

# Wood-to-Wheels: A Multidisciplinary Research Initiative in Sustainable Transportation Utilizing Fuels and Co-Products from Forest Resources

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## ABSTRACT

Michigan Technological University has established a broad-based university-wide research initiative, termed Wood-to-Wheels (W2W), to develop and evaluate improved technologies for growing, harvesting, converting, and using woody biomass in renewable transportation fuel applications. The W2W program bridges the entire biomass development-production-consumption life cycle with research in areas including forest resources, bioprocessing, engine/vehicle systems, and sustainable decisions. The W2W chain establishes a closed cycle of carbon between the atmosphere, woody biomass, fuels, and vehicular systems that can reduce the accumulation of CO<sub>2</sub> in the atmosphere. This paper will summarize the activities associated with the Wood-to-Wheels initiative and describe challenges and the potential benefits that are achievable.

## INTRODUCTION

Currently 55% of U.S. daily oil supply is provided through import, which is forecasted to rise to 70% by 2025. Over 49% of these imports come from politically volatile areas, such as the Persian Gulf (22%) [1]. The dependence on imported oil is a great concern for the U.S. due to not only energy supply for economic development, but also national security. U.S. energy policy is committed to reducing dependence on imported petroleum with domestic alternatives, including biomass derived fuels and hydrogen [2]. Continuing to diversify the nation's energy supply is one of four areas President Bush has

called on Congress to act for benefiting America's economy, national security, and environment. The national Renewable Fuels Standard (RFS) created in August 2005 established a baseline targeting 7.5 billion gallons per year of renewable fuel use by 2012. Recently, the President set a more ambitious goal of reducing gasoline usage in the United States by 20 percent in the next 10 years through increasing the supply of alternative fuels and reforming and improving fuel efficiency standards [3]. The growing biofuel industry contributes significantly to the American economy and employment. In 2005, the ethanol industry added \$32.2 billion to gross output through the combination of spending for annual operations and capital spending for new refineries under construction and supported the creation of 153,725 jobs in all sectors of the economy, including more than 19,000 jobs in America's manufacturing sector [4].

Ethanol made from cellulosic sources such as woody biomass and switchgrass has the potential to provide unique environmental, economic, and strategic benefits as documented by Wyman [5], and to overcome some of the criticisms against large-scale, conventional biofuel production as identified by Giampietro et al. [6] and Pimental [7]. For example, whereas fossil fuels used in fuel cells, or even corn ethanol used in conventional internal combustion engines, reduce fossil energy consumption between 28% and 50%, only ethanol from cellulose can achieve reductions over 90% [8]. Cellulosic ethanol emits virtually no net greenhouse gases such as carbon dioxide, and cellulosic biomass is a renewable resource that regenerates from year to year

without replanting. The use of these feedstocks could allay criticisms that bioenergy crops compete with traditional crops on agricultural lands and has a concomitant effect on traditional crop prices and farm income as noted by Walsh et al. [9]. The Department of Energy estimates that 10% of current annual U.S. petroleum consumption can be replaced with products derived sustainably from forest lands [10]. Michigan and other areas in the Upper Midwest are covered with forest lands ideally suited to support cellulosic biomass production to support biorefinery operations. The utilization of ethanol, biodiesel, and other bio-products in transportation applications is feasible, but requires considerable research to achieve economic, technological, and environmental objectives. Benefits of the research include improved national security, a more favorable trade balance, rural U.S. job creation, decreased demand for petroleum, and lower emission of fossil-derived CO<sub>2</sub> from transportation.

Michigan Technological University has established a broad-based university-wide research initiative, termed Wood-to-Wheels (W2W), to develop and evaluate improved technologies for growing, harvesting, converting, and using woody biomass in renewable transportation fuel applications. The W2W program, shown in Figure 1, bridges the entire biomass development-production-consumption life cycle with research in areas including forest resources, bioprocessing, engine/vehicle systems, and sustainable decisions. The W2W chain establishes a closed cycle of carbon between the atmosphere, woody biomass, fuels, and vehicular systems that can reduce the accumulation of CO<sub>2</sub> in the atmosphere.

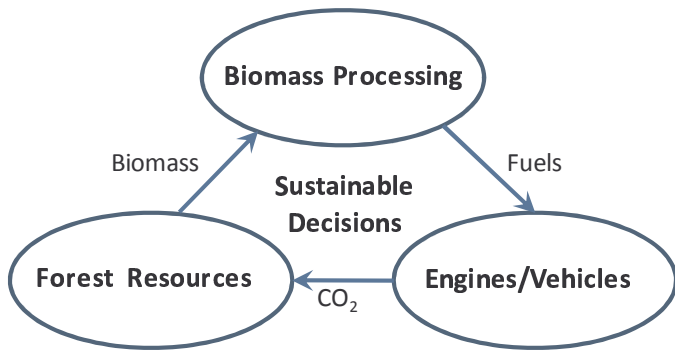


Figure 1: Wood-to-Wheels research program and material flow cycle.

There are fundamental and technological barriers to achieving biofuels derived from cellulosic biomass and the purpose of the W2W program is to perform research aimed at overcoming these barriers. Cellulosic biomass feedstock is less expensive and more abundant than corn grain, but cellulosic ethanol production is less efficient than corn ethanol production. This is due to key biological barriers such as “biomass recalcitrance” [11] – the natural resistance of plant cell walls to microbial and enzymatic deconstruction, which create the need for different fermenting microorganisms for different sugars resulting in inefficient biomass utilization for the diverse

carbohydrates present in feedstock mixtures found in the real world (e.g. multiple biomass species, branches, and bark). Logistic challenges, such as biomass harvesting, storage, processing, and transport, have to be addressed for economical cellulosic ethanol production. Ethanol’s lower vapor pressure (causes the problem of engine ignition in cold weather) and its lower energy content (about 70% of gasoline per unit volume) represent important challenges to increased ethanol use. Finally, sustainability issues need to be addressed: for example, will there be a consistent and reliable biofeedstock supply? Is transportation from harvest site to production site assured? Will the public use biofuels? By how much are greenhouse gas emissions reduced by biofuels over the life cycle?

Through research, the goal of the W2W is to generate new knowledge of lignocellulosic biofuel-based transportation and to deliver technologies and products for each stage of the life cycle. Research related to the W2W program includes:

- Sustainable forest planning and woody biomass harvesting, geographic information systems, soil element cycling, molecular biology and genetic engineering of trees.
- Processes for biochemical and thermal conversion of biomass; including chemical pretreatment and enzymatic hydrolysis of cellulose, fermentation and product purification, and enzyme/microorganism improvement.
- Developing, adapting, and testing engines and other system components to utilize ethanol and other biofuels.
- Logistical issues related to facility location, harvesting, and community-related issues.
- Environmental and economic assessments of biofuel production and usage life-cycle chain and comparison with conventional alternatives.

This paper will summarize some current research activities associated with the Wood-to-Wheels initiative as well as describe the potential benefits that are achievable through these research activities.

## WOOD-TO-WHEELS RESEARCH ACTIVITIES

**FOREST RESOURCES** - Sustainable forest management is a complex research field with many interrelated components. The forest is a multi-faceted environment which encompasses people, native flora and fauna, soil and soil nutrients, and water resources above and below ground. To say we are going to harvest excess woody biomass for renewable transportation fuel applications without considering this multi-faceted environment is an egregious error. Sustainably harvesting biofuels can provide not only fuel for our cars, but also improved wildlife habitat, cleaner water, carbon sequestration, support for stagnant rural economies, and better recreational opportunities for a growing population. Careful consideration must also be given to harvesting,

transporting, and processing of woody biomass in order to minimize fossil fuel usage.

Two upper Midwest states, Minnesota and Wisconsin, have developed biomass harvesting guidelines and/or policies for both timber lands and brush lands within the last year [12-13]. These guidelines provide important information to managers who want or need to begin planning for biofuel harvesting in addition to managing for traditional forest products such as timber and pulp. However, these types of guidelines do not provide any spatially explicit information about the woody biomass resource. We need to know “where” as well as knowing “what”.

Consequently, Wood-to-Wheels is involved in ascertaining how to utilize geographic information systems (GIS) technology to: inventory and assess current woody biomass availability; determine how and where it can be managed to meet current and future supply demands; evaluate the impact of land use changes on biodiversity (in particular, its impact on avian populations); and identify issues and potential solutions relating to the transport of feedstocks and the resultant products.

Once the spatial component is developed we are investigating how to build a robust, widely applicable biomass inventory and assessment model based within the GIS to identify marginal agriculture and forest lands which could be planted to biomass feedstocks for optimal productivity as well as environmental considerations, such as biodiversity. One of our ultimate objectives is to have guidelines and recommendations on spatial and temporal landscape patterning to provide a steady flow of biomass for ethanol production (and eventually hydrogen fuel) while maintaining or even improving habitat diversity while following policy guidelines such as those under development in Minnesota and Wisconsin. A listing of critical metrics for developing the guidelines will be compiled.

However, feedstock availability is just one piece of the puzzle. It is also important to understand how private and public forest landowners perceive the costs and benefits of cellulosic ethanol development and what they see as their goals for their land. For instance, if they do not plan future timber harvests, this means that their land will not contribute to availability. On the other hand, if they are interested in harvesting, but unsure about its benefits, having another market for forest materials from their land may make a harvest more economically viable. They may also perceive themselves as contributing to the protection of U.S. energy security and a reduction in the risk of future climate change.

We have therefore conducted a two-tiered study of specialists in key state and federal organizations and of residents, including forest landowners, of the three state study region of Minnesota, Wisconsin, and Michigan. This study included interviews and a mail survey. One of our ultimate objectives is to have guidelines and

recommendations on spatial and temporal landscape patterning to provide a steady flow of biomass for ethanol production (and eventually hydrogen fuel) while maintaining or even improving habitat diversity. We are in the analysis stage at this time, but believe that our results will contribute greatly to understanding how regional residents view the potential for regional biofuel and cellulosic ethanol development.

**BIOPROCESSING OF WOODY BIOMASS** – In recent years, growing attention has been devoted to the use of lignocellulosic biomass as a feedstock to produce renewable fuels, including liquid alternatives to fossil fuels. The technological barriers to achieving economic competitiveness and environmental sustainability for cellulosic-ethanol must be overcome using a systems biology approach [14]. One of the preferred methods for biomass-ethanol production is to thermochemically pretreat the biomass material and then enzymatically hydrolyze the pretreated material to fermentable sugars that can then be converted to ethanol using specialized microorganisms. Research on this bioprocess through the W2W initiative spans all three of the main processes in this conversion, the pretreatment stage, the enzymatic hydrolysis stage, and the fermentation stage.

The main goal of pretreatment is to enhance enzymatic conversion of the cellulose fraction, and hopefully, obtain a higher ethanol yield. Dilute acid hydrolysis is utilized as the method for pretreatment. Dilute acid hydrolysis is one of the more promising pretreatment technologies [15] and also one of the most commonly studied. Most previous studies on biomass pretreatment have involved pure species, but mixtures of biomass are likely to be actual feedstocks for forest biorefineries. One research initiative has investigated the pretreatment of mixtures of several timber species from the Upper Midwest region of the United States plus switchgrass to obtain kinetic data for dilute acid hydrolysis [16]. Figure 2 shows the pretreatment results for a 50/50 (wt) balsam/red maple mixture in 500 ml of 0.5% (wt) sulfuric acid in an experiment where temperature increased from 25 to 175°C in approximately 75 minutes. These results are being used to identify optimum reaction conditions to maximize production of fermentable sugars and minimize production of non-fermentable byproducts.

A mathematical model has been developed to predict formation and degradation of xylose in a well-mixed reactor during dilute acid hydrolysis of woody biomass. The parameters used in the pseudo-first order kinetic model were obtained after a comprehensive literature review of published data, including our own [16]. The isothermal model predicts that maximum xylose yield increases from 0.844 to 0.901 as temperature increases from 150 to 200°C. In addition, the model exhibited xylose concentration profiles very similar to experimental data obtained in our laboratory. The model will be used in the future to investigate optimum reactor conditions of temperature and acid concentration to achieve maximum sugar yields from dilute acid hydrolysis of woody biomass. For preliminary results using this model, see Figure 3.

Preliminary enzymatic hydrolysis work has also been completed with four timber species local to the Upper Peninsula of Michigan using a commercial cellulase formulation (Spezyme<sup>®</sup>CP, Genencor International, Inc.). Results showed that pretreatment of the species was necessary for the enzymatic hydrolysis to be effective and also that liberation of up to 80% of the initial glucan and xylan in the biomass are achievable for hardwoods when dilute acid pretreatment is followed by enzymatic hydrolysis. In addition, we have found that more severe dilute acid hydrolysis pretreatment conditions are necessary to increase effectiveness of enzymatic hydrolysis for these timber species. However, under these more severe conditions, yields of hemicelluloses sugars, including xylose, are reduced. Therefore, there is a tradeoff between the sugar recoveries from the glucan and xylan fractions of the biomass when pretreatment severity is changed. Work is ongoing to investigate this trend more completely.

Additional enzyme work is being completed using genetic engineering. Although the structure and function of cellulases are well established, less is known about how to improve cellulases through genetic modifications and selection of improved variants. We will employ both random and site-directed mutagenesis approaches that have been very successful in generating high activity and thermostable enzymes for pharmaceutical and in-vitro toxicity applications [17- 20]. The goal of this research is to increase fundamental knowledge of the role of cellulose binding in cellulose degradation activity, and will generate high activity cellulase formulations.

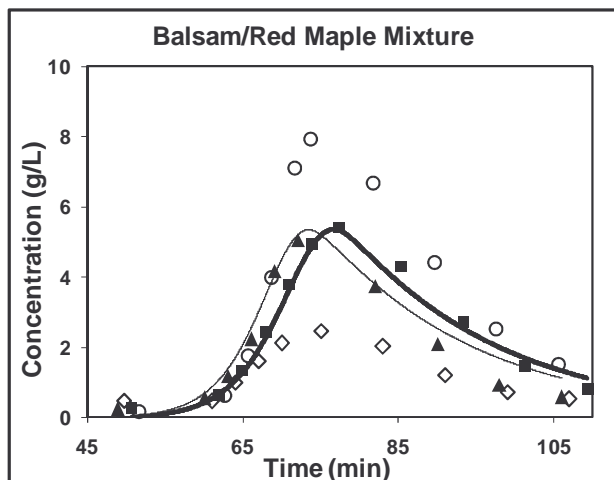


Figure 2: Xylose concentration versus time for single species and mixtures experiments plotted with mixtures xylose model prediction: ■ experimental data mixture 1, ▲ experimental data mixture 2, — (thick line) model mixture 1, — (thin line) model mixture 2. Single species experimental data: ◇ Balsam, ○ Red Maple.

Finally, studies will be completed for the fermentation stage of the biomass-ethanol process. Woody tissues vary in their carbohydrate content and composition. The preference of fermenting organisms for glucose impedes efficient use of the entire carbon pool in any given biomass sample. We are currently cloning enzymes,

such as epimerases, involved in interconverting sugars with the goal of creating strains of yeast and bacteria that can use alternate sugars, such as mannose, galactose, and xylose, more efficiently even in the presence of high glucose levels. We will examine the efficiency of these modified organisms alone and in concert with one another to improve bioprocessing efficiency.

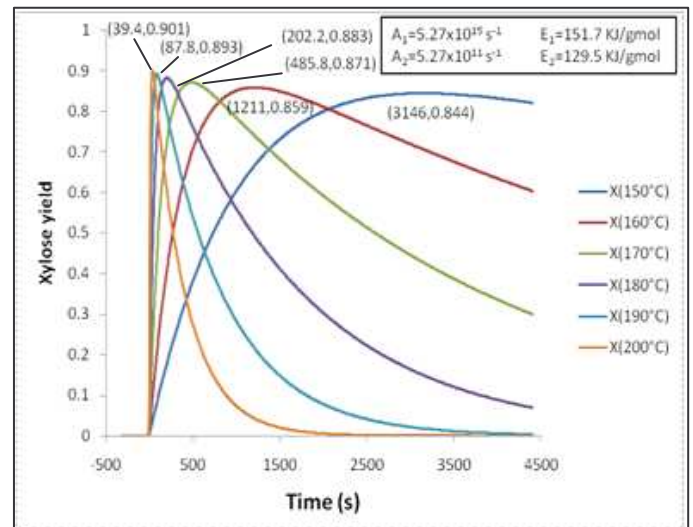


Figure 3: Effects of reactor temperature on xylose yield assuming an isothermal reactor. Kinetic constants for the model are in the boxed area of the graph. Optimum times to achieve maximum yield (x,y) at each reactor temperature are also indicated.

By completing studies in all three of the main stages of the biomass-ethanol process, the overall efficiency can be improved and hopefully, the technological barriers to achieving economic competitiveness and environmental sustainability for biomass-ethanol will be overcome.

APPLICATION OF BIOFUELS IN ENGINE AND VEHICLE SYSTEMS - Internal combustion (IC) engines continue to be the primary power generation system for land based transportation because of their power scalability, low cost, low toxic emissions, wide power band coupled with a rapid dynamic response, and high power density. Another advantage is their ability to operate on a wide range of fuels from petroleum derived gasoline and diesel to a number of bio-derived and alternative fuels. With the production of biofuels including ethanol and methyl-ester biodiesel continuing to increase, the automotive and engine manufactures have developed vehicles and powertrains [21-23] to operate with these fuels. However a number of challenges and opportunities remain as the development, control, and tuning of powertrains to this expanding fuels array continues.

Table 1 illustrates some of the challenges when an engine has to operate efficiently and cleanly on different fuels. This is shown by comparing properties important to the combustion and mixing of a typical gasoline and ethanol. The table compares gasoline and ethanol for illustration rather than a blend such as 85% ethanol – 15% gasoline, because even in the E85 fuel available in

the US market, the concentration of ethanol can vary significantly depending upon the blend and is allowed to be as low as 70% for winter fuel [49]. Also it is important to note that while some of the properties in Table 1 including the density and specific (normalized) energies scale with the ethanol concentration, others including the octane number and vapor pressure do not.

The table is organized into four groups of properties. The first group of four values listed in Table 1 compares composition and combustion mixture properties of the two fuels. The first two values listed in this group are the atomic ratios of hydrogen to carbon and oxygen to carbon. Whereas gasoline is primarily hydrogen and carbon, ethanol has a 60% higher hydrogen to carbon ratio and the addition of oxygen significantly changes the combustion reaction fuel and air composition characteristics (combustion stoichiometry). This will be detailed further shortly, but spark-ignition (SI) engines typically operate with the chemically ideal ratio of fuel and air (stoichiometric ratio). Given the composition of the fuels, the stoichiometric fuel-to-air ratios can be determined. This is listed on a mass basis as the last property in group 1 in Table 1. From the table it is seen that the stoichiometric fuel-to-air ratio for ethanol is 62% higher than that for gasoline indicating that the engine must adjust for this significant difference in the fuel and air composition requirement of the two fuels.

Table 1: Property comparisons of gasoline and ethanol [compiled from references 46, 47, and 48].

Grp	Property	Gasoline (C <sub>x</sub> H <sub>y</sub> )	Ethanol (C <sub>2</sub> H <sub>5</sub> OH)	Units	Change (%)
I	Hydrogen/Carbon	1.87	3.00	(-)	60%
I	Oxygen/Carbon	0.00	0.50	(-)	(-)
I	Density	760	785	(kg/m <sup>3</sup> )	3%
I	Stoich Fuel/Air Ratio	0.0685	0.1110	(kg <sub>Fuel</sub> /kg <sub>Air</sub> )	62%
II	Energy Density - Vol.	33.4	21.1	(MJ/L)	-37%
II	Energy Density - Mass	44.0	26.9	(MJ/kg <sub>Fuel</sub> )	-39%
II	Energy Stoich. Mixture	3.01	2.99	(MJ/kg <sub>Air, Stoich</sub> )	-1%
III	Heat of Vapor. (Fuel) <sup>*</sup>	350	840	(kJ/kg <sub>Fuel</sub> )	140%
III	Heat of Vapor. (Stoich) <sup>*</sup>	24.0	93.2	(kJ/kg <sub>Air-Stoich</sub> )	289%
III	Boiling Temp	25 - 215	78	(°C)	(-)
III	Vapor Pressure (37.8°C)	40 - 100	16	(kPa)	(-)
IV	Pump Octane # (PON)	87-93	98	(RON+MON)/2	(-)
IV	Laminar Flame Speed <sup>**</sup>	42	27	(cm/s)	-36%

\* Latent Heat of Vaporization at 1 atm and 25°C

\*\* Stoichiometric mixture at 1 atm and 25°C

The disparities in fuel composition and the combustion stoichiometry also result in significant differences in the energy density of the fuels. The second group of properties in Table 1 lists and compares important specific energies of the fuels. As seen in the table, the energy density per unit volume and per unit mass of ethanol is 37 and 39% less than that of gasoline. This is a second challenge in engine operation and control in

that to obtain the same power output of the engine, additional fuel must be added when ethanol is blended in the fuel.

We can examine the impact of combustion stoichiometry and energy further if we consider the operation and control of a spark-ignition (SI) engine. Nearly all SI engines in production for on-highway transportation in the US and the majority of similar engines around the world need to operate within a narrow,  $\pm 0.5\%$ , range of the chemically ideal stoichiometric ratio of fuel-to-air. This close regulation of the fuel-to-air ratio is necessary in order for three-way catalysts to have high simultaneous conversion efficiencies of the three primary regulated emissions: carbon monoxide, unburned hydrocarbon, and nitric oxides [50] and therefore meet governmental mandated emissions [51]. As air is typically metered and measured in an SI engine and the control system estimates and controls the fuel metering to get to this precise stoichiometric mixture, the system must compensate for these differences in fuel. For most of the operation time there is an air-to-fuel ratio sensor<sup>1</sup> in the exhaust system that monitors the ratio of the combustion products of the mixture and provides feedback for the fuel correction. With the measured air and metered fuel controlled to the precise stoichiometric ratio, the control system can determine the fuel-to-air ratio and from this estimate the percentage of ethanol in the fuel. In case for most SI engines, the air flow is controlling and limiting the power output of the engine and thus the energy of a stoichiometric mixture per unit of air is the correct property to compare the expected change in power output of the engine with changes in fuel. This is the third property in group II in Table 1 and as can be seen, the energy on this basis is nearly equal between the fuels with ethanol only being 1% less than that of gasoline. This indicates that the typical SI engine which is limited by the air induction system produced nearly the same power whether run on gasoline or ethanol/gasoline mixtures. However, the fuel system will have to deliver more ethanol on a volume or mass basis as discussed previously. This is typically achieved by using higher flow injectors in flex-fuel vehicles.

There is one key period however when the air-to-fuel ratio sensor is not active. This is during the start of the engine and for the first few seconds of operation. This period is also key to achieving low unburned hydrocarbon (HC) emissions. As much as 90% of the cycle HC emissions come during this period when closed-looped fuel control is not active and the catalyst has not warmed up sufficiently for conversion of the HCs emitted from the engine. The other challenge during this period is proper mixture preparation of the fuel-air for ignition at the spark plug and complete combustion. During this period the engine is much cooler than during normal operation so it is more difficult in general to vaporize sufficient fuel to get to the required mixture ratio of fuel-to-air. Properties of the fuel important for this are

<sup>1</sup> This sensor is sometimes referred to as an oxygen sensor, but this is an incorrect characterization as it measures the combustion products and determines if the gases are rich (too much fuel) or lean (too little fuel) of the ideal (stoichiometric condition).

listed in group III. The energy to vaporize the fuel (latent heat of vaporization) on a per mass and per unit of stoichiometric mixture are listed. As shown in the table, the energy to vaporize the stoichiometric amount of ethanol is 289% greater than that for gasoline. In addition, the volatility of ethanol is significantly lower than gasoline as shown by the higher boiling point of ethanol at 78°C compared to the distillation range of gasoline, 25-215°C and the significantly lower vapor pressure. The combination of higher energy required to vaporized ethanol, lower volatility and no available closed-loop-control during starting and initial operation provide one of the most challenging engineering problems in application of ethanol and achieving low emissions. This is one of the primary reasons the ethanol concentration is limited in flex-fuel and that different blends are required for winter and summer [49]. The issue of clean starts is further exaggerated for hybrid vehicles which undergo numerous start-stop-start cycles during driving.

The final group, group IV, in Table 1 lists the octane number and laminar flame speed, properties of the fuel which directly impact combustion. The lower the octane number the higher the fuels propensity to abnormal autoignition causing combustion knock which is detrimental to engine performance and can readily cause engine damage if left uncontrolled. As can be seen in this table, ethanol has a higher octane rating (98 PON) than even premium gasoline (93 PON). Combustion knock is the primary limiter to the compression ratio in an SI engine. A higher octane enables an engine to operate at a higher compression ratio without combustion knock, which enables higher efficiencies. However, because current flex-fuel engines must operate with both low octane regular gasoline and high octane ethanol mixtures the compression ratio is limited by the gasoline operation. Methods exist for closed-looped control of combustion knock [52] and some advantage can be made of the higher octane fuels, but not to their full extent. Methods to change the compression ratio have been proposed [53, 54, and 55], but as of yet none have been adopted to production applications. Further advancements in combustion knock detection and control along with further development of technologies including variable compression ratio would enable flex-fuel SI engines to continuously tune themselves to the operation conditions that maximize the fuels potential.

The second property in group IV and the last property in Table 1 is the laminar flame speed. SI engines operate under a turbulent combustion regime and often operate with high residuals of combusted gases. The laminar flame speed is however an indicator of higher combustion rates and higher tolerances to residuals. Changes to these mean that the engine tuning and control for combustion phasing and systems with variable valve phasing capability can be operated with different calibrations and improve performance including efficiencies.

As stated in the discussion above, fuel plays a key role in the operation, tuning and control of an IC engine. An engine that is to operate on a range of fuels including SI ethanol flex-fuel, needs to continually adapt to the fuel in

order operate robustly with high efficiency and low emissions. The research listed below discusses some of the work ongoing in the W2W program at Michigan Tech to address the issues and maximize the potential of biofuels.

The focus of the engine and vehicle programs within the Michigan Tech W2W program is to investigate and compare engine and aftertreatment operation on biofuel-petroleum based fuel mixtures and examine opportunities for improved performance and reduced emissions. These activities lie both within the W2W program and under the *Advanced Power Systems Research Center* [24] at the university. The goal of these research programs is not only to improve the application of alternative fuels in advanced powertrains, but to provide education to the work force of engineers required to continue the research and development in these areas. To enable these objectives, a wide set of programs, laboratories, and capabilities have been established including the four engine test-beds as listed in Table 2. These multi-fuel capable engines include two single cylinder spark-ignition (SI) engines and two diesel compression ignition (CI) engines.

The first spark-ignition engine is a modified Cooperative Fuels Research (CFR) engine [25] that has been setup for the study of gaseous fuels including hydrogen and syngas, and liquid fuels including mixtures

Table 2. Engine Test Beds at MTU

Engine	Modified CFR	Hydra	Automotive Diesel	Heavy Duty Diesel
Combustion Type	Single-Cylinder Variable CR PFI SI	Single-Cylinder DI-SI	HPCR Turbo-Charged Cooled EGR DI diesel	HPCR Turbo-Charged Cooled EGR DI diesel
Fuels	Gaseous and Liquid	Gasoline and Alcohols	Diesel & biodiesels	Diesel & biodiesel

of the alcohols and gasoline. Modifications include changes to increase the compression-ratio range to 4.5:1 to 17.5:1, external exhaust gas recirculation (EGR), fuel system, ignition system, and development of electronic engine control and monitoring using a target-based rapid-prototyping system [26]. The fuel system includes dual port-fuel-injectors (PFI) for operation on gaseous and liquid fuels independently or simultaneously. A number of studies have been completed and reported for hydrogen [27-30] and testing and results are being published for gasoline-ethanol mixtures [31]. In addition to the work already published for ethanol, analysis of the effect of ethanol concentration at levels of 0, 20, 40, 60, 85% on combustion rates, efficiencies, knock limits, and emissions over the expanded compression ratio range with varying EGR levels is underway. These results include those as shown in Figure 4 of combustion rates based upon mass fraction burn (MFB) profiles [31] for the various ethanol blends. This result is shown for a compression ratio of 8:1 and at engine load of 330 kPa

net Indicated Mean Effective Pressure (NIMEP) with results for other compression ratios to 16:1 having been analyzed. The MFB profiles shown in Figure 4 show the non-linear effect that the ethanol concentration has on the burn rate. The largest difference in the burn rates occur between gasoline (UGT 91) and E20 (20% ethanol), with the changes between the burn rates decreasing as the ethanol concentration increases. Similar non-linearities have been found for other aspects of ethanol concentration including knock limits. These results show some of the challenges that occur when developing an engine and tuning its performance for flex-fuel operation where the engine must operate over a range of biofuel concentrations.

The second SI engine in Table 2 is a high pressure direct-injection (DI) single cylinder research engine based upon a Ricardo Hydra block [32]. The head and combustion chamber has been designed from GM's advanced DI SI combustion systems and includes independent cam phasing for the intake and exhaust [33]. A CAD drawing of the head showing the intake and exhaust cam phasers is show in Figure 5, and the engine installation at an earlier stage is shown in Figure 6. Research with this engine is focused on combustion optimization and crank-start hydrocarbon emissions reduction which is a significant problem with high ethanol concentrations because of ethanol's high heat of

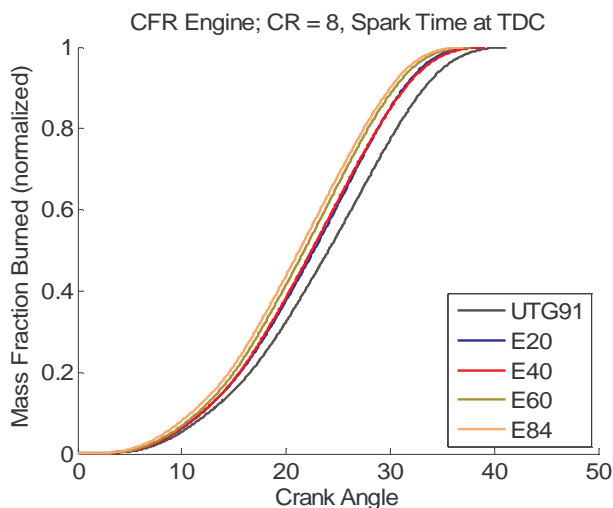


Figure 4: MFB profiles for ethanol-gasoline blends at a compression ratio of 8:1 and a NIMEP 330 kPa .

vaporization and low vapor pressure. A specially designed fast sampling probe shown in Figure 7 with a sample duration of less than 1 ms will be used in conjunction with a five-gas exhaust emissions analyzer and a V&F mass spectrometer [34].

The third and fourth engines are diesel engines for examination of biodiesel and biodiesel blends on combustion, emissions and aftertreatment operation. The third engine is a 1.9 L turbocharged high-pressure common-rail engine with EGR for which electronic control and monitoring using the target based rapid prototyping control system has been developed [35]. Research on this engine is focused not only on

characterizing the combustion and emissions differences with the biodiesel mixtures but in developing direct combustion feedback control for adaptive and closed-loop operation on multi-fuels with varying cetane and other characteristics [36]. The fourth engine is an 11 L Cummins ISM engine that has been used in diesel aftertreatment characterization and modeling [see for example 37 & 38]. This engine is mounted on a dual ended dynamometer and a second 5.9L Cummins ISB engine is placed on the other end which has also used for diesel aftertreatment characterization [39]. New activities on determining the impact biodiesel blends have on the aftertreatment systems will be done after the current phase of testing is completed.

Combined, these laboratories provide a wide range of capability to develop research and educational activities within the W2W program. Further expansion is underway to study in-cylinder combustion details, gasification, and in developing a dedicated IC engine instructional laboratory. Through collaboration with the other thrusts in the program, we can examine detailed impacts of these forest based biofuels from their source to final application.

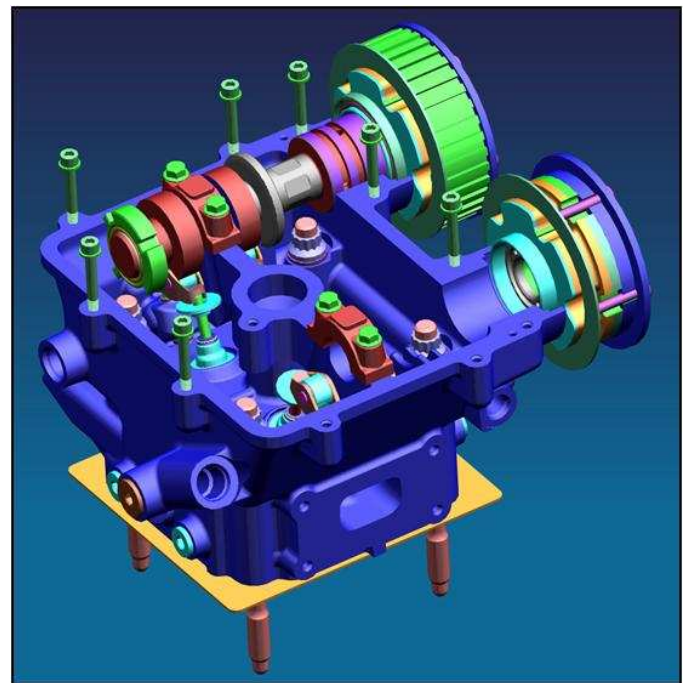


Figure 5: Modified cylinder head for hydra DI-SI engine with independent intake and exhaust cam phasing.

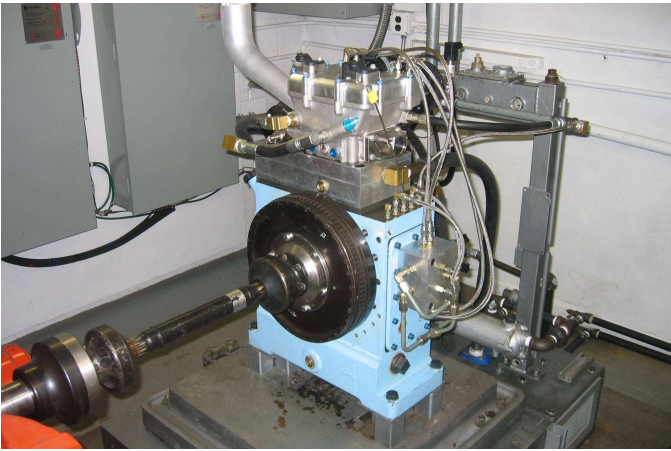


Figure 6: Hydra DI-SI engine installation for combustion and emissions studies with ethanol-gasoline mixtures.

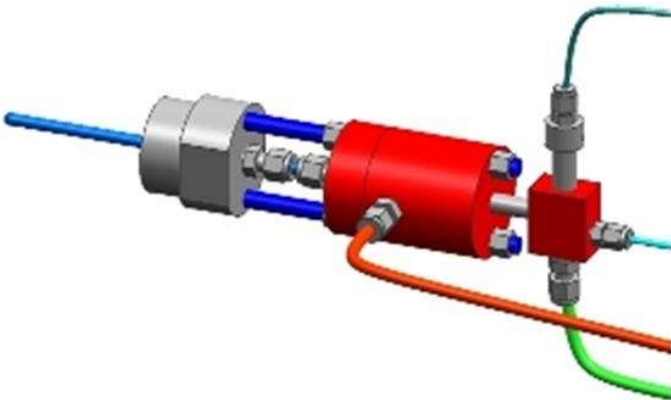


Figure 7: Fast response, direct emissions sampling probe with integrated dilution for characterizing unburned hydrocarbon emissions during crank-starts.

#### SUSTAINABLE DECISIONS – *Supply Chain Logistics:*

The proposition of displacing petroleum through biofuels derived from forest-based biomass resources has tremendous appeal. To seize on the opportunity to use forest biomass in a manner that is economically viable, environmentally sound, and acceptable to society requires that careful consideration be given to all stages of the supply system or “value chain”.

In considering the environmentally, economically, and societally sustainable use of forest resources for the creation of biofuels, a variety of factors must be considered. These factors include harvesting, transportation, storage, facility location, as well as impacts on the communities where the production facilities might be located. Fundamentally, all of these factors should be simultaneously considered, in an integrated manner, to select technologies and make decisions that are the best from a life-cycle sustainability perspective. The extraction of forest resources, pre-processing, storage, and movement to a processing facility are critical steps in the conversion of biomass to liquid fuels. These steps often have significant costs and do not add value to the biomass. Thus, the decisions associated with these steps require careful consideration.

Harvesting and collection of forest resources, namely industrial wood, are done in typically two ways; whole tree and cut-to-length methods. In order to successfully collect the subsequent fuelwood, which includes forest residues, an integrated approach within these harvesting methods is widely considered to be the most cost effective. Several studies [40-42] have concluded that integrated one- and two-pass methods as part of normal logging operations achieve better results over collection of the unmerchantable wood (fuelwood) separately.

Once harvested, forest residues are mustered (collected) to a central landing at the field site where they are either loaded for transport or densified before transport. Forest residues or biomass have moisture contents around 55 percent and are not desirable from a transportation standpoint. Densification techniques such as comminution and drying have been discussed as a means to increase the mass of cellulosic material that can be transported per load. The most predominant comminution method is roadside chipping, where the material at the landing or roadside location is ground or chipped before loading into chip vans. Another method that is receiving increased interest is bundling. The forest residues are compressed and tied into composite residue logs (CRLs) and can be transported to the roadside using a conventional forwarder and on to the terminal or processing facility using a conventional timber truck.

Transportation seems to be the weak link in the logistics chain for forest residues. Because the material is almost half water and the trucks return from the processing facility empty, the costs are substantial. Further limiting factors are that only two types of trailers exist currently, the logging trailer and panel (chip) van. Therefore it presupposes that all residues will be either ground or chipped or bundled in order to improve densification and increase the mass per load.

At some point during the movement of biomass from the field site to a processing facility it is likely that the biomass will be stored. The need to store forest resources is driven by such issues as: the need to keep a processing facility running year-round, seasonal availability of biomass, processing facility size, and transportation constraints. Balancing these supply and demand issues can be eased by using centralized or decentralized storage sites (log yards) [43].

Finally, size and location of the processing facility is driven both by cost (mainly transportation) and the availability of the forest resources. Though abundant in many parts of the U.S. as already described, yield per acre and total harvestable land play a critical role in deciding how big the processing facility will be and where it will be located in addition to factors such as available infrastructure and community concerns. Ultimately, the choices made at each step should be jointly determined, since the decision at one step can influence the performance at other steps; thus, the supply chain must be established in an integrated manner [44].

*Environmental Life-Cycle Assessment.* Several studies have been completed in W2W to assess environmental impacts of bio-fuel and bioenergy life cycle chain, including the projects “Evaluation of Low Greenhouse Gas Bio-Based Energy Technologies”, “Life Cycle Assessment Comparing Green Diesel to Biodiesel”, “Life Cycle Inventory of Energy and Greenhouse Gases for Woody Biomass Production: A Comparison of Regional Feedstocks”, and “A Review of Life Cycle Assessment Studies on Renewable Energy Derived from Forest Resources.”

In recent years, numerous life cycle assessment case studies and several review studies have been conducted on biomass renewable energy. For example, the study of von Blottnitz and Curran [45] analyzed 47 studies on bio-ethanol for use as a transportation fuel compared with traditional fuels on a life cycle basis. However, most work has focused on agricultural biomass resources and limited environmental impact categories such as energy and greenhouse gases assessment. This project reviews a large number of LCA case studies on renewable energy primarily from forest resources. The results of this project were compiled to become a chapter of the book titled “Renewable Energy From Forest Resources in the United States.” In the chapter, the feedstocks, conversion processes, end products, system boundaries, allocation methods, impact metrics of those studies, and findings and conclusions drawn from those studies were summarized. Consensus and disagreement from these studies and gaps in methodologies and impact categories were discussed, and recommendations for LCA in general and cellulosic bioenergy in particular were provided. It was found that life cycle fossil energy demand and GHG emissions were significantly lower for bioenergy compared with conventional alternatives [46]. However, other impacts such as acidification and eutrophication generally favor fossil fuel counterparts. For future cellulosic bioenergy LCA studies, in addition to acidification and eutrophication, soil erosion and impact on the land and water supply, human toxicity, ecotoxicity and effects of land use change should be examined in detail to fill the knowledge gap in those impact categories.

## CONCLUSION

With the establishment of the W2W initiative, MTU has created a broad-based university-wide research program that will be beneficial to the development and improvement of technologies for growing, harvesting, converting, and using woody biomass in renewable transportation fuel applications. By bridging the entire biomass development-production-consumption life cycle of biomass-ethanol research with an interdisciplinary focus, the W2W research is on not only forest resources, bioprocessing, engine/vehicle systems, and sustainable decisions; but on the importance of the interdependence between each of these areas.

This research could lead to industrial process efficiency improvements and decrease the minimum ethanol

selling price (MESP) [56] to make cellulosic ethanol more competitive in the market with both corn ethanol and petroleum. Minimum ethanol selling price has been defined as “the ethanol sales price required for a zero net present value for the project when the cash flows are discounted at 10% real-after tax [56].” According to a study completed by Eggeman et al., the dilute acid pretreatment stage of bioprocessing accounts for approximately 12% of the capital costs of a biorefinery which is a large portion; especially considering that this process is not needed for ethanol made from corn or sugarcane. A sensitivity analysis showed overall yields from both five and six carbon sugars to have a considerable effect on MESP [56]. The hydrolysis of these sugars greatly depends on the optimal pretreatment conditions. Analysis of alternate pretreatment methods gave similar results [56]. In the Eggeman et al. study, the total fixed capital for dilute acid pretreatment of corn stover was determined to be \$3.72/gal annual capacity, whereas for corn using the dry milling technique, it was \$1.00-\$1.50/gal annual capacity [56]. Improvements from feedstock selling price through bioprocessing will be necessary for cellulosic ethanol; and forest resources, bioprocessing, and sustainable decisions research integrated through W2W has the potential to lead to recommendations that could create significant reductions in capital cost. Finally, the incorporation of vehicles and engines research in addition to those previously mentioned, closes the gap between industries and allows for faster, more efficient technology transfer. With gas prices surpassing \$4/gallon and federal policies such as the Energy Independence and Security Act of 2007 setting minimum requirements (0.1 billion gallons) for cellulosic biofuels beginning in 2010 [57], research such as that being completed through W2W is crucial in order to produce economically competitive fuels from cellulosic biomass.

A new initiative was established in 2007 between Michigan Technological University and Michigan State University to identify high priority research topics and to move forest-based biofuel discoveries into the market. A stakeholder summit was convened February 25, 2008 in Escanaba, MI representing local and state government, industry, academia, and non-governmental organizations, to discuss research needs over the entire W2W value chain. Five key research needs were identified to establish a successful forest-based bioeconomy in Michigan: (full report - - drshonna@mtu.edu)

1. Complete a comprehensive **inventory** of forest-associated woody biomass feedstocks.
2. Establish **sustainability guidelines** for the management and use of forest-associated woody biomass.
3. Aggressively expand **technology and information transfer**.
4. Develop a **supply chain model** to be used to understand the economic effects of technological innovation.
5. Continue W2W **technological innovation**.

The automobile industry, in collaboration with other industry partners from the W2W value chain, will play an important role in the realization of a forest-based bio-economy by supporting fundamental and applied research over the entire W2W value chain.

## ACKNOWLEDGMENTS

Support of the Wood-to-Wheels project is being provided by the National Science Foundation through the IGERT (DGE-0333401) and MUSES (BES-0524872) programs, by General Motors, and UOP LLC-Honeywell. Dr. Heather Youngs is conducting the epimerases research.

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