, water quality and long term soil productivity. In 1990, in response to a citizen petition, the State of Minnesota, Environmental Quality Board commissioned a large scale study of the state's forests entitled the Generic Environmental Impact Statement (GEIS) on Forestry (Jaakko Poyry Consulting, 1994). The purpose of the GEIS was to evaluate the interaction of timber harvesting and environmental impacts on the state's forests. The GEIS on Forestry is one of the largest undertakings of its kind in the nation and serves as a model to other states.

The GEIS considered the impact of forest harvesting on environmental values at several harvest levels and recommend mitigation strategies to reduce environmental impacts. The harvest levels chosen were intended to approximate the current annual harvest level as of 1990 (4.0 million cords), expected near-term harvest levels anticipated in 1995 (4.9 million cords) and a maximum harvest level of 7.0 million cords (FIA total net growth). In addition, mitigation strategies such as extended rotation forestry, riparian buffers and uneven aged management were included in harvest simulations to estimate the effect of implementing these strategies on timber supply. This analysis was done at the FIA plot-level to allow summarization of impacts and harvest levels by forest cover type and ownership within seven major ecoregions over time.

Criteria for assessing impacts on wildlife species were based on a maximum of 25% change in a species' habitat within any of the seven ecoregions. In addition, for those species considered threatened or endangered, a maximum allowable threshold for habitat change in any ecoregion was 5%. The results of this effort, in addition to many useful background products, was an estimate of the sustainable harvest level for the state and strategies to maintain the health of forest ecosystems over the long term. Based on the GEIS analysis, the maximum harvest level that may be sustained while maintaining ecological values is estimated to be 5.5 million cords. It should be noted that this value is assuming implementation of mitigation strategies to the level assumed in the GEIS.

A followup study entitled the GEIS Report Card (Kilgore, et.al. 2005) was published to evaluate changes in harvest levels, wildlife populations, old-growth forests and application of mitigation strategies since completion of the GEIS. This report identified several changes or sources of variance from that predicted by the GEIS. First, harvest levels were found to be slightly lower than expected. Bird populations fluctuate widely with some species showing unexpected increases and some showing unexpected decreases with a net decrease in habitat for 10 of the total 136 species included in the study. The area of old forest did not increase as much as expected due to a greater amount of acreage undergoing mortality than originally assumed. Little change in designated old growth forest was noted due to changes in management of a portion of forestland managed by the Department of Natural Resources. Finally, a survey of land managers indicated widespread adoption of Best Management Practices on forestlands. Given the overall agreement of the Report Card report with conditions predicted by the GEIS, the potential harvest value of 5.5 million cords will be assumed to be a sustainable harvest level for purposes of this analysis. Related to this, the Governor's Task Force on the Competitiveness of the Forest Products Industry (Governor's Task Force on the Competitiveness of Minnesota's Primary Forest Products Industry, 2007) recommended that the annual harvest level of 5.5 million cords be a goal for the state's forests.

Estimate of Available Timber Supply

Beginning with a total sustainable harvest level of 5.5 million cords from forestlands in Minnesota and assuming that imported fiber will not be available in the future; subtracting the current demand of the forest products industry of 2.9 million cords produces an estimated 2.6 million cords potentially available annually. This is the maximum sustainable amount potentially available for industrial expansion. In addition, identification of high-risk stands and thinning may capture a portion of the volume lost to mortality each year. An analysis of mortality by covertype and age class using the USDA-FIA Mapmaker Program shows that approximately seventy percent of the total mortality occurs in stands older than fifty years of age. This suggests that the bulk of mortality would be captured through identification of stands at risk for pathogenic mortality losses.

Additional Biomass Sources

Red Pine Thinning

Based on analysis of the FIA data, thinning of stands to capture competition-induced mortality (mortality in stands less than 50 years of age) could account for a maximum of thirty percent of the total mortality loss reported in the FIA inventory. Thinning of Red Pine and Aspen stands could contribute additional harvest volume assuming the price for thinning products and harvesting technology make thinning of these stands economically feasible.

Of the total 309,000 acres of Red Pine plantations in the state, roughly half are less than age thirty and a large amount of acreage will be ready for first thinning over the next decade (Fig. 4). Current annual harvest of Red Pine is approximately 160,000 cords compared to a short term allowable harvest of 270,000 cords annually. As stands age and become ready for first thinning, the average annual harvest could rise to 356,000 cords, or 409,000 dry tons by 2012 and increase annually thereafter (Minnesota DNR, 2006). Based on our experience, about half of this volume is small-diameter sawbolts with the remaining half being pulpwood. Compared to current harvest levels, Red Pine thinning could supply an additional 225,000 dry tons annually including all products.

Markets for Red Pine pulpwood are soft which limit opportunities to thin plantations at this time. Because care must be taken to avoid damage to the stand, productivity of a logging operation is reduced which decreases the value of volume from thinnings. A critical factor in first-thinning of Red Pine is the amount and size of material that can be removed while still maintaining the proper number and quality of trees to maintain value in the future. For example, if a greater proportion of the larger, more valuable sawbolt-sized trees can be removed at the first thinning without impacting the future value of the stand, greater value can be extracted which offsets the cost of handling smaller diameter material that is an inevitable part of harvested volume, particularly in the first thinnings. In contrast, if only lower-valued pulpwood is able to be removed, the financial returns to the logger and landowner are reduced which limits opportunities to practice first thinning in a timely manner. Research is underway by the NRRI under the auspices of the Minnesota Forest Productivity Research Cooperative to determine the optimal mix of residual stand volume and stem size distribution for first-thinning of Red Pine plantations to maximize value to the landowner.

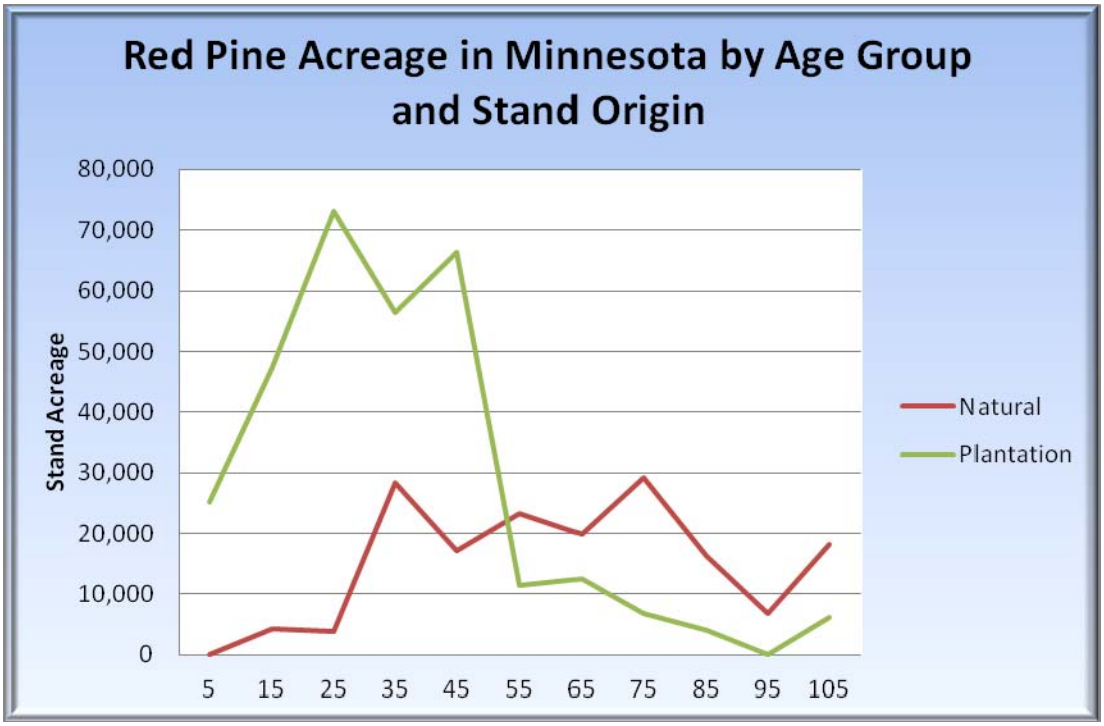


Figure 2. Age class of Red Pine timberland acreage - natural regeneration and plantations.

Forest Harvest Residues

The most immediately available, lowest cost source of wood for energy is residual top and limb material. Forest harvest residues are produced through delimbing and slashing of merchantable trees as a part of the logging operation. A low level of demand for harvest residuals from forest products mills producing board products have existed for decades but markets have been limited. With the construction of the biomass burning facilities in St. Paul and the Laurentian Energy Authority project on the Iron Range, demand for energy wood has increased considerably.

<u>Harvesting Systems</u>

The production of forest harvest residues is particularly well suited to conventional logging systems commonly in use in Minnesota today. There are two dominant logging systems in use in Minnesota; conventional and cut-to-length (CTL) systems. According to Minnesota Logger Education Program staff (Dave Chura, personal communication), conventional systems account for the majority of timber volume harvested in the state. Conventional logging systems consist of a feller-buncher which falls trees and produces bunches of trees to accommodate skidding. Skidders then move the bunch of trees from the site of felling to a central landing area. Using a stroke delimber or processor, trees can either be delimbed near the site of felling or at the landing, depending on whether the logger wants to process tops and limbs or leave them scattered on site. If the intention of the logger is to collect harvest residues for further processing, the trees are typically skidded in whole-tree form to the landing where delimbing occurs. The main bole is then either loaded onto a truck directly in tree-length form or slashed to 100-inch lengths as shortwood, the most common form delivered to mills in the state. Due to the fact that trees can be felled and skidded to the landing in whole-tree form, there is little additional cost to transporting the tops and limbs to the landing area. However, further processing requires additional chipping or grinding equipment to produce a form of material that is easily transported and handled at the mill. Given the setup of the conventional logging system, production of harvest residues can be integrated into the current logging system with little modification. The issue of producing additional quantities of harvest residues in the future is not the need for different harvesting equipment but more a lack of steady markets to allow a logger to recoup an investment in additional equipment. As markets for energy chips become better established, the logging infrastructure could be expanded to accommodate demand through purchase of additional chippers, grinders and chip vans assuming long-term contracts are made with wood-using facilities.

In contrast to conventional systems, CTL systems buck trees in the woods at the point of felling. The CTL system is generally more flexible than a conventional system with respect to operating conditions and the type of products that can be produced. CTL systems are particularly well suited to produce a wider variety of products, such as longer length sawlog-sized material in those stands having larger diameter, sawlog quality trees. However, because the tops and limbs are severed at the point of felling, the CTL system does not lend itself as readily to collection of forest harvest residues. The residual material must be piled in windrows or piles separate from the roundwood to allow collection by the forwarder. While it is possible to produce harvest residues using the CTL harvesting system, more effort is involved which will likely add to the expense of the residue product.

Estimate of Forest Harvest Residue Volumes

The amount of biomass available from forest harvest residues is dependent on the species being harvested, top-diameter utilization criteria for roundwood, guidelines to mitigate soil and wildlife concerns as well as the overall amount of timber being harvested in the state. There are a variety of methods used to estimate forest harvest residue amounts ranging from on-site surveys, whole tree biomass measurements and individual-tree biomass estimation equations. Because of the potential impact of assumptions about forest harvest residue availability on the overall future energy industry in the northern part of the state, a review of methods and development of a reasonable estimate of harvest residue percentage is presented.

In a study done by Grigal (2004) as part of analyses associated with the LEA project, he states that crown biomass accounts for 25 and 21 percent of total biomass for hardwoods and conifers, respectively. A large dataset of equations developed on individual trees published by Jenkins (Jenkins et.al. 2004) suggests similar numbers with hardwoods and conifers accounting for 25% and 15%, respectively. These data sources generally agree that biomass of nonmerchantable material is likely to comprise approximately 25 percent of hardwood total biomass and between 15 and 20 percent of merchantable softwood stem biomass. In cooperation with the USDA Forest Service at Rhinelander, we have collected data on biomass components of hybrid poplar in plantations in Minnesota and Wisconsin for many years. While hybrid poplar and aspen are not directly comparable, they are similar in taper. Based on individual biomass of hybrid poplar trees, the average proportion of branch biomass as a percentage of total tree biomass (bole bark and wood + branch bark and wood, without foliage) is 25%. Residues percentage expressed as a proportion of total stem biomass is 33%. At the NRRI, we have measured harvest residue biomass on winter-logged sites with particular emphasis on aspen. The average branch and top biomass percentage using a three inch top limit was found to be 15.3% of the total main bole biomass with a minimum site average of 11% and maximum of 18%. Based on the available individual-tree data, the average residue percentage value is approximately 25% with a minimum value for aspen of 15% assuming pure-aspen stands. In reality, stand-level residue percentages will be higher due to the hardwood component present in most aspen cover types having higher residue percentages. Conversations with loggers operating in the area indicate that the 15% residue proportion is not uncommon in relatively pure aspen stands based on their experience of shipping one to two loads of chips per day producing 100 cords of roundwood per day.

The most extensive and recent study of stand-level residue amounts was done by the Minnesota Department of Natural Resources entitled the "Minnesota Logged Area Residue Analysis" published in August of 2006 and revised in April 2007. This project measured coarse and fine biomass on 124 sites throughout the state and included a range of forest types. The results in terms of cordage per acre of coarse and fine woody material are shown in Table 5 below.

Table 5. Coarse and fine woody debris of forest types from MN DNR Logged Area Analysis study.

Forest Cover	Coarse and Fine Woody Debris (cords/acre)	Coarse and Fine Woody Debris Biomass (green tons/ac)
Aspen	5.7	12.8
Other Hardwoods	7.54	19.2
Lowland Conifers	4.3	9.5
Upland Conifers	4.71	10.9
Unknown	6.12	13.8

While the data produced in the Logged Area Analysis study is very helpful and the best data of its kind available, a limitation to application of these data is the lack of information on stand volumes and amounts of roundwood removed from these sites. Having information on the amount of roundwood removed and stand volumes prior to harvest allows calculation of the percentage of harvest residuals which is necessary to estimate annual production of harvest residues on a statewide basis. Through the cooperation of the Minnesota Department of Natural Resources, Division of Forestry, we were provided an extensive database of sale volumes. This database contains sale data from slightly less than 60,000 acres of timber sales on state lands. Table 6 shows the DNR Cover Type, the Logged Area Analysis grouping, acres and average stand volume for each cover type in the DNR timber sale database. Using a combination of the sale data volumes and the forest harvest residue data from the Logged Area Analysis, the percent of harvest residues that can be expected to be available from within each of the Logged Area Analysis groupings can be calculated.

Table 6. DNR timber sale data by cover type, average volume per acre and residue percentages calculated from a combination of sale data and residue volumes.

Cover Type	LAA Group	Acres Sold	Roundwood Cords/Acre	Group Cords/acre Wt.Average	LAA Residue Biomass (cords)	% Residue
Aspen	Aspen	29,041	22.2	22.2	5.7	25.7%
Northern Hardwoods	Hardwoods	545	14.3	16.6	7.54	45.4%
Oak Species	Hardwoods	301	15			
Paper Birch	Hardwoods	8,586	16.8			
Black Spruce	Lowland Conifers	5,189	18.8	17.4	4.3	24.7%
Tamarack	Lowland Conifers	3,362	15.3			
Balsam Fir	Upland Conifers	1,572	15.1	17.2	4.71	27.4%
Jack Pine	Upland Conifers	6,519	21			
Red Pine	Upland Conifers	4,879	12.75			

Table 7 shows the estimated timber harvest levels by species group reported by the DNR in the 2010 Forest Resources document, the percentage residues reported by the DNR Marketplace, conversions to estimate green tons from cordage and the resulting estimated amount of residues produced through harvesting of pulpwood and sawlog products.

Table 7. Volumes harvested by major species, residue percentages and estimated residue availability statewide.

			Fuelwood					
Species	Pulpwood	Sawlog	Residential	Commercial	Total	Residue %	Green tons/cord	Residue (gr tons)
Aspen and Balm	1359.3	51.8	31.9	7.3	1450.3	25%	2.25	815,794
Paper Birch	117.7	14.2	31	7.6	170.5	33%	2.3	129,410
Ash	25.2	8.6	27.1	12.6	73.5	33%	2.5	60,638
Oak	0.1	73	57.5	1.2	131.8	33%	2.75	119,609
Basswood	12.9	19.8	6.3	0	39	33%	2.3	29,601
Maple	136	10.5	31.2	1.7	179.4	33%	2.5	148,005
Cottonwood	26.6	8.2	0.3	0	35.1	25%	2.5	21,938
Other Hdwood	1.3	16.9	2.3	8	28.5	33%	2.5	23,513
Red Pine	28.6	142.4	2.9	0	173.9	11%	2.35	44,953
White Pine	4.7	7	0.4	0	12.1	11%	2.2	2,928
Jack Pine	43.5	88.4	1.8	0	133.7	11%	2.3	33,826

Spruce	217.5	24.5	0.3	0	242.3	23%	2.1	117,031
Balsam Fir	149.5	11.1	0.2	0	160.8	23%	2.35	86,912
Tamarack	51.4	7	2	10	70.4	11%	2.5	19,360
White Cedar	0.9	6.6	0.8	0	8.3	23%	1.45	2,768
Other Softwood	7.5	0.4	0.1	2.2	10.2	23%	2.2	5,161
Total	2182.7	490.4	196.1	50.6	2919.8			1,661,445

From the above table, the total biomass produced annually is estimated to be roughly 1.7 million green tons or 800,000 dry tons assuming a 50% moisture content (green weight basis). The ratio of green tons of harvest residues to the overall cordwood volume is 0.56 (1,661,445 green tons divided by 2,919,800 cords harvested). Assuming the same species mix is harvested in the future, this ratio can be applied to the maximum cordage harvest level of 5.5 million cords to estimate potentially available harvest residues assuming future harvest should approach the 5.5 million cord level. The estimated amount of harvest residues associated with this level of harvesting is 1,540,000 dry tons of forest harvest residues. This value must be reduced to account for mitigation of environmental effects. For purposes of this analysis, I have used a 25% reduction to account for management guidelines. Therefore, a more realistic maximum value is closer to 1,155,000 dry tons of harvest residues potentially available in the future.

Using a weighted average conversion of cordwood to dry tons of 1.15 (2.3 green tons/cord at 50% moisture content on a green-weight basis) and 2.4 million additional cords of roundwood potentially available (see above discussion regarding maximum allowable cut and current harvest) yields a value of 2,760,000 dry tons of additional roundwood biomass. Taken together, the total amount of forest harvest residues and additional roundwood volume is approximately 3,590,000 dry tons.

As mentioned above, demand for harvest residues has increased in the recent past and could increase significantly in the near future. At this time the total estimated demand for forest harvest residues is not known precisely as some estimates include both material sourced specifically for energy and some biomass in the form of bark that is produced from the roundwood harvested for paper and board production. Including current annual demand by the Laurentian Energy Authority of 125,000 dry tons and an estimated demand of 150,000 dry tons per year (includes current Minnesota Power plants, St. Paul District Energy, SAPPI-Cloquet, Georgia Pacific-Duluth), the total near-term demand is approximately 275,000 dry tons. Based on this analysis, the potential exists to expand the resource-based economy assuming technology and markets develop to cost-effectively produce energy products.

Wood Price

There are three fundamental components of the ultimate delivered price of wood resources. These are stumpage price, harvest cost and transportation cost. These will vary depending on the type of biomass being processed. In the case of forest harvest residues, the conventional logging systems typically skid trees to a central collection point on the site (a landing) where top- and limb-material is separated from the main merchantable bolewood. As a result, the harvesting cost association with the collection of forest harvest residue is borne primarily by the roundwood production system where the primary goal is the production of high-valued roundwood. In other words, the harvest residues are a byproduct of the roundwood production system. However, because the top- and limb-biomass cannot be trucked in whole form, this material must be reduced in size through chipping or grinding resulting in additional cost for equipment and operation. Alternately, if the primary goal of a timber sale is to harvest both the main bolewood and all harvest residues for energy, as is the case if the majority of the timber sale were composed of low-demand species, then the entire harvest cost must be assessed against biomass energy with no additional higher-valued roundwood products. Therefore, the species composition of the timber sale and ultimate markets will affect the efficiency of harvest.

The following section will discuss cost components and their relative effect on the price of wood biomass delivered to a conversion facility.

Land Management Agencies and Stumpage Pricing

Wood is brought to market either by public land management agencies or a sale is arranged by foresters or loggers on private woodlands. Public land management agencies include the U.S. Forest Service, the State Department of Natural Resources and the County land management agencies. In the case of timber sales administered by public land management agencies, timber stands are typically cruised to estimate volumes prior to a public bidding, either by oral or sealed bids. Privately-owned timber is sold through arrangements between foresters and loggers and landowners. As mentioned previously, stumpage price in Minnesota varied significantly with prices for roundwood ranging from $15.00 per cord for species that are considered only marginally merchantable to $80 to $100 per cord for high-valued timber such as aspen and pine sawlogs. However, due to reduced demand, stumpage prices have moderated with average aspen stumpage being slightly less than $30.00 per cord and many less merchantable species such as birch, maple, basswood and tamarack ranging in price from $5.00 to $15.00 per cord (Table 8). Unlike the situation in 2005, roundwood of some lower-value species may be considered for energy applications due to low price. As shown in Table 8, the stumpage price for the majority of low-demand species ranges between $5.00 and $10.00 per cord. This compares to a price range of $20.00 to $30.00 per cord for higher demand species such as aspen and spruce. Assuming an average conversion of 1.15 dry tons per cord (equal to 2.3 green tons per cord) for a variety of species, the average stumpage price for low-value pulpwood species on a weight basis would be roughly $4.00 to $9.00 per dry ton.

The current pricing policy for those landowners selling forest harvest residues is similar across agencies. The Minnesota Department of Natural Resources assesses $0.60 per 1000 pounds of material with no distinction between dead and green biomass (Lillian Baker, personal communication). The St. Louis County Land Department procedure is to assess a charge of $1.00 per cord-equivalent (Matt Butorac, personal communation). This results in an estimated cost of less than $0.50 per green ton. These prices are relatively low and it is likely that prices will increase with increasing competition for the resource. For purposes of this analysis, we assumed that prices will increase to $5.00 per green ton on all ownerships. As can be seen in Table 8, the assumed price for biomass in this analysis is higher than the current prevailing market price but we assume some increased competition for the resource should energy applications become economically feasible.

Table 8. Prevailing stumpage price for common Minnesota species from DNR annual stumpage price review (MN-DNR, Forestry Division, 2011).

All	Sawtimber		Pulp and Bolts		Pulpwood		Fuelwood		Biomass	
Species Name	MBF	Avg Price	Cords	Avg Price	Cords	Avg Price	Cords	Avg Price	Tons	Avg Price
Aspen	19	$33.67	0	$0.00	812,617	$25.16	7	$4.00	744.7	$0.95
Balm of Gilead	0	$0.00	0	$0.00	11,479	$21.22	0	$0.00	0	$0.00
Birch Species	164	$38.92	37,662	$14.48	81,503	$8.48	118	$1.60	316.7	$1.03
Ash Species	154	$56.27	3,857	$17.41	20,822	$6.97	119	$5.37	0	$0.00
Elm Species	18	$45.08	0	$0.00	75	$4.05	0	$0.00	0	$0.00
Oak Species	1,849	$243.09	30,8640	$21.49	9,968	$13.41	1,266	$8.87	26.1	$0.80
Basswood	468	$63.47	10,787	$13.15	9,885	$7.50	0	$0.00	0	$0.00
Other Hardwood	3,250	$29.80	0	$0.00	59,964	$12.29	2,900	$5.47	0	$0.00
Balsam Fir	0	$0.00	17,160	$23.44	81,357	$16.10	0	$0.00	0	$0.00
Spruce Species	553	$102.15	22,264	$26.54	107,500	$21.58	0	$0.00	290	$0.90
Tamarack	0	$0.00	0	$0.00	60,380	$5.03	207	$2.43	0	$0.00
White Cedar	0	$0.00	0	$0.00	1,678	$6.19	0	$0.00	0	$0.00
Jack Pine	0	$0.00	59,2350	$28.34	5,365	$17.21	277	$5.27	2,458	$0.24
Red and White Pine	10,982	$123.36	120,722	$31.04	9,577	$9.08	0	$0.00	848	$1.00
Maple	62	$219.83	1,037	$17.41	58,412	$9.21	72	$4.53	9.5	$0.80
Mixed Biomass	0	$0.00	0	$0.00	0	$0.00	0	$0.00	108,427	$0.92
All Agencies-All Species	17,519	$115.16	303,590	$25.87	1,330,584	$20.39	4,968	$6.09	113,120	$0.90

A potential advantage of using roundwood in addition to delivered chips is the opportunity to air-dry roundwood in piles during the summer months and increase flexibility in terms of seasonal availability as well as the efficiency of a conversion process. This is particularly true in those instances where the biomass is combusted for thermal energy. The effect of additional moisture on the efficiency of the conversion process depends on the ultimate end use. Air drying of wood is has advantages in those applications such as biomass-to-electricity where the presence of water reduces the output of the conversion system. Liquid fuels conversion systems based on biological processes will likely be less affected by additional moisture than a thermochemical conversion system. However, according to conversations with researchers developing thermochemical liquid fuels conversion systems, some liquid fuels conversion systems require supplemental hydrogen derived from water to balance the stoichiometric demand with carbon and make complete use of the carbon present in the biomass to produce the liquid fuel. It is likely that a combination of low-valued roundwood stored at a concentration yard and just-in-time delivered fresh chips will comprise the feedstock for emerging energy technologies using wood from the forests.

Logging Equipment and Cost Calculations

The cost and practical feasibility of efficiently producing forest harvest residues is dependent on the harvesting system being used. Forestry operations in Minnesota are done using two dominant harvesting systems, conventional and cut-to-length, often referred to as CTL. The conventional harvesting system involves felling of trees and skidding of whole trees to a centralized landing for further processing. Trees are delimbed and bucked into 100-inch or tree-length sections and loaded onto trucks for delivery to the mill. In the case of the conventional system, trees can either be delimbed on the landing or at some other location within the logging site. However, once trees are felled, skidders are able to efficiently transport the whole tree to the landing. This system facilitates relatively straightforward collection of tops and limbs because they can be skidded in whole-tree form, delimbed and the harvest residue processed at the landing. The residue material can be chipped on-the-fly as roundwood is being produced or residues can be piled and chipped or ground at a later date after the logging operation has been completed.

The CTL system employs a felling, delimbing and bucking system in one processing machine and produces small piles of roundwood near the site of felling of the tree. The roundwood is moved and loaded onto trucks via a forwarder. These systems don’t readily lend themselves to collection of top and limb material because the trees are processed on-site and not skidded to a landing in whole-tree form. According to communications with the Minnesota Loggers Education Program, approximately twelve percent of the logging firms use the CTL system in Minnesota. Given this fact, as markets develop for forest harvest residues, about ninety percent of the logging system currently in place is equipped to readily produce forest harvest residues.

We assume that the harvest cost associated with the collection of top and limb material is zero and is allocated entirely to the roundwood production operation. This assumption is true if harvest residues are indeed residues and not the primary product of the timber sale. In the case where both low-value roundwood and associated residues are harvested for energy markets, we make the assumption that logging costs are allocated to the roundwood portion of the stand and residues are delivered to the landing at no cost. These costs and total delivered wood cost are discussed further in this section of the report.

We have gathered information on the cost of a variety of chipping and grinding equipment to estimate the cost of processing forest harvest residues integrated with a conventional timber harvesting operation. For purposes of our analysis, we considered three separate harvesting and equipment scenarios used to process forest harvest residues. These are; 1) use of a smaller chipper integrated into a roundwood harvesting operation with harvest residues chipped at the same time as roundwood is being produced (in-line system), 2) the logger piles tops and limbs at a landing and the material is chipped by a chipping contractor at a later time using a larger-sized (higher throughput) chipper and, 3) harvest residues are piled near the landing and is processed using a horizontal or tub grinding system. Options 2 and 3 are similar in concept with the only difference being the equipment used to process the residue material. We have analyzed the various cost components associated with these processing options including ownership and operating costs as well as factoring in the practical realities of operating equipment in a typical logging operation. While the details of these analyses won't be presented in this report, the following information is useful in evaluating the various biomass processing options.

In-Line Chipping Systems

We spoke with logging firms currently operating chippers to determine the type of equipment needed to process logging residues. Those operating chippers in-line (processing residues simultaneously as roundwood is being produced) have used chippers on the smaller end of the range of whole-tree chipping product lines. Our contacts indicated that the smaller family of chippers are preferred because they took less space on a log landing and were more cost-effective than a larger chipper while, at the same time, were sufficiently large to process slash and smaller whole-trees. For purposes of our analysis, we assumed that the chipper was operated by remote control (an option for all chippers quoted) and fed by the slasher operator. Therefore, we didn't assume an additional labor cost in our calculations of variable costs. This method is currently used by chipping contractors and was the assumed system for our analysis.

Quotes on purchase price and information on operating and maintenance costs for forestry chippers were obtained from regional manufacturers including Morbark, Dynamic and Bandit. The models used in this type of application are assumed to be a Morbark Model 20/36, Bandit Model 1850 or similar models. It should be stated that the various models vary in purchase price and fuel consumption and slight variations in processing costs will result depending on the specific model chosen. The purpose of this analysis is to estimate an average expected production cost assuming a representative chipping system. Chippers in this range are priced from approximately $150,000 to $175,000 with no cab and loader. Chippers typically include the option of a conveyor bed feeding system to handle unconsolidated slash in addition to whole trees.

Utilization rate is an important issue in this analysis as it affects the quantity produced annually in operation and fixed costs are directly affected by utilization rate. In this type of use, fixed costs are distributed over a lesser amount of tonnage thereby increasing the fixed cost per ton of product. Also, the size of the logging operation will obviously affect the number of hours that the chipper is run in a given year. We assumed that the average operation is producing 15,000 cords per year. According to a survey conducted by Applied Insights North (John Powers, 2004) for the Blandin Foundation, a level of 15,000 cords per year is near the average for many producers. According to this survey (based on MLEP numbers), there are a total of 454 logging operations in the state with the average logging operation producing roughly 12,000 cords annually. In order to estimate a range of realistic prices, we conducted our analysis assuming, two levels of residual value (20% and 50%) at an annual production rate of 15,000 cords.

In most cost analyses obtained from manufacturers, the chipper is assumed to run anywhere from 100 to 200 days per year, eight hours per day. This is not realistic for purposes of an in-line operation. Operating hours and annual variable costs were modified to more realistically reflect the use of a chipper in an in-line application. These modifications were done to account for the reality that a chipper in this type of system is "captive" on a logging job and is not being moved from site-to-site. Therefore, the amount of forest harvest residues that could be processed in any given day depends on the output of the total logging system, not the theoretical maximum output of the chipper itself. Considering the fact that most chippers can process roughly thirty green tons per hour, the chipper has significant overcapacity relative to the logging system as a whole. For example, a typical 100-cord per day logging operation is expected to produce roughly 40 green tons of residue per day, or approximately 1.5 trucks per day. In conversations with logging contractors, slash material is allowed to accumulate and the slash is processed periodically during the day. We assumed that the chipper would be operated for 1.5 hours per day to process residues. This fact was confirmed with a larger logging contractor who indicated that a chipper used in his operation is run approximately 400 hours per year in the type of application. Given this situation, we assumed that the chipper was run 1.5 hours per day for 200 days per year for a total of 300 hours per year.

We obtained price quotes from manufacturers which included estimated purchasing, financing, insurance and operating costs. Costs such as purchase, interest and insurance are fixed and don't vary with the quantity of residue material processed. In our calculations of annual fixed costs, we assumed that the chipper was financed for a five-year period at a seven percent interest rate and had a 20% residual value after the five year period. This is conservative assumption (i.e. more expensive to the mill than may be the actual case) due to the fact that the typical life of a chipper is approximately 10,000 hours.

As explained above, the utilization rate assumed by the manufacturers is too high for purposes of this analysis and the chipper will likely have considerably fewer hours per year than assumed by manufacturers; 1,500 hours in a five-year span. This is assuming a logger producing 15,000 cords per year, a slightly higher production rate than the average logger in Minnesota. However, we used the five-year, 20% residual value as the baseline estimate. In addition, we recalculated the fixed costs using a higher residual value to evaluate the effect of a 50% residual ratio.

Using the assumption of a $175,000 purchase price and a 20% residual value, the annual fixed costs were estimated to be $38,783. Assuming a 50% residual value, the annual fixed costs are reduced by $10, 500 to $28,283. This equates to a reduction in processing cost of $1.55 per green ton assuming a logging operator was processing 6,750 green tons annually. Table 8 shows the calculations of fixed and variable costs used in this analysis assuming a 20% residual value, 15,000 cords per year scenario. As shown, the total estimated output of harvest residuals using a 20% ratio of residues to roundwood is 6,750 green tons annual output for a 15,000 cord per year operation. Variable costs for knife maintenance and fuel on an hourly basis are estimated to be $54.00 per hour. The total annual variable cost for this operation is estimated to be $16,200 (300 hours X $54.00/hour). Incorporating fixed and variable costs, the chipping cost per green ton is estimated to be $8.14 per green ton.

Table 9. Summary of cost calculations for a mid-sized chipper assuming a 20% residual value and 15,000 cord/year logging production level.

Cost Estimate for Mid-Sized In-Line Chipper	
Purchase Price	$175,000
Residual Value	0.2
Fixed Costs (annual basis)	
Depreciation	$28,000
Interest (9% for 60 months)	$6,583
Insurance	$4,200
Variable Costs/Hour	
maintenance - chipper knives	$14.00
fuel (10 gals/hr @ 4.00)	$40.00
Total Variable/hour	$54.00
Operating Assumptions	
operating hours/day	1.5
operating days/yr	200
operating hours/yr	300
Total Fixed Costs/yr	$38,783
Total Variable Costs/yr	$16,200
Total Annual Costs	$54,983
Cords logged annually	15,000
Green tons:Cords Ratio	0.2
Cord-green ton conversion (tons/cord)	2.25
Harvest residues/yr (green tons)	6,750
Chipping Cost ($/green ton)	**$8.14**

Cost Example 2. Larger Chipping and Grinding System

The second system analyzed assumes that a contractor purchases a large grinder and loader to process slash from sites that have been previously logged. This assumes a contractor would pay the logger to stack slash near the landing or roadside and the grinding system would follow the logging operation. Due to seasonal considerations, we assume that the grinding and loading takes place shortly after the logging operations have ceased. Therefore, the same road system is used for both the logging and chipping or grinding operation.

Unlike the in-line chipping system, this approach is not constrained by the size of the logging operation itself. Thus, we assume that harvest residues from any logging operation that is operating a convention system would be potentially available for collection of harvest residues. The same general financial calculations were done as in case 1 above with a five year payback period and 20% residual value. We assumed that the sites are an average of 30 acres in size with 25 cords per acre of roundwood volume per acre. Therefore, the total residue biomass per site is estimated to be 338 green tons. In addition to the grinder, a loader is assumed to be needed to load slash into the machine. Also, the cost of staff needed to arrange sites for processing is assumed to be $10,000 annually. A fee is paid to the logger to stack the slash in an orderly way for processing at a cost of $2.00 per green ton. The net result of this analysis is that processing costs are estimated to be $11.64 per green ton for the grinding system. The assumptions and calculations for the grinding/loading system are shown below.

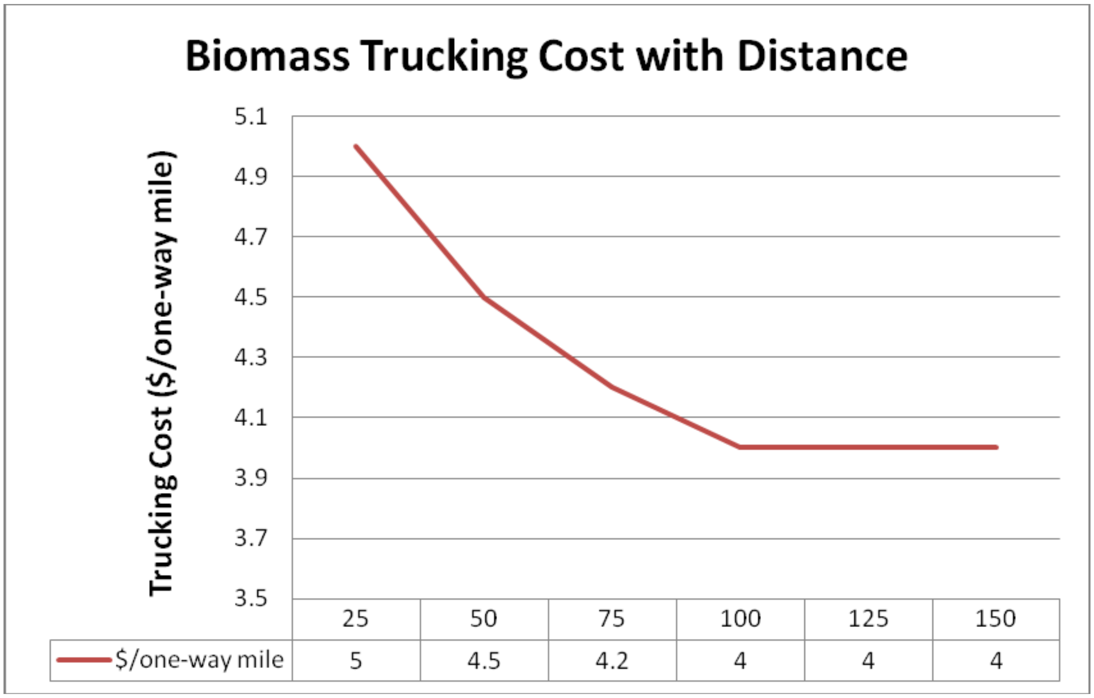
Table 10. Cost and operating assumptions and calculations for a grinder/loader production system.

	Grinder	Loader
Purchase Price	$284,180	$174,880
Residual Value	20%	20%
Fixed Costs (annual basis)		
Depreciation	$45,469	$27,981
Interest (7% for 60 months)	$10,689	$6,578
Insurance	$6,820	$4,197
Variable Costs/Hour		
maintenance - other than bits	$25.14	$10.93
maintenance – bits	$17.49	
fuel (20 gals/hr @ $4.00, 15 gal/hr-loader)	$80.00	$60.50
operator ($/hr) - remote from loader	$0.00	$27.33
Total Variable/hour	$122.63	$98.76
Total Fixed Costs/yr	$62,978	$38,756
Total Variable Costs/yr	$183,945	$148,140
Total Annual Costs	$261,919	$197,388
Operating Assumptions		
Acres/sale	30	
Cords/acre	25	
Residue %	20%	
cord-equivalents of residues per acre	5	
green lbs/cord	4,500	
green tons/cord-equivalent	2.25	
green tons of residue per sale	338	
operating hours per sale	11.25	
days/sale (includes moving)	1.5	
working days	200	
sales/year	133	
green tons processed per year per unit	45,000	
Operating Hours/year	1,500	
Other services		
Staff needed to line up sales	$10,000	
Stacking of residue (paid to loggers)	$90,000	
Processing/Loading Cost ($/green ton)	$5.49	$4.15
Staff	$0.22	
Stacking	$2.00	
Total Estimated Cost/Green Ton	**$11.64**	

Trucking Cost

Besides stumpage price and processing costs, trucking cost can be a significant component of the delivered price of biomass. Trucking cost is obviously dependent on distance from the logging site to the mill. The most common form of delivery for harvest residues is in 25 ton-capacity chip vans. Based on information developed by NRRI through contacts with area loggers, we developed a simple non-linear distance-dependent cost function to estimate trucking costs. Trucking cost can then be applied to the total tonnage of harvest residues available at any particular distance to calculate a delivered cost for biomass to a mill location. As shown in Figure 5, the trucking cost is not linear with distance with higher prices per one-way mile assumed closer to the mill. This was done to capture the fact that short hauls involve a greater proportion of time in unloading and delivery than longer hauls in which the truck is travelling at highway speed for a greater proportion of the trip. Based on conversations with logging contractors, the additional time needed for loading and unloading on short hauls requires that fixed costs such as driver salaries and capital expenses be distributed over fewer miles resulting in higher per-mile charges for short hauls.

It should be noted that the trucking costs are calculated on straight-line distance and do not account for the additional distance involved in moving freight on the road system. The effect of this will vary by direction and distance. Longer hauls will tend to have less of an effect of adjustment for the road system due to the fact that a greater proportion of the trip will likely be on major highways. In contrast, shorter hauls as calculated by straight-line distance may vary in the actual miles travelled depending on the specific location of the sale.



	25	50	75	100	125	150
$/one-way mile	5	4.5	4.2	4	4	4

Figure 5. Estimated biomass trucking cost with distance.

Estimation of Delivered Costs

Once the various factors of forest location, land management policies, equipment costs, trucking costs and environmental policies are determined, estimates of total volume and price can be made. For purposes of this analysis, the stumpage price for residue material is assumed to be $5.00 per green ton which is higher than current market assuming increased competition for the resource in the future. Using a combination of chipping and grinding equipment, we assume an estimated weighted average processing cost of $10.00 per green ton. This includes a mix of in-line chippers and larger chipping or grinding operations.

Combining all of the components of stumpage, harvest, processing and trucking costs produces a total estimated delivered cost to the mill. Assuming a 50 mile average haul, delivered wood cost is summarized in Table 11 for two scenarios; harvest residues and low-value roundwood. Using the set of assumptions shown in Table 11, the delivered cost per green ton of biomass ranges from $24.00 to $36.78 depending on if residue or low-value roundwood is the biomass source. Using a ratio of 80% roundwood and 20% residue in an average timber sale, the weighted average delivered cost is estimated to be $34.23 per green ton. If the average haul were assumed to be 75 miles (a large centralized mill), the total delivered cost would rise to $27.60 and $40.38 per green ton for residues and roundwood, respectively. It should be noted that a 75 mile procurement radius encompasses a total of over eleven million acres of land, a large land area roughly one fifth the size of Minnesota.

Table 11. Cost components and total estimated cost of biomass assuming a 50-mile haul ($/green ton)

	Harvest Residues	Low-Value Roundwood	Notes
Stumpage	**$5.00**	**$10.87**	**Roundwood - $25.00/cord stumpage, 2.3 green tons per cord**
Harvest	**$0.00**	**$13.91**	**Roundwood assumption - $32.00 /cord harvest, 2.3 green tons per cord**
Processing	**$10.00**	**$3.00**	**Chipping on site for residues, central log yard for roundwood**
Trucking	**$9.00**	**$9.00**	**50 mile haul one-way, $4.50/loaded mile, 25 ton load**
Total	**$24.00**	**$36.78**	**Assuming 80/20 roundwood:residues, weighted average cost = $34.23**

We acknowledge that our assumption about stumpage cost is higher than the current prevailing price. However, the intent of this report is to estimate the expected future cost in an environment in which alternate energy technologies are economically feasible and a higher level of competition exists for the resources. For sake of context, if a cellulosic ethanol plant were to achieve a yield of 80 gallons per dry ton, the contribution of raw material to the end-product price would be $0.60 and $0.92 per gallon in the case of harvest residues and roundwood, respectively. In contrast, at the current price of $6.00 per bushel and a yield of 2.7 gallons/bushel, raw material comprises $2.22 per gallon of corn-based ethanol produced. While capital and processing costs associated with cellulosic ethanol will undoubtedly be higher than the more mature corn-based ethanol technology, it is instructive to put wood raw material in perspective compared to current ethanol production systems. Also, it should be noted that some technologies under development report expected per-ton yields ranging from 100 to 135 gallons which could further reduce the per-gallon cost of raw material in these production systems.

Hybrid Poplar on Agricultural Lands

In addition to wood derived from natural forests, the potential exists to produce wood on plantations of fast-growing trees such as hybrid poplar. Analyses of national biomass resources such as the “Billion Ton Study” (Perlack, et.al. 2005) and the Billion Ton Update study (USDOE, 2011) indicate that agricultural residues (e.g. corn stover, wheat straw, other plant parts), forest harvest residues and thinnings, and energy crops are expected to be the dominant sources of available cellulosic feedstock. Of the total 1.4 billion tons identified in the original 2005 Billion Ton Study, approximately one fourth (377 million dry tons) was estimated to be produced annually through planting of energy crops on agricultural lands. However, the updated Billion Ton Report puts even greater reliance on dedicated energy crops including hybrid poplar, willow, switchgrass, energy cane and other herbaceous material.

The NRRI has been conducting research on tree energy crops since the early 1980s and manages one of the largest poplar breeding and field-testing programs in the United States. Also, work is underway by a number of groups to evaluate yield and management inputs of grass crops and mixed prairie species (Tilman et.al. 2006, Casler and Boe, 2003). Based on work done by the UM-Crookston, NRRI and the Agricultural Utilization Research Institute over the past decade, yields of poplar plantations on CRP sites in northwestern Minnesota, an area of high CRP enrollment, have been shown to average 3.5 ovendry tons per acre annually. Research is ongoing to better define yields of other energy crops in other areas of the state. Using an average annual yield of 3.5 tons per acre of energy crops, the total potential biomass production of this resource could approach 5.6 million ovendry tons. This resource will require a significant investment to achieve but a portion of wood supply for future energy production could come from energy crops. Work is needed to identify optimum sites, inputs needed and yields of energy crops on a range of site throughout Minnesota.

Poplar Development and Commercial Application in Minnesota

Research in the Upper Midwest on the intensive culture of hybrid poplar began in the mid-1970s through the efforts of Dave Dawson and the team of researchers at the USDA Forest Service, Forestry Sciences Laboratory at Rhinelander, Wisconsin.   Research included evaluation of biomass yields, genetics, physiology and cultural practices such as plant spacing and weed control. This was seminal research that established the foundation for woody crops for fiber and energy in the region. Subsequent to this program, research began at other universities in the late 1970’s as part of the DOE Biomass Feedstock Development Program administered at the Oak Ridge National Laboratory under contract to the DOE. While much of the USFS research was concentrated at the Harshaw experimental farm near Rhinelander, Wisconsin, studies expanded to other sites across the region and included clone tests, herbicide trials and

yield studies. New research programs included, among others, those at the University of Minnesota, University of Wisconsin, Iowa State and Purdue.
The establishment of a research base in the Upper Midwest was critical to the eventual commercial application of poplar culture in Minnesota. Prior to the 1970s, little information was available on suitable hybrids, potential yields and management practices. The infrastructure of genetics tests, yield studies and plantation culture research produced information on clonal performance in the region, inputs necessary for successful plantation establishment and resulting wood yield. Without this established infrastructure, it is doubtful that a commercial program would have taken place. Research done by the USDA Forest Service and the University of Minnesota provided the foundation for selection of poplar hybrids that were suited to central Minnesota conditions and expected yield of those hybrids on moderately productive agricultural soils in the state. This document describes the process of genetic improvement that was done to facilitate the commercial production of poplar in the region and ongoing genetic improvement efforts. Also, a discussion of production economics and future research direction is included.

Plantation Yield

One of the most important factors influencing the economics of biomass production is yield. We have established a series of yield tests across the state of Minnesota to assess the impact of soils, climate and genetics on yield. For our purposes, the value of interest is the total aboveground leafless biomass. For purposes of this discussion, yields are measured as total aboveground dry biomass (moisture free basis) included main stemwood, tops and branches. Also, we are assuming that plantations have been well maintained either in a commercial or a research setting. In most cases in our network of yield research plots, yield blocks are embedded within commercially managed plantations and, as such, reflect yields that can be expected under actual commercial management.

Our studies indicate that yield of hybrid poplar using superior clones such as DN5 and D124 on moderately productive agricultural sites in Minnesota is expected to be between 4.0 and 4.5 dry tons per acre per year. Data are needed on long-term growth characteristics of new clones. Behavior of clones at higher stand basal area later in the rotation is an important factor and has the potential to greatly affect the suitability of some clones to produce high biomass yields. Also, based on our research to date, the incremental stand basal area growth of the more productive clones ranges from 18 to 25 square feet per acre per year. This value can be used as the minimum expected baseline for closed-canopy stands of new candidate clones at mid-rotation.

Performance of clones vary considerably with DN34 being among the lowest yielding clones at all sites and as mentioned above, has been discontinued for use in commercial production. DN5 appears to be the most stable, high yielding clone across the range of sites in our studies. This underscores the potential variation among clones and the need to continue to improve genetics of poplar for production in the Lakes States. Clone NM6 is demonstrated to be a moderate- to high-yielding clone with stability across the range of sites. In commercial production, NM6 has been shown to yield 3.6 dry tons mean annual increment acre^{-1} year^{-1} on moderately productive agricultural sites in central Minnesota (personal communication, Mike Young, Verso Paper).

Based on our experience to date, the average yield that can be expected in new plantations on land of average agricultural productivity in Minnesota is approximately 4.0 tons acre^{-1} year^{-1}. While data are not complete at this time, ongoing yield tests of a selected number of clones near Waseca, MN on high quality agricultural soils (180 bushel corn yield) show that yields of new clones will likely range from 5.0 to 5.5 dry tons increment acre^{-1} year^{-1}. The yield value of 4.0 dry tons acre^{-1} year^{-1} is used as the starting point for economic analysis in the following section.

Poplar Production Economics and Agricultural Crop Profit

While yield is a critical part of biomass production, it is helpful to combine yield and production costs to provide a more complete picture of the economic feasibility of producing biomass energy through dedicated energy crops such as poplar. Through the cooperation of Verso Paper staff managing the large-scale industrial program, we have developed a cash-flow model that contains management inputs necessary to achieve optimal production on agricultural soils typical of those in Minnesota. Input on the management practice, frequency of application and other information such as herbicide rate applied were verified through discussion with Verso Paper staff. In order to provide some degree of “arms-length” from disclosure of industrial cost of production, we used a combination of published custom rate sheets for agricultural operations (Edwards, Iowa State 2010, https://www.extension.iastate.edu/store/ItemDetail.aspx?ProductID=1792) and contacts with agricultural contractors to fill in the cost data for each practice. Table 1 shows the cash flow model, practice and cost on a per-acre basis throughout the life of the plantation. We have assumed a single-harvest, twelve year rotation with one year added for site preparation and an average annual yield of four dry tons acre^{-1} year^{-1}. We then vary the stumpage price (direct revenue to the landowner) to estimate a breakeven production price using a real discount rate of four percent annually. As shown in the table below, the total discounted production cost is $450.00 per acre with the total yield held at 48 dry tons per acre at harvest. The breakeven price per dry ton at a 4% discount rate is estimated to be $15.63 per dry ton.

While breakeven prices for a specific production system are useful as a starting point, a more relevant question concerns alternate uses for the land and revenue to the landowner assuming competing crops. Thus, the appropriate question is; what does the stumpage value for poplar biomass have to be to provide the same profit as other crop options? To address this question, we used published production cost data from the FINBIN website, maintained by the University of Minnesota (http://www.finbin.umn.edu/). Using this information, the total direct (site prep, seed, planting, cultivation, herbicide, fertilizer, etc.) and indirect costs (buildings, machinery, interest, etc.) costs for selected crops was calculated. The total cost of corn production on owned land is reported to be $522 per acre including direct and indirect costs of $348 and $174, respectively. Assuming an average yield of 180 bushels per acre and a current market price of $6.49 per bushel, gross revenue minus expenses is $659 per acre. The corn-competitive stumpage price for poplar biomass after discounted annualized production costs of $58 per year for a coppice management system is $179 per dry ton assuming a four ton/acre/year yield. Assuming a harvest cost of $20.00 per dry ton and a transportation cost of $18.00 per dry ton (50 mile one-way haul), the estimated delivered cost of biomass would be $181.00 per dry ton. Conducting a similar analysis for wheat in Minnesota, the estimated stumpage price would have to be $38.23 per dry ton to produce the same revenue growing wheat. The delivered price for wheat-competitive biomass is estimated to be $68.59 per dry ton. While we do not advocate growing biomass in direct competition with major commodities, it is nevertheless instructive to understand the range of production cost for biomass assuming that energy crops are grown on some portion of the United States cropland base. This analysis highlights the obvious conclusion that competing uses such as corn production will preclude dedicated energy crops on these highly productive lands. It is important to highlight that of the 440 million acres of land classified as cropland in the United States, approximately 60 million acres is in the “cropland-as-pasture” category and an additional 40 million acres in the “idled lands” category.

Table 12. Cash flow model for a single-harvest, 12-year rotation poplar plantation in Minnesota.

		Year of Operation												
Practice	Info Source	0	1	2	3	4	5	6	7	8	9	10	11	12
Burn-down Herbicide1	personal comm - Central Ag Services	13.5												
Primary Tillage2	Custom Rate – IA St – Edwards	14.1												
Secondary Tillage3	Custom Rate – IA St – Edwards	11.4												
Secondary Tillage3	Custom Rate – IA St. – Edwards		11.4											
Secondary Tillage3	Custom Rate – IA St. – Edwards		11.4											
Marking	AURI/UM - hybridpoplar.org		15											
Planting														
cuttings (450/acre @ $0.10)	personal comm - Jake Eaton - GWR, Mike Young, Verso		45											
planting (450/acre @ $0.05)	personal comm - Jake Eaton - GWR, Mike Young, Verso		22.5											
Pre-mergent Herbicide4	personal comm - Central Ag Services		43	43										
Cultivation	Custom Rate – IA St. – Edwards		9.3											
Cultivation	Custom Rate – IA St. – Edwards		9.3	9.3										
Cultivation	Custom Rate – IA St. – Edwards		9.3	9.3										
Cultivation	Custom Rate – IA St. – Edwards													
Post-Emerge Herbicide5	personal comm - Central Ag Services		43	43	43									
Fertilizer Application	personal comm - Central Ag Services							38.2		38.2		38.2		
Annual Sum of Costs		39	219.2	104.6	43	0	0	38.2	0	38.2	0	38.2	0	0
Revenue														750
Cash Flow		-39	-219.2	-104.6	-43	0	0	-38.2	0	-38.2	0	-38.2	0	750

Conclusion

As shown in this report, the question of price and availability of wood biomass for energy depends on many factors, some under a level of control and others uncontrollable, particularly when considering the long time horizons for investments in liquid fuels conversion infrastructure. In addition, fluctuation in the market price of the end product, notably liquid fuels for transportation or electrical production will result in greater uncertainty in the price of raw material for proposed processes. Based on this analysis, there is potential to procure biomass for conversion to liquids with the range in price for the biomass being approximately $25 to $40 per green ton or $50 to $80 per dry ton from natural stands in Minnesota. The development of this industry will depend on the prevailing price of the competing energy source and the long-term price stability of the end product. Based on current costs of wood resources, it appears that development of efficient conversion technologies could contribute to increased economic activity in rural areas of the state. While not unlimited, wood supplies currently exist to supply raw material for this emerging industry.

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APPENDIX B

REPORT FROM IDATECH ON METHANOL TESTING IN A FUEL CELL REFORMER

Evaluation of BioMethanol from the University of North Dakota EERC as a Potential Fuel for IdaTech LLC Methanol-Reforming Fuel Cell Systems

OVERVIEW: The University of North Dakota EERC provided 15 gallons of BioMethanol to IdaTech LLC for evaluation and testing as a potential fuel source for methanol reforming fuel cell systems currently manufactured by IdaTech. IdaTech uses a methanol/water blend (HydroPlus^{TM} fuel) in their methanol reforming fuel cell systems. The mixture consists of nominally 62 wt% methanol with the balance being de-ionized water. The quality of the fuel is very important since out of specification fuel can cause vaporizer plugging, reactor coking and reactor overheating. IdaTech requires that the methanol supplier meets IMPCA (International Methanol Producers and Consumers Association) methanol standards (Appendix A).

CHEMICAL CHARACTERIZATION: The EERC biomethanol was blended with de-ionized water (57 wt% biomethanol due to the presence of heavier hydrocarbons). The mixed fuel was evaluated using the same tests and observations conducted by IdaTech personnel on HydroPlus^{TM} methanol fuel currently in use (the testing procedure is in Appendix B):

Test	Standard	Typical HydroPlus	NDEERC	Results
Appearance	Clear	Clear	Some suspended particles	Fail
Odor	No unusual odor	No unusual odor	Strong aromatic	Fail
Water miscibility	Clear	Clear	Cloudy white	Fail
Boil down	Compare to chart	Acceptable residue	Unacceptable residue	Fail
Silica	<0.5 mg/L	<0.25 mg/L	<0.25 mg/L	Pass
Conductivity	<3 microMHO	<0.2 microMHO	235 microMHO	Fail

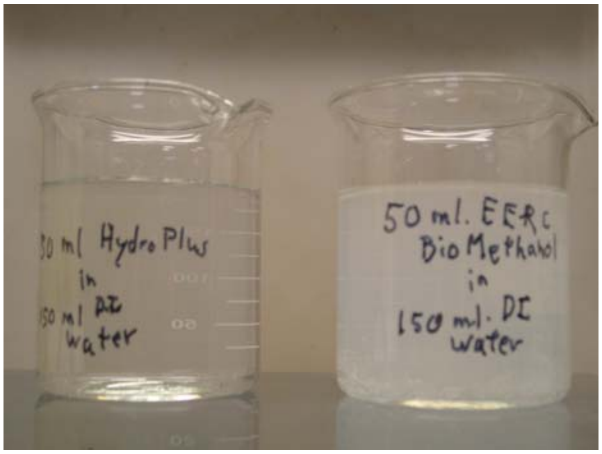
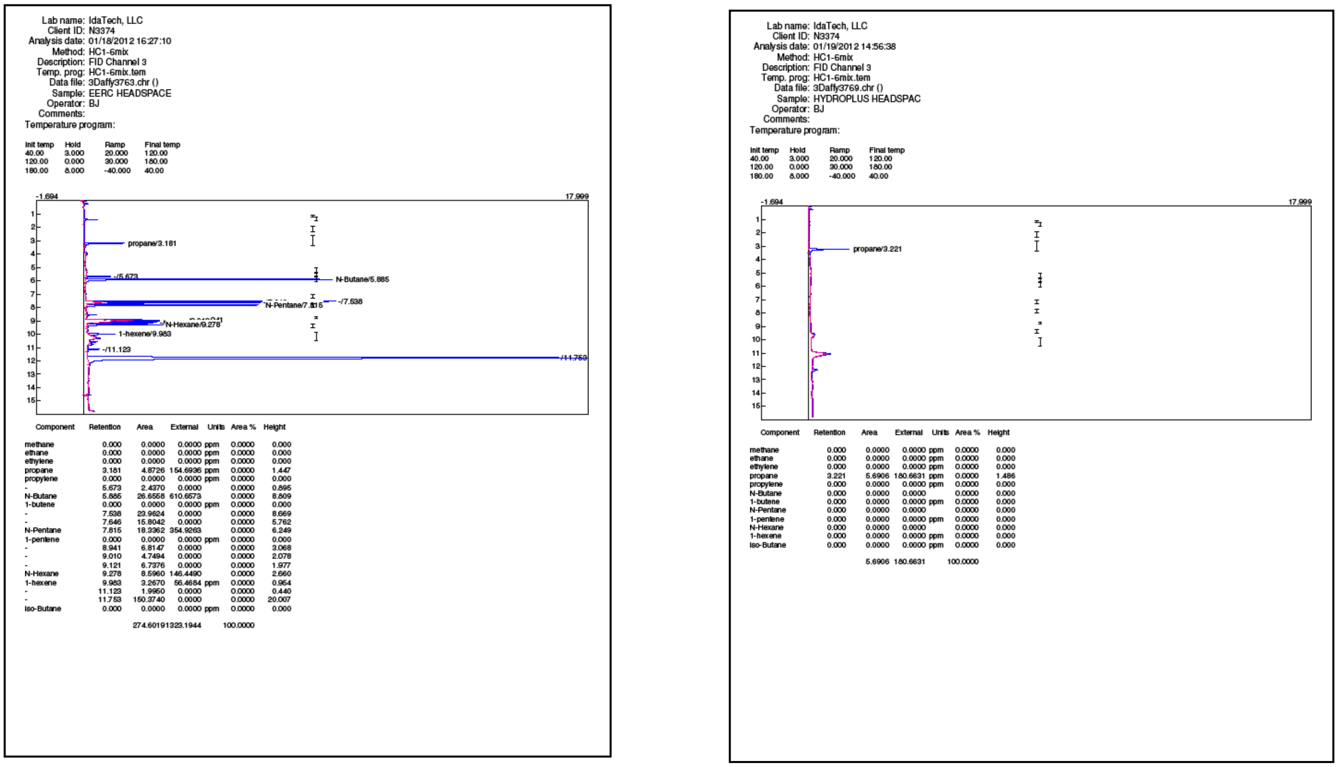


Figure 1. Miscibility tests.

A sample of EERC BioMethanol was sent to Umpqua Research Company Analytical Laboratory for Volatile Organic Compound testing (EPA 8260). The laboratory reported the following concentrations of volatile organics:

1,3-Dichloropropane	13.4 mg/L
Benzene	5,520 mg/L
Cis-1,3-Dichloropropane	2.5 mg/L
Ethyl Benzene	34.4 mg/L
m,p-Xylene	17.3 mg/L
o-Xylene	5.1 mg/L
Toluene	952 mg/L

HEADSPACE ANALYSIS BY GAS CHROMATOGRAPH: A sample of the gas headspace above a sealed volume of the EERC BioMethanol at room temperature was analyzed by gas chromatograph for comparison to a similar headspace sample of HydroPlus. The EERC Biomethanol headspace sample revealed the presence of several hydrocarbon compounds, indicating the BioMethanol was incompletely refined (Figure 2). Retention times indicated on the chromatograms reflect times for standard components normally tested at IdaTech and their relative concentrations. Peaks with similar retention times are not necessarily the same as the component listed. Analysis was conducted with an SRI Gas Chromatograph equipped with a 50m × 0.53mm × 15.0um HP AL/S column and FID detector. The peaks on the chromatogram were not positively identified by GC/MS or other means.



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    Client ID: N3374
Analysis date: 01/18/2012 16:27:10
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  Description: FID Channel 3
   Temp. prog: HC1-6mix.tem
    Data file: 3Daffy3763.chr ()
       Sample: EERC HEADSPACE
     Operator: BJ
     Comments:
Temperature program:

Init temp  Hold    Ramp     Final temp
40.00      3.000   20.000   120.00
120.00     0.000   30.000   180.00
180.00     8.000   -40.000  40.00

Component   Retention   Area      External  Units  Area %   Height

methane       0.000     0.0000     0.0000 ppm   0.0000    0.000
ethane        0.000     0.0000     0.0000 ppm   0.0000    0.000
ethylene      0.000     0.0000     0.0000 ppm   0.0000    0.000
propane       3.181     4.8726   154.6936 ppm   0.0000    1.447
propylene     0.000     0.0000     0.0000 ppm   0.0000    0.000
-             5.673     2.4370     0.0000       0.0000    0.895
N-Butane      5.885    26.6558   610.6573       0.0000    8.809
1-butene      0.000     0.0000     0.0000 ppm   0.0000    0.000
-             7.538    23.9624     0.0000       0.0000    8.669
-             7.646    15.8042     0.0000       0.0000    5.762
N-Pentane     7.815    18.3362   354.9263       0.0000    6.249
1-pentene     0.000     0.0000     0.0000 ppm   0.0000    0.000
-             8.941     6.8147     0.0000       0.0000    3.068
-             9.010     4.7494     0.0000       0.0000    2.078
-             9.121     6.7376     0.0000       0.0000    1.977
N-Hexane      9.278     8.5960   146.4490       0.0000    2.660
1-hexene      9.983     3.2670    56.4684 ppm   0.0000    0.954
-            11.123     1.9950     0.0000       0.0000    0.440
-            11.753   150.3740     0.0000       0.0000   20.007
Iso-Butane    0.000     0.0000     0.0000 ppm   0.0000    0.000

                      274.60191323.1944       100.0000
```

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  Description: FID Channel 3
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    Data file: 3Daffy3769.chr ()
       Sample: HYDROPLUS HEADSPAC
     Operator: BJ
     Comments:
Temperature program:

Init temp  Hold    Ramp     Final temp
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120.00     0.000   30.000   180.00
180.00     8.000   -40.000  40.00

Component   Retention   Area      External  Units  Area %   Height

methane       0.000     0.0000     0.0000 ppm   0.0000    0.000
ethane        0.000     0.0000     0.0000 ppm   0.0000    0.000
ethylene      0.000     0.0000     0.0000 ppm   0.0000    0.000
propane       3.221     5.6906   180.6631 ppm   0.0000    1.486
propylene     0.000     0.0000     0.0000 ppm   0.0000    0.000
N-Butane      0.000     0.0000     0.0000       0.0000    0.000
1-butene      0.000     0.0000     0.0000 ppm   0.0000    0.000
N-Pentane     0.000     0.0000     0.0000       0.0000    0.000
1-pentene     0.000     0.0000     0.0000 ppm   0.0000    0.000
N-Hexane      0.000     0.0000     0.0000       0.0000    0.000
1-hexene      0.000     0.0000     0.0000 ppm   0.0000    0.000
Iso-Butane    0.000     0.0000     0.0000 ppm   0.0000    0.000

                        5.6906   180.6631       100.0000
```

Figure 2: GC headspace analysis of EERC BioMethanol sample (left) vs. HydroPlus (right).

BENCH TESTING: The EERC BioMethanol was filtered through a 0.5 µm PTFE membrane filter and blended with deionized water to produce a methanol:water mix similar to HydroPlus (61.8% methanol by weight). The BioMethanol was reported to contain 6% water which would cause the actual methanol:water mix to be lower (57.0% by weight). The excess water content would be beneficial by reducing the possibility of coking forming in the vaporizer or reactor. For bench testing, the methanol/water mix was pumped through a 1 in. o.d. × 10 in. stainless steel reactor loaded with reforming catalyst. Fuel was preheated by passing through a ⅜" o.d × 11 in. stainless steel fin-tube vaporizer loaded with 1/16 in. stainless steel shot. Both the vaporizer and reactor were heated in a bench-top furnace to maintain catalyst temperatures between 350°C and 400°C at 150 psig. (Figures 3, 4)

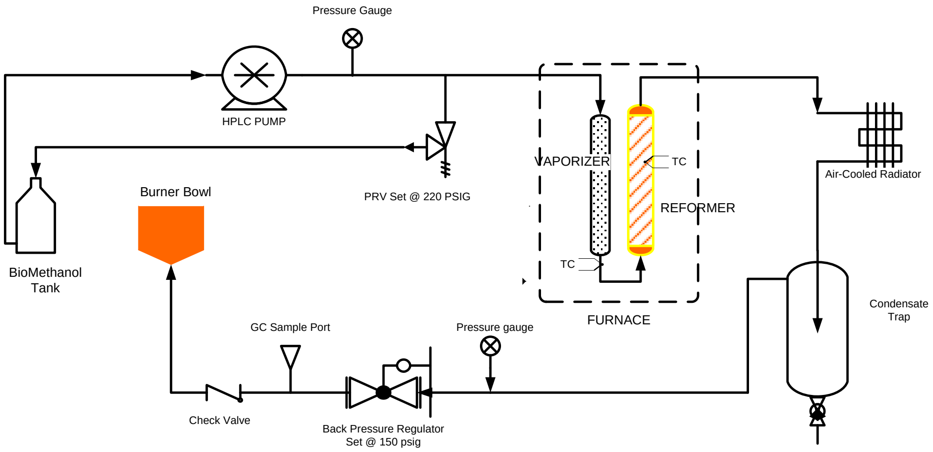


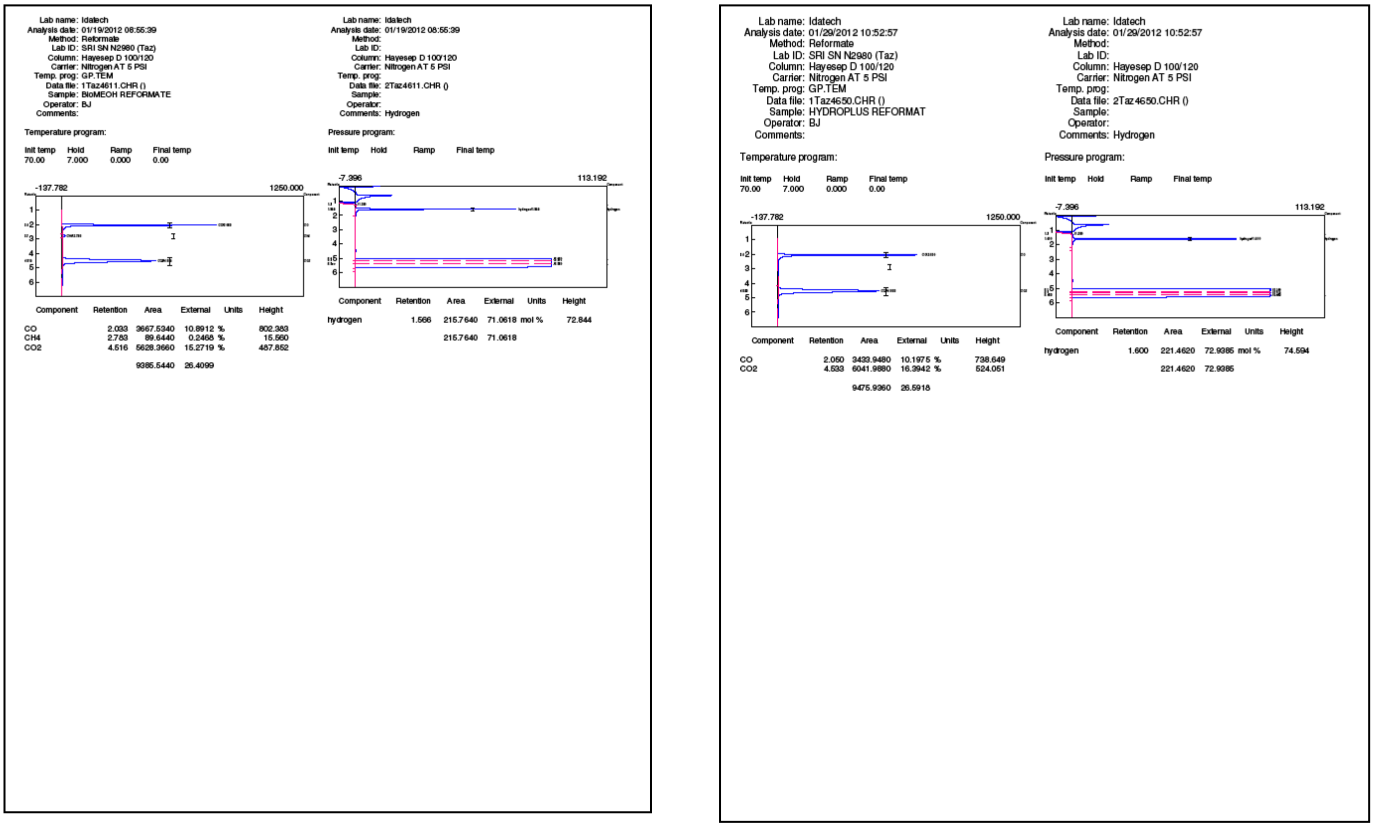
Figure 3: Process and Instrumentation Diagram for Bench Testing

Figure 4: Image of test bench furnace with reactor (left) and fin-tube vaporizer (right).

REFORMATE COMPOSITION: Gas samples were drawn from the post-reactor gas stream (also called the reformate stream) after the bulk of the water was removed by the condenser and subsequent trap. The gas samples were analyzed for basic reformate composition (Carbon Monoxide, Methane, Carbon Dioxide and Hydrogen) with an SRI gas chromatograph equipped with a Haysep D 100/120 column and for trace hydrocarbons by the SRI gas chromatograph equipped with the HP AL/S column. Results were compared to gas chromatograph analysis conducted on HydroPlus reformate from the same test set-up. (Figure 5)

<u>Basic Reformate Composition</u>:

	EERC BioMethanol Reformate	HydroPlus Reformate
CO:	9.67 – 11.56%	9.97 – 10.20%
CH4:	0.09 – 0.37%	0%
CO2:	15.27 – 16.33%	16.3 – 16.4%
H2:	70.32 – 73.26%	72.1 – 72.94%



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Analysis date: 01/19/2012 08:55:39
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       Column: Hayesep D 100/120
      Carrier: Nitrogen AT 5 PSI
   Temp. prog: GP.TEM
    Data file: 1Taz4611.CHR ()
       Sample: BIoMEOH REFORMATE
     Operator: BJ
     Comments:

Temperature program:

Init temp   Hold    Ramp    Final temp
70.00       7.000   0.000   0.00

Component   Retention   Area        External   Units   Height

CO              2.033   3667.5340   10.8912 %          802.383
CH4             2.783     89.6440    0.2468 %           15.560
CO2             4.516   5628.3660   15.2719 %          487.852

                        9385.5440   26.4099
```

```
     Lab name: Idatech
Analysis date: 01/19/2012 08:55:39
       Method:
       Lab ID:
       Column: Hayesep D 100/120
      Carrier: Nitrogen AT 5 PSI
   Temp. prog:
    Data file: 2Taz4611.CHR ()
       Sample:
     Operator:
     Comments: Hydrogen

Pressure program:

Init temp   Hold    Ramp    Final temp

Component   Retention   Area       External   Units    Height

hydrogen        1.566   215.7640   71.0618    mol %    72.844

                        215.7640   71.0618
```

```
     Lab name: Idatech
Analysis date: 01/29/2012 10:52:57
       Method: Reformate
       Lab ID: SRI SN N2980 (Taz)
       Column: Hayesep D 100/120
      Carrier: Nitrogen AT 5 PSI
   Temp. prog: GP.TEM
    Data file: 1Taz4650.CHR ()
       Sample: HYDROPLUS REFORMAT
     Operator: BJ
     Comments:

Temperature program:

Init temp   Hold    Ramp    Final temp
70.00       7.000   0.000   0.00

Component   Retention   Area        External   Units   Height

CO              2.050   3433.9480   10.1975 %          738.649
CO2             4.533   6041.9880   16.3942 %          524.051

                        9475.9360   26.5918
```

```
     Lab name: Idatech
Analysis date: 01/29/2012 10:52:57
       Method:
       Lab ID:
       Column: Hayesep D 100/120
      Carrier: Nitrogen AT 5 PSI
   Temp. prog:
    Data file: 2Taz4650.CHR ()
       Sample:
     Operator:
     Comments: Hydrogen

Pressure program:

Init temp   Hold    Ramp    Final temp

Component   Retention   Area       External   Units    Height

hydrogen        1.600   221.4620   72.9385    mol %    74.594

                        221.4620   72.9385
```

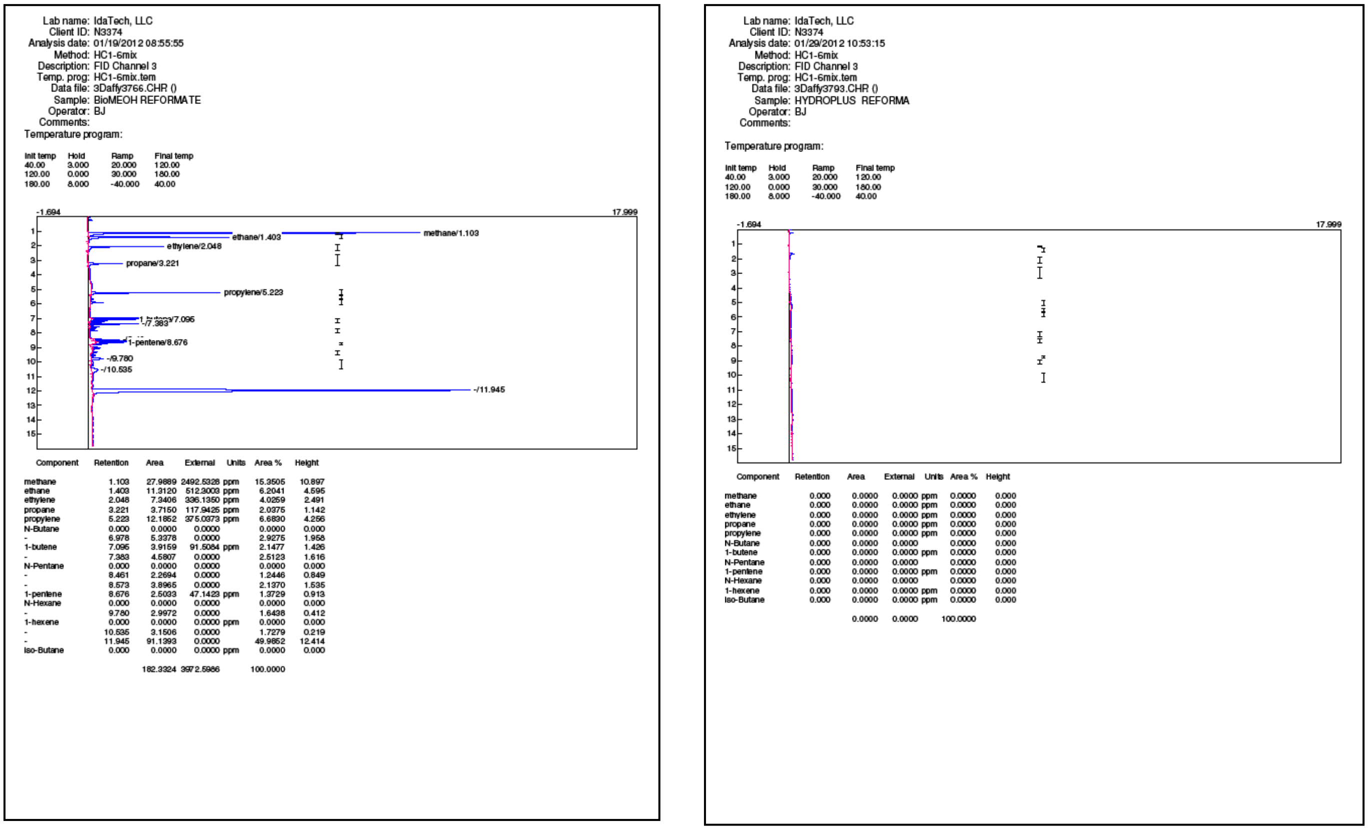
Figure 5: GC analysis of reformate composition of EERC BioMethanol (left) vs. HydroPlus (right).

Trace Hydrocarbons:

GC analysis of the HydroPlus reformate showed no additional hydrocarbons, indicating that the methanol fuel had been completely converted to the expected reformate composition of carbon monoxide, carbon dioxide and hydrogen. (Figure 6)

GC analysis of the EERC BioMethanol reformate revealed multiple hydrocarbon compounds. The peaks on the chromatogram were not positively identified by GC/MS or other means, however retention times are similar to standard retention times for methane through hexane. The largest peak had a retention time longer than hexene (Figure 6).

The EERC BioMethanol reformate had a strong aromatic odor, similar to the fuel.



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Client ID: N3374
Analysis date: 01/19/2012 08:55:55
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Description: FID Channel 3
Temp. prog: HC1-6mix.tem
Data file: 3Daffy3766.CHR ()
Sample: BioMEOH REFORMATE
Operator: BJ
Comments:
Temperature program:

Init temp	Hold	Ramp	Final temp
40.00	3.000	20.000	120.00
120.00	0.000	30.000	180.00
180.00	8.000	-40.000	40.00

Component	Retention	Area	External	Units	Area %	Height
methane	1.103	27.9889	2492.5328	ppm	15.3505	10.897
ethane	1.403	11.3120	512.3003	ppm	6.2041	4.595
ethylene	2.048	7.3406	336.1350	ppm	4.0259	2.491
propane	3.221	3.7150	117.9425	ppm	2.0375	1.142
propylene	5.223	12.1852	375.0373	ppm	6.6830	4.256
N-Butane	0.000	0.0000	0.0000		0.0000	0.000
-	6.978	5.3378	0.0000		2.9275	1.958
1-butene	7.095	3.9159	91.5084	ppm	2.1477	1.426
-	7.383	4.5807	0.0000		2.5123	1.616
N-Pentane	0.000	0.0000	0.0000		0.0000	0.000
-	8.461	2.2694	0.0000		1.2446	0.849
-	8.573	3.8965	0.0000		2.1370	1.535
1-pentene	8.676	2.5033	47.1423	ppm	1.3729	0.913
N-Hexane	0.000	0.0000	0.0000		0.0000	0.000
-	9.780	2.9972	0.0000		1.6438	0.412
1-hexene	0.000	0.0000	0.0000	ppm	0.0000	0.000
-	10.535	3.1506	0.0000		1.7279	0.219
-	11.945	91.1393	0.0000		49.9852	12.414
Iso-Butane	0.000	0.0000	0.0000	ppm	0.0000	0.000
		182.3324	3972.5986		100.0000	

Lab name: IdaTech, LLC
Client ID: N3374
Analysis date: 01/29/2012 10:53:15
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Description: FID Channel 3
Temp. prog: HC1-6mix.tem
Data file: 3Daffy3793.CHR ()
Sample: HYDROPLUS REFORMA
Operator: BJ
Comments:

Temperature program:

Init temp	Hold	Ramp	Final temp
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120.00	0.000	30.000	180.00
180.00	8.000	-40.000	40.00

Component	Retention	Area	External	Units	Area %	Height
methane	0.000	0.0000	0.0000	ppm	0.0000	0.000
ethane	0.000	0.0000	0.0000	ppm	0.0000	0.000
ethylene	0.000	0.0000	0.0000	ppm	0.0000	0.000
propane	0.000	0.0000	0.0000	ppm	0.0000	0.000
propylene	0.000	0.0000	0.0000	ppm	0.0000	0.000
N-Butane	0.000	0.0000	0.0000		0.0000	0.000
1-butene	0.000	0.0000	0.0000	ppm	0.0000	0.000
N-Pentane	0.000	0.0000	0.0000		0.0000	0.000
1-pentene	0.000	0.0000	0.0000	ppm	0.0000	0.000
N-Hexane	0.000	0.0000	0.0000		0.0000	0.000
1-hexene	0.000	0.0000	0.0000	ppm	0.0000	0.000
Iso-Butane	0.000	0.0000	0.0000	ppm	0.0000	0.000
		0.0000	0.0000		100.0000	

Figure 6: GC analysis for trace hydrocarbons in the reformate from bench tests of EERC BioMethanol (left) vs. HydroPlus (right).

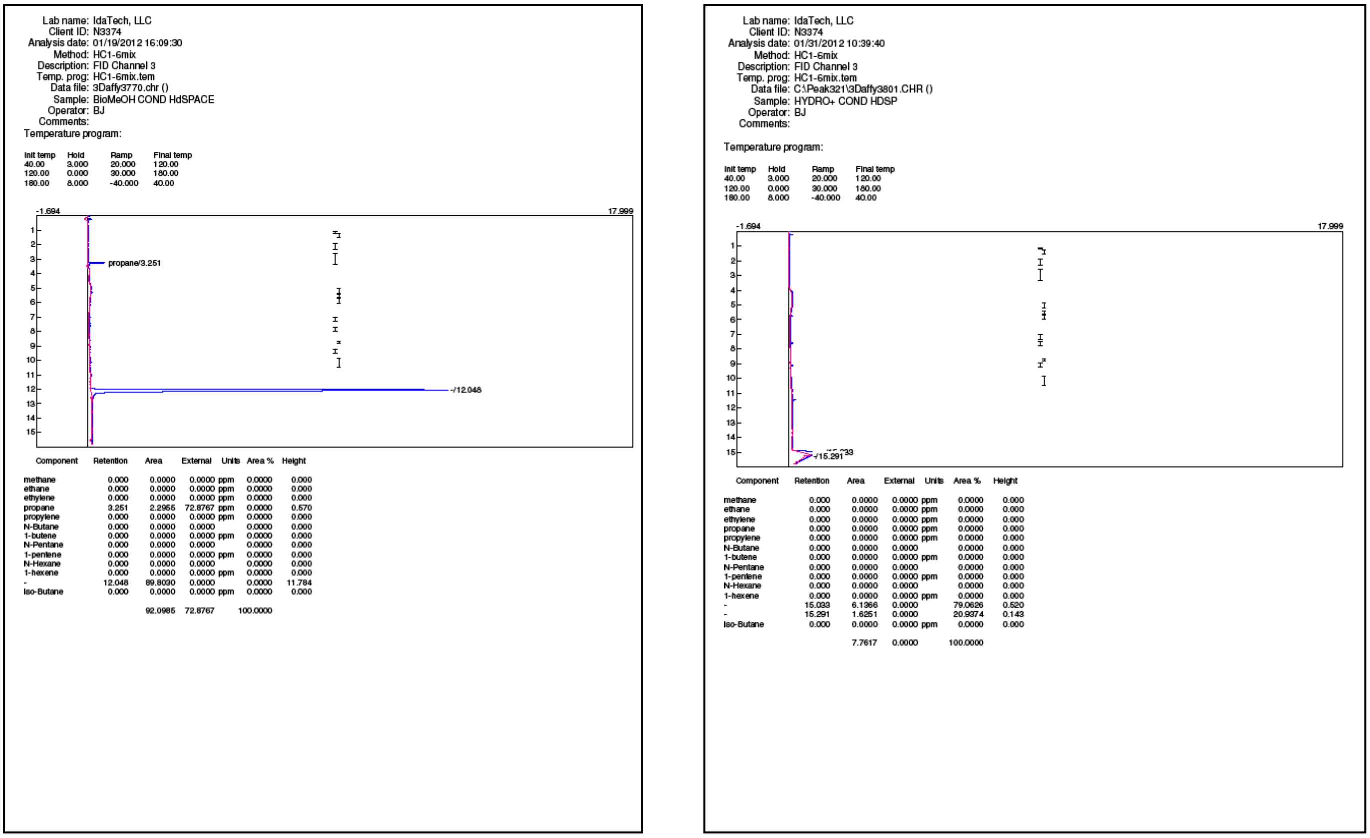
CONDENSATE EXAMINATION: Condensate, caught in the trap after the reformate gas was cooled by the radiator, was examined for total volume, density and composition to determine if the fuel was completely converted in the reactor.

<u>EERC BioMethanol Condensate</u>

	Condensate	HydroPlus Condensate
Density:	0.994 – 0.999 g/ml	0.999 – 1.003 g/ml
Volume Condensate/Volume Fuel In:	0.206	0.130

The higher ratio of condensate to fuel in the BioMethanol test is probably due, at least in part, to a higher concentration of water in the methanol:water fuel mix.

GC analysis of condensate from the EERC Biomethanol fuel showed a prominent peak at approximately at the same retention time as an unidentified prominent peak that was detected in both the BioMethanol headspace sample and the BioMethanol reformate sample. (Figure 7).



Lab name: IdaTech, LLC
Client ID: N3374
Analysis date: 01/19/2012 16:09:30
Method: HC1-6mix
Description: FID Channel 3
Temp. prog: HC1-6mix.tem
Data file: 3Daffy3770.chr ()
Sample: BioMeOH COND HdSPACE
Operator: BJ
Comments:
Temperature program:

Init temp	Hold	Ramp	Final temp
40.00	3.000	20.000	120.00
120.00	0.000	30.000	180.00
180.00	8.000	-40.000	40.00

Component	Retention	Area	External	Units	Area %	Height
methane	0.000	0.0000	0.0000	ppm	0.0000	0.000
ethane	0.000	0.0000	0.0000	ppm	0.0000	0.000
ethylene	0.000	0.0000	0.0000	ppm	0.0000	0.000
propane	3.251	2.2955	72.8767	ppm	0.0000	0.570
propylene	0.000	0.0000	0.0000	ppm	0.0000	0.000
N-Butane	0.000	0.0000	0.0000		0.0000	0.000
1-butene	0.000	0.0000	0.0000	ppm	0.0000	0.000
N-Pentane	0.000	0.0000	0.0000		0.0000	0.000
1-pentene	0.000	0.0000	0.0000	ppm	0.0000	0.000
N-Hexane	0.000	0.0000	0.0000		0.0000	0.000
1-hexene	0.000	0.0000	0.0000	ppm	0.0000	0.000
-	12.048	89.8030	0.0000		0.0000	11.784
iso-Butane	0.000	0.0000	0.0000	ppm	0.0000	0.000
		92.0985	72.8767		100.0000	

Lab name: IdaTech, LLC
Client ID: N3374
Analysis date: 01/31/2012 10:39:40
Method: HC1-6mix
Description: FID Channel 3
Temp. prog: HC1-6mix.tem
Data file: C:\Peak321\3Daffy3801.CHR ()
Sample: HYDRO+ COND HDSP
Operator: BJ
Comments:

Temperature program:

Init temp	Hold	Ramp	Final temp
40.00	3.000	20.000	120.00
120.00	0.000	30.000	180.00
180.00	8.000	-40.000	40.00

Component	Retention	Area	External	Units	Area %	Height
methane	0.000	0.0000	0.0000	ppm	0.0000	0.000
ethane	0.000	0.0000	0.0000	ppm	0.0000	0.000
ethylene	0.000	0.0000	0.0000	ppm	0.0000	0.000
propane	0.000	0.0000	0.0000	ppm	0.0000	0.000
propylene	0.000	0.0000	0.0000	ppm	0.0000	0.000
N-Butane	0.000	0.0000	0.0000		0.0000	0.000
1-butene	0.000	0.0000	0.0000	ppm	0.0000	0.000
N-Pentane	0.000	0.0000	0.0000		0.0000	0.000
1-pentene	0.000	0.0000	0.0000	ppm	0.0000	0.000
N-Hexane	0.000	0.0000	0.0000		0.0000	0.000
1-hexene	0.000	0.0000	0.0000	ppm	0.0000	0.000
-	15.033	6.1366	0.0000		79.0626	0.520
-	15.291	1.6251	0.0000		20.9374	0.143
iso-Butane	0.000	0.0000	0.0000	ppm	0.0000	0.000
		7.7617	0.0000		100.0000	

Figure 7: GC analysis of trace hydrocarbons in the headspace above a sample condensate from EERC BioMethanol fuel (left) vs. HydroPlus fuel (right) reforming.

REACTOR EXAMINATION: After testing the EERC BioMethanol fuel for 113 hours, the vaporizer and reformer were emptied and examined for evidence of material build-up. The reactor and vaporizer contents were compared to the contents of a reactor and vaporizer that were previously used to reform HydroPlus^{TM} fuel in the same test apparatus and configuration.

The reforming catalyst in the BioMethanol reactor appeared similar to the reforming catalyst in the HydroPlus^{TM} reactor. The steel shot in the BioMethanol vaporizer showed significant black material deposition build-up that was not apparent on the shot from the HydroPlus^{TM} vaporizer. (Figures 8, 9)

Figure 8: Image of the contents of the reactors used to reform HydroPlus (top) and EERC BioMethanol fuel (second from top) and steel shot from vaporizers for EERC BioMethanol fuel (second from bottom) and HydroPlus (bottom).

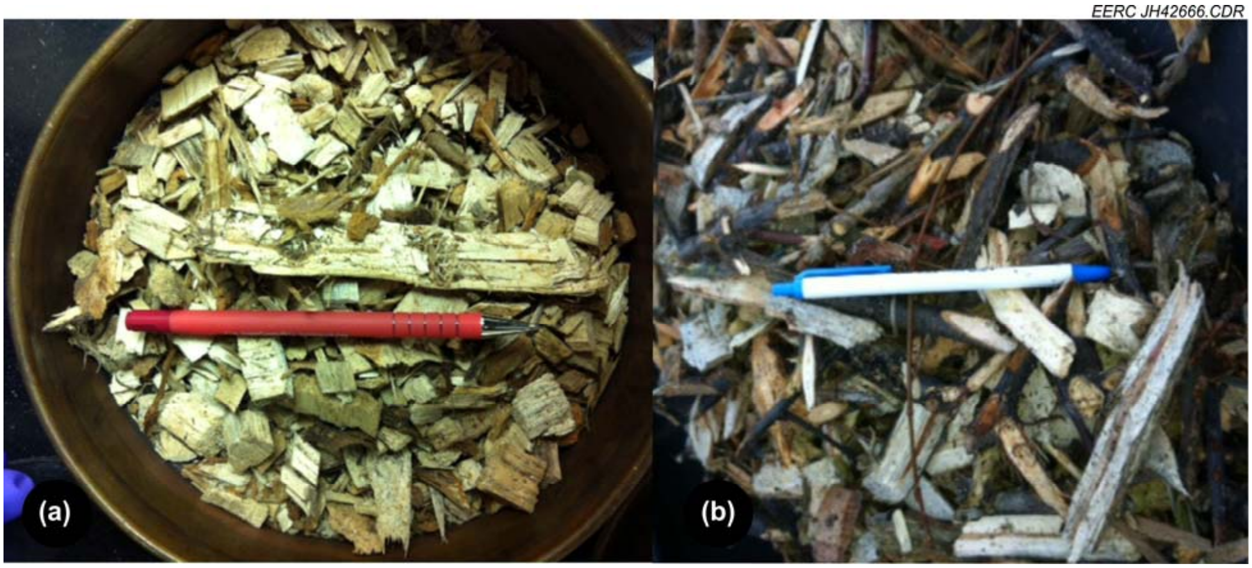


Figure 9: Close-up of deposits on steel shot used in vaporizers for EERC BioMethanol (left) and HydroPlus (right).

CONCLUSIONS and RECOMMENDATIONS: The EERC BioMethanol failed five out of six fuel quality tests and would be rejected as a fuel in IdaTech's methanol fueled fuel cell systems. Additional observations were:

1) The conductivity of the EERC BioMethanol is 78× greater than the maximum allowed by IdaTech specifications and 1175 × higher than the HydroPlus fuel provided by a commercial fuel supplier. The higher conductivity indicates the presence of excessive concentrations of dissolved solids that could cause premature failure of the systems.

2) Significant deposits were noted in the vaporizer of the test reactor for the EERC BioMethanol bench test after only 113 hours of testing. These deposits would soon plug the vaporizer and/or reactor of IdaTech's fuel cell systems, causing system failure.

3) The presence of undesirable trace hydrocarbons in the EERC BioMethanol, in particular 0.55% wt/vol. Benzene, present unnecessary health and environmental concerns.

4) Benzene and other impurities, including Toluene and Xylene, in the EERC BioMethanol are chemically incompatible with EPDM diaphragms used in fuel pumps and silicone rubber seals elsewhere in IdaTech's fuel cell systems.

5) The presence of multiple hydrocarbons in the reformate stream could present unanticipated problems in downstream processes in the ME systems (poisoning of the membrane purifier). No further testing was conducted in full systems due to the unsuitability of the EERC BioMethanol fuel.

Bruce A. Johnson
Test Technician, IdaTech LLC

APPENDIX C

BIOMASS FINAL PRESENTATION AND UPDATES

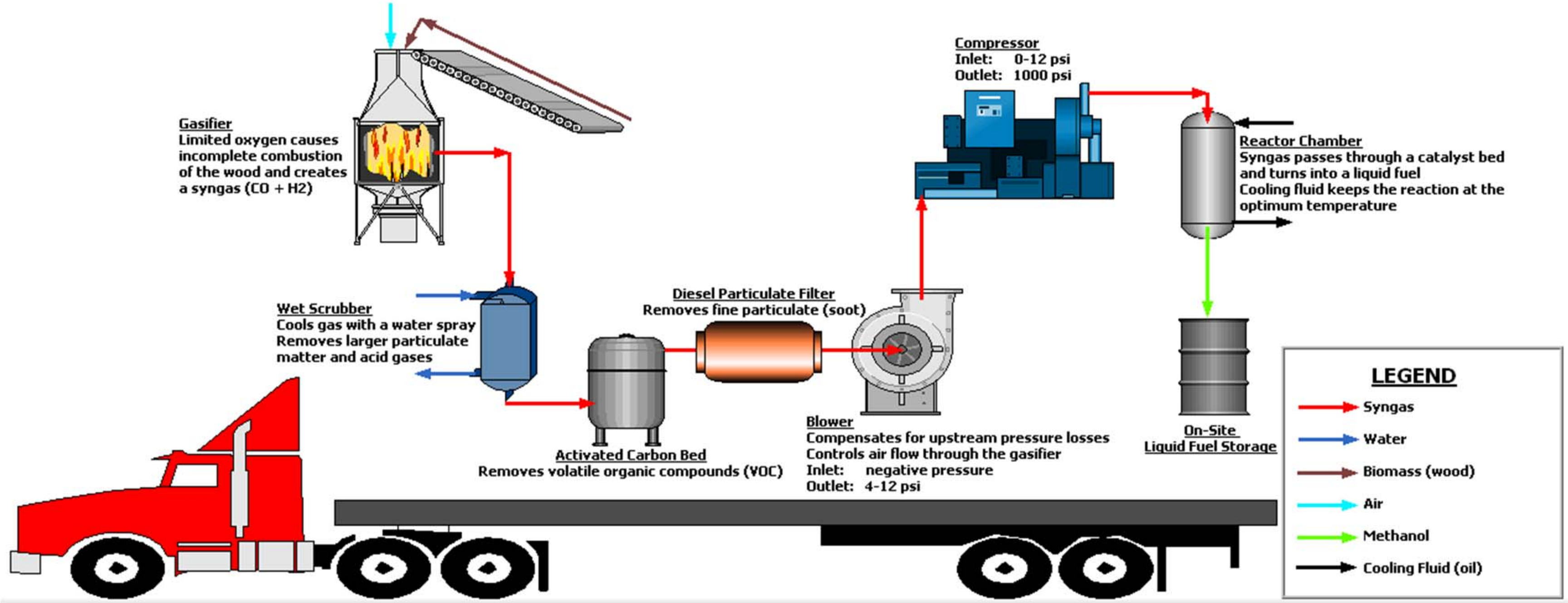
Liquid Fuels from Biomass: A Mobile Indirect Liquefaction System

Biomass 2011
Grand Forks, North Dakota
July 26, 2011

John Hurley
Senior Research Advisor

UND University of North Dakota
Grand Forks

Schematic of Mobile Indirect Liquefaction System (MILS)



Gasifier
Limited oxygen causes incomplete combustion of the wood and creates a syngas (CO + H2)

Wet Scrubber
Cools gas with a water spray
Removes larger particulate matter and acid gases

Activated Carbon Bed
Removes volatile organic compounds (VOC)

Diesel Particulate Filter
Removes fine particulate (soot)

Blower
Compensates for upstream pressure losses
Controls air flow through the gasifier
Inlet: negative pressure
Outlet: 4-12 psi

Compressor
Inlet: 0-12 psi
Outlet: 1000 psi

Reactor Chamber
Syngas passes through a catalyst bed and turns into a liquid fuel
Cooling fluid keeps the reaction at the optimum temperature

On-Site Liquid Fuel Storage

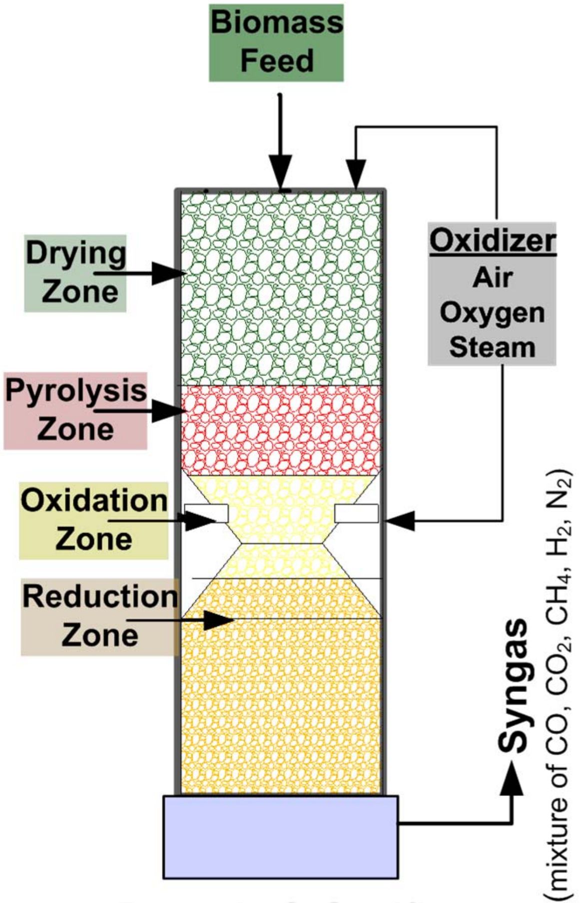
LEGEND
- Syngas
- Water
- Biomass (wood)
- Air
- Methanol
- Cooling Fluid (oil)

Advantages of Distributed Wood Conversion to Liquid Fuels

- Biomass has a low energy density so it is expensive to ship very far – better to ship higher-density liquid fuel.
- Conversion of new or legacy waste piles to liquids for off-site power or chemical use.
- Additional revenue stream for biowaste producers.
- Possible market advantage for green fuels, especially with carbon taxes.
- Indirect job creation in rural areas.

Processing Options for Biofuels

Process	Biofuel
Enzyme hydrolysis → fermentation	Ethanol
Gasification → fermentation	Ethanol
Gasification → alcohol synthesis	Mixed alcohols
Gasification → Fischer–Tropsch	Green diesel
Pyrolysis → bio-oil→ hydrogenation	Green diesel



Downdraft Gasifiers

Basic Gasification Reactions

- Need to force as much H_2 production as possible for gas-to-liquids (GTL)
- Solid–Gas Reactions

  $C + ½O_2 = CO$ *(exothermic – partial oxidation)*

  $C + O_2 = CO_2$ *(highly exothermic – complete oxidation)*

  $C + CO_2 = 2CO$ *(highly endothermic – Boudouard)*

  $C + H_2O = CO + H_2$ *(highly endothermic – steam gasification)*

  $C + 2H_2 = CH_4$ *(exothermic)*

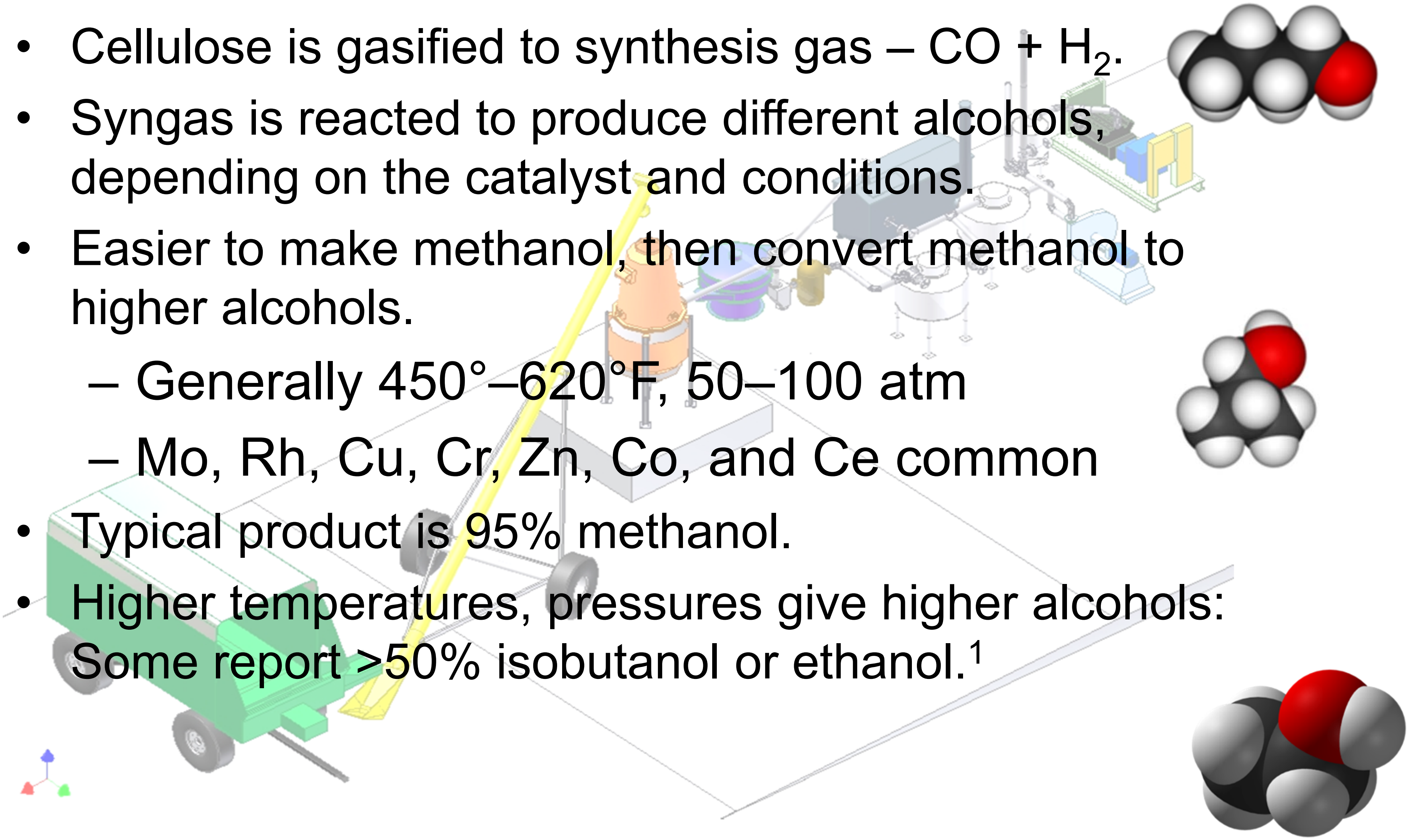
- Gas–Gas Reactions

  $CO + H_2O = H_2 + CO_2$ *(mildly exothermic – water–gas shift)*

  $CO + 3H_2 = CH_4 + H_2O$ *(highly exothermic – methanation)*

Gasification → Alcohols

- Cellulose is gasified to synthesis gas – CO + H_2.
- Syngas is reacted to produce different alcohols, depending on the catalyst and conditions.
- Easier to make methanol, then convert methanol to higher alcohols.
    - – Generally 450°–620°F, 50–100 atm
    - – Mo, Rh, Cu, Cr, Zn, Co, and Ce common
- Typical product is 95% methanol.
- Higher temperatures, pressures give higher alcohols: Some report >50% isobutanol or ethanol.[1]



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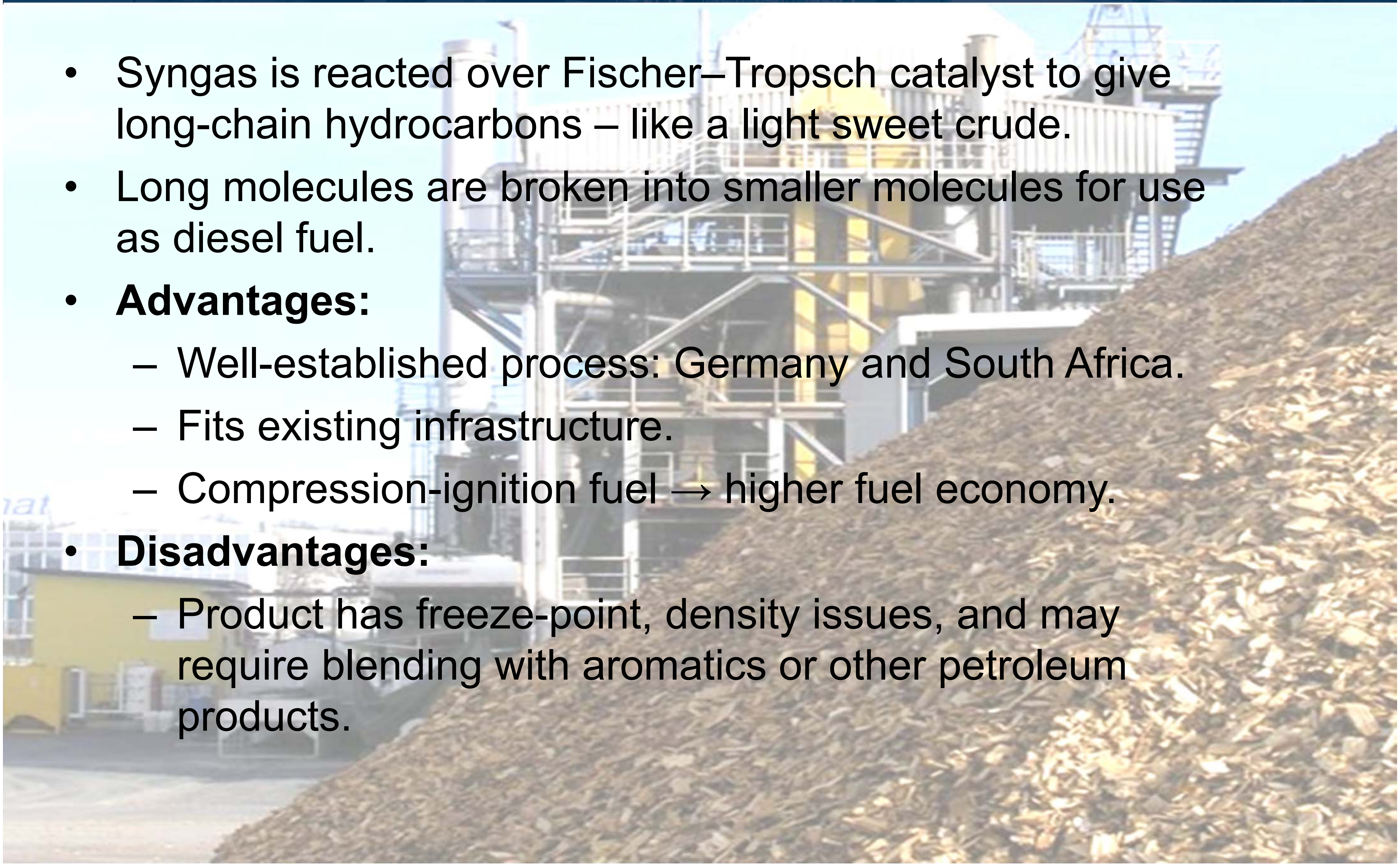
[1] Brown, D. "Ecalene™ – an Ethanol-Rich Fuel Additive from Syngas." *CatCon 2005*, Philadelphia, PA Oct 25–26, 2005.

Gasification → Diesel



- Syngas is reacted over Fischer–Tropsch catalyst to give long-chain hydrocarbons – like a light sweet crude.
- Long molecules are broken into smaller molecules for use as diesel fuel.
- **Advantages:**
  - Well-established process: Germany and South Africa.
  - Fits existing infrastructure.
  - Compression-ignition fuel → higher fuel economy.
- **Disadvantages:**
  - Product has freeze-point, density issues, and may require blending with aromatics or other petroleum products.

Engineering Analysis of Systems for Converting Wood to Methanol

- The EERC worked with IdaTech (Bend, OR) on the analysis of an indirect wood-to-methanol conversion system.
- IdaTech markets a fuel cell system for converting methanol to heat and power.
- Performed engineering and economic analysis of a 5-ton/day mobile system.
- Analyzed air-blown, oxygen-blown, steam gasification, and thermally integrated gasifiers.

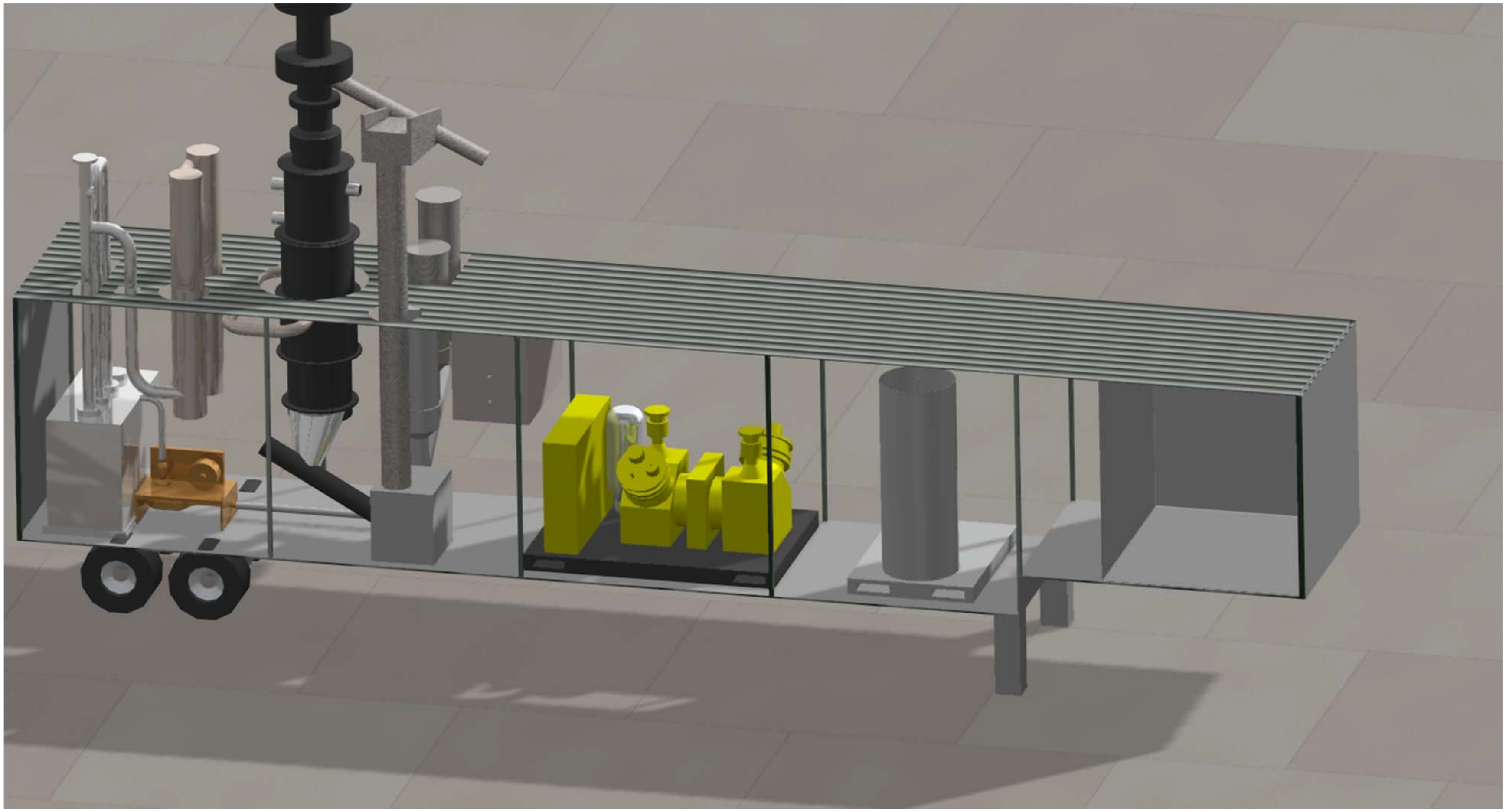
Economic Comparisons at 5- and 10-year Debt Loading

Annual Figures	Air	Oxygen	Steam	Thermal Integ.
Debt Loading, $/yr over 10 yr	$103,800	$100,624	$115,286	$92,622
Debt Loading, $/yr over 5 yr	$179,561	$174,068	$119,432	$160,225
Direct Operating/yr	$90,196	$126,416	$195,036	$79,591
Total Operating +10 yr payback	$193,996	$227,040	$310,322	$172,213
Total Operating + 5 yr payback	$269,757	$300,484	$394,467	$239,816
MeOH Production, gal/yr	114,172	165,798	310,250	176,967
Cost per Gallon Debt-Loaded, first 10 yr	$1.70	$1.37	$1.00	$0.97
Cost per Gallon Debt-Loaded, first 5 yr	$2.36	$1.81	$1.27	$1.36
Cost per Gallon Debt-Free	$0.79	$0.76	$0.63	$0.45
Long-Term 20-yr Breakeven	$1.38	$1.16	$0.87	$0.79

Mobile Indirect Liquefaction System Demonstration

- $1 million from Xcel Energy Renewable Development Fund.
- Matching $1 million from the EERC–U.S. Department of Energy Center for Biomass Utilization cooperative agreement.
- Build and operate a 200-lb/hour wood waste indirect liquefaction system.
- Construction to be completed in August 2011.
- Operation at the EERC over an 8-week period in September and October of 2011.

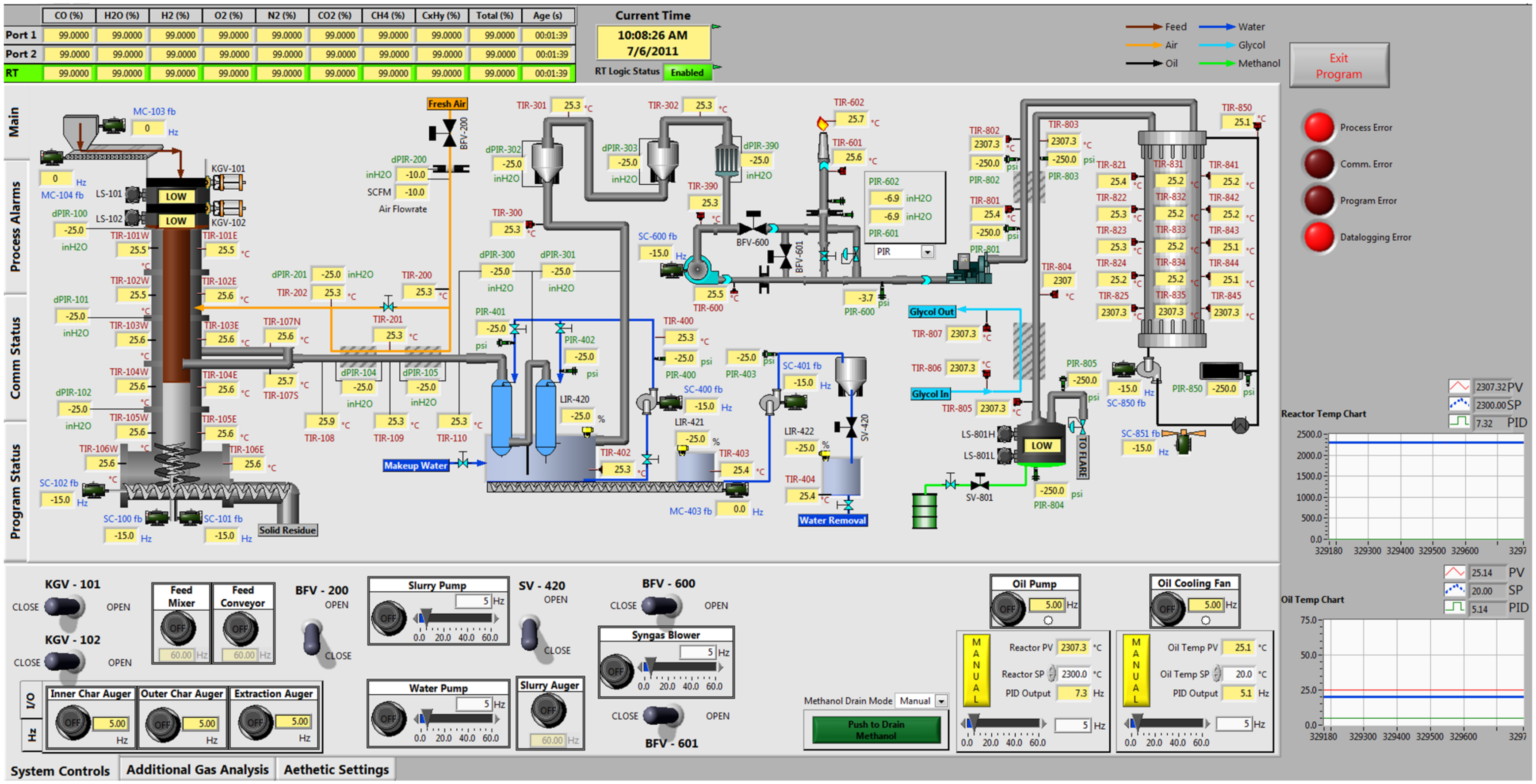
EERC Mobile Indirect Liquefaction System (MILS)



Advantages of the EERC Gasification System

- Mobile so it can be moved to the wood source.
- Can gasify wood with up to 50% moisture (green).
- Produces a higher H_2/CO ratio syngas for easier conversion to liquid fuels.
- Very low labor requirements.

Computer Controls for the MILS



	CO (%)	H2O (%)	H2 (%)	O2 (%)	N2 (%)	CO2 (%)	CH4 (%)	CxHy (%)	Total (%)	Age (s)
Port 1	99.0000	99.0000	99.0000	99.0000	99.0000	99.0000	99.0000	99.0000	99.0000	00:01:39
Port 2	99.0000	99.0000	99.0000	99.0000	99.0000	99.0000	99.0000	99.0000	99.0000	00:01:39
RT	99.0000	99.0000	99.0000	99.0000	99.0000	99.0000	99.0000	99.0000	99.0000	00:01:39

Current Time: 10:08:26 AM 7/6/2011

RT Logic Status: Enabled

Methanol Drain Mode: Manual

Reactor PV 2307.3 °C

Reactor SP 2300.0 °C

PID Output 7.3 Hz

Oil Temp PV 25.1 °C

Oil Temp SP 20.0 °C

PID Output 5.1 Hz

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Putting Research into Practice

Summary – State of the EERC Art

- A new gasifier design – the Sandwich – has been developed and tested at the pilot scale.
- Wet or green wood can be gasified directly, without time or energy needed for drying, which produces syngas with a higher H_2/CO ratio for conversion to liquid fuels.
- GTL testing on the bench scale indicates approximately 50 gallons of methanol can be produced per ton of moist wood for a single reactor, up to 80 gallons/ton for two reactors.
- Construction to be completed in August 2011.
- Operation at the EERC over an 8-week period in September and October of 2011.

Future Improvements

- Adding a hydrogen separation membrane to a single reactor could double production to 100 gallons of methanol per ton of wet wood.
- Adding a water–gas shift reactor plus the hydrogen separation could triple production to 150 gallons/ton.
- Add char conveyor system to clean wastewater in an internal loop.

Future Improvements (continued)

- Harvest energy of compression from unreacted gas with a turboexpander to produce electricity and cooling, or throttle expander to produce cooling. Both would reduce the input power requirements.
- Modify the compressor or a generator to run on excess syngas to produce power.
- Need to find funding to test these concepts.

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Update on a Mobile Indirect Biomass Liquefaction System

BY JOHN P. HURLEY

Minnesota's forestry operations produce 300,000 tons a year of wood waste that is not used in any existing or proposed facility. Through the process of indirect liquefaction, this waste can be converted into liquid fuels that could be transported to remote off-grid sites and reformed to hydrogen to power fuel cells to produce electricity. Using distributed power generation to off-grid sites eliminates the need to build transmission lines at remote sites, which ultimately saves utility ratepayers money. In addition, the wood-to-fuel technology provides a non-fossil energy-based, nearly carbon dioxide neutral method to fuel backup generators. Even in areas that are served by the grid, this saves utility ratepayers the cost of maintaining large backup power production systems. Ratepayers may also be able to take advantage of future carbon credits or avoid carbon taxes applied to fossil energy-based power production.

The Energy & Environmental Research Center (EERC) has developed and tested at small scales much of the technology necessary for distributed indirect liquefaction systems. With funding provided by customers of Xcel Energy through a grant from the Renewable Development Fund and the U.S. Department of Energy through the EERC Centers for Renewable Energy and Biomass Utilization, the EERC designed and built a mobile, demonstration-sized indirect wood waste liquefaction system and operated it in order to determine best construction and operating practices, overall system productivity, and necessary design changes to make the concept more commercially viable. The system was originally described in this column in the April 2011 issue.

The system uses a unique gasifier to convert the wood waste into synthesis gas, which is cleaned and compressed and flows to a gas-to-liquids (GTL) reactor to convert the gas to a liquid. In this program, we focused on the production of methanol, the simplest alcohol, because it can be easily reformed into hydrogen which can be used to power fuel cells to efficiently make electricity at sites separate from the biomass resource. The gasifier was specially designed by the EERC to handle wet wood waste with up to 40% moisture, thereby saving the need to separately dry the wood before gasification, as most commercial gasification units require.

Two types of wood waste were tested in the system: chipped hybrid poplar and chipped ash. In both cases, the hydrogen content of the gas produced was lower than expected. The methanol production rate was approximately 15 gallons per ton of biomass for both wood types. This initial production rate was relatively low but did serve to validate computer models of the system performance. Using those models, engineers have evaluated several improvements to the system to increase the hydrogen content of the syngas which should allow production rates as high as 50 gallons/ton with the existing design and as much as 100 gallons/ton with additional hardware.

Demonstrating this technology and using it to validate our engineering models has been an important step toward making use of neglected biomass residues to ultimately provide renewable distributed power generation. But an essential question must be answered: at what cost? In a future article, the economics of the production of methanol by this technology will be discussed.

Project funding provided by customers of Xcel Energy through a grant from the Renewable Development Fund, and the U.S. Department of Energy.

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Economic Analysis of a Mobile Indirect Biomass Liquefaction System

BY JOHN P. HURLEY

As I described in last month's column, the Energy & Environmental Research Center (EERC) has built and tested a mobile system for converting wood waste into liquid products such as methanol. The system uses a unique gasifier to convert the wood waste into synthesis gas, which is cleaned, compressed, and converted in a reactor to a variety of possible liquid products. We have initially focused on the production of methanol because it can easily be reformed into hydrogen to power fuel cells to make electricity at remote sites separate from the biomass resource. The gasifier was specially designed by the EERC to handle wet wood waste with up to 40% moisture, thereby saving the need to separately dry the wood before gasification, as most commercial gasification units require.

We have found that the maximum wood feed rate of the system is largely determined by the size of the compressor which can fit on the trailer. The production rate of methanol is greatly enhanced at higher pressures, so we compress the gas to 900 psi before it enters the gas-to-liquids reactor. Given our current configuration, we are limited to converting approximately 160 standard cubic feet a minute of gas into methanol liquids using a system mounted on a single trailer. This is the amount of gas produced from gasifying approximately 200 lb of wet wood an hour. The information gained from recent tests was used to validate a computer model of the system based on gas production rates and composition. Using the model results, engineers have come up with several improvements to the system that should increase the hydrogen content of the syngas and permit production rates as high as 100 gallons/ton.

At that production rate, the 300,000 tons of unused forest residue produced each year in Minnesota could be converted to approximately 30 million gallons of methanol. A fuel cell uses approximately 1 gallon of methanol to create 5 kWh of electricity, so 30 million gallons of methanol could be used to create 150,000 MWh of electricity by fuel cell in remote locations.

The system is primarily operated via computer control that can be largely automated. This significantly reduces labor requirements to that of handling upset conditions such as plugged filters, rather than continuous monitoring. Therefore, the system is designed to be operated at sites where labor is available sporadically from other ongoing activities, significantly reducing labor costs. One of the biggest operating costs is the price of electricity needed to run the compressor. One way to reduce this cost would be to use excess syngas to fire a modified generator to produce the electricity on-site, technology that the EERC is currently developing in cooperation with a generator manufacturer. If we assume that electricity is purchased at 7 cents/kWh, then production costs are predicted to be $1.58/gallon using grid power, but as low as $0.95/gallon if electricity is produced using excess syngas. Both of these costs are based on using wood waste that has no commercial value and is, therefore, free of charge.

In addition to the operating cost of the system, the capital cost of the system must be paid off. We estimate that the cost of the trailer-mounted system with an additional syngas-fired generator and other improvements to increase the production rate to 100 gallons/ton would be approximately $1 million. Assuming an 8% interest rate and payoff of the loan over 10 years, the combined capital and operating cost is approximately $3.05/gallon using grid power or $2.59/gallon using onboard generation. These costs are considerably higher than the current delivered cost of methanol created from natural gas, especially because of the low cost of shale gas being produced. However, in some situations, even these relatively high costs are acceptable, in particular, operation in very remote locations where the delivered cost of methanol may be very high or cases where additional incentives, such as carbon credits, are available. More commonly, production of other liquids, such as Fischer–Tropsch fuels or other organic chemicals, may be more economical at this time than methanol production, at least at the scale of a mobile system mounted on a single trailer.

Project funding is provided by customers of Xcel Energy through a grant from the Renewable Development Fund and the U.S. Department of Energy.

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A MOBILE INDIRECT BIOMASS LIQUEFACTION SYSTEM

BY JOHN P. HURLEY

The biomass industry knows all too well that transportation costs often stymie a project. Distributed or even portable energy and fuels production may be one method for diminishing the economic impacts of transportation costs in biomass utilization.

To test this idea, the University of North Dakota Energy & Environmental Research Center (EERC) is building a mobile system for converting cellulosic waste into liquid products. The work is being funded through the Xcel Energy Renewable Development Fund and the U.S. Department of Energy through the EERC Centers for Renewable Energy and Biomass Utilization. The system is currently (March 2011) under construction. Parametric testing will be performed with the system during the summer and fall of 2011.

In the EERC program, the technology will be demonstrated by building and testing a 200-lb biomass/hour fixed-bed downdraft biomass gasifier, air-blown and with specialized gas cleaning to produce the syngas. The system will be integrated with approximately 3-meter-long packed-bed catalytic reactors for producing the liquid fuels and highly automated to minimize labor requirements. A design review has already confirmed the fixed-bed biomass gasifier selection as the lowest-capital-cost system for indirectly producing methanol. The methanol produced will then be tested by IdaTech LLC of Bend, Oregon, to determine if it is of sufficient purity to power a fuel cell used to produce heat and electric power.

A strong advantage of the EERC gasification system is that it can be used with green or very wet wood. This reduces the need for drying the wood before gasification, resulting in substantial energy and processing savings. In fact, the high moisture content creates a syngas with a significantly higher hydrogen content than if the moisture were not present. A high hydrogen content is especially useful when making a liquid fuel from the gas stream since the hydrogen-to-carbon ratio in a liquid fuel is much greater than that of the wood itself. By increasing the hydrogen content in the gas stream, higher carbon conversion efficiencies can be reached.

By producing a liquid fuel for electricity generation elsewhere, overall biomass-to-electric power conversion efficiency is reduced relative to firing the syngas directly in a generator. However, by making a liquid fuel, the site at which the power is required can be decoupled from the site of the biomass resource. In this project, the biomass resource targeted is wet legacy piles of wood waste found at sawmills throughout Minnesota. These are piles, often produced years ago, that still contain a significant energy content but that have degraded to the point at which they cannot easily be used as commercial products such as garden mulch. Rather than incinerating them, the EERC technology would turn the waste piles into a revenue stream through the production and sale of a carbon-neutral liquid fuel.

Although the gasification design is new and unique, the EERC will be using commercially available technologies for gas compression and conversion. Initial laboratory testing of some of the subsystems shows that it may be possible to significantly improve the productivity of the system by using more experimental methods such as gas separation membranes or by modifying commercially available equipment to make it more useful in remote settings. These modifications will be the subject of a future article.

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