An Assessment of the Potential for Bioenergy and Biochemicals Production from Forest-Derived Biomass in Minnesota

A Report for the Blandin Foundation Vital Forests/Vital Communities Initiative and Iron Range Resources

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Table of Contents[1]

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Executive Summary

After decades of debate about how long the age of petroleum abundance might last, it now appears that the year of peak petroleum production worldwide may be in sight. With the peak now likely to occur within one to three decades, complacency is beginning to be replaced by a sense of urgency.

Potential petroleum demand/supply imbalances pose a significant challenge for the people and economies of all regions, but particularly those regions such as Minnesota and the Lake States that do not have petroleum or other fossil fuel reserves. On the other hand, regions rich in biomass such as Minnesota and the Lake States may have a substantial opportunity going forward to ensure future energy supplies while enhancing economic growth.

Current technology provides a number of options for conversion of biomass and other biomaterials to energy. The options available include direct firing for electrical generation, production of ethanol and bio-diesel, and use as a fuel in steam generation for either large-scale district heating or for powering manufacturing operations.

Transportation fuels (gasoline, diesel, jet fuel) account for the greatest quantity of energy consumed in Minnesota, followed by coal and natural gas used primarily for electrical generation and home heating. Annual energy expenditures exceed $16 billion.

In 2005 renewables accounted for about 86 trillion Btu of Minnesota's energy production, or about 7.1 percent of total energy consumption and in 2006 renewable energy production included about 11 percent of electricity, 10 percent of gasoline, and 2 percent of diesel. The state currently ranks 4th in production of wind energy, 4th in production of ethanol, and 8th in production of biodiesel.

It is clear that there is considerable potential for generating electricity from agricultural and forest biomass in Minnesota given the right economic conditions. There is also substantial potential for increasing liquid fuels production from biomass, with the caveat that the technology needed to bring about that payoff is as yet unproven from a commercial standpoint. Production of industrial chemicals from biomass offers another great yet-untapped opportunity for Minnesota. The vast majority of industrial chemicals and feedstocks for production of products ranging from plastics and butyl rubber to synthetic fibers and pharmaceuticals are derived from petroleum. As petroleum becomes more expensive, and perhaps less available, the need for new supplies of a wide range of chemicals will arise; the technology for producing many such chemicals from biomass now exists, or is in various stages of development. The stage is set for the emergence of biorefineries, capable of producing energy, chemical, and fiber products from wood and other forms of biomass.

The majority of renewable energy produced in Minnesota comes from biomass – ethanol from corn starch, biodiesel from soybeans; heat from burning of firewood; and electricity and heat from spent pulping liquor and waste wood. In 2005 these sources of energy provided about 6 percent of the total non-transportation energy consumed in the state and about 15 percent of all industrial energy consumed.

While corn is today by far the leading raw material for bioenergy production in Minnesota, emerging technology is likely to expand bio-fuels options to include energy crops such as switchgrass, agricultural crop residues, and broader applications of forest-biomass. Such materials will also become important as a source of industrial chemicals and industrial feedstocks.

Increasing importance of biomass as a source of energy and chemicals translates to substantial opportunity for Minnesota's farm economy, as well as potential for revitalization of the State's forestry and wood products sector. Farm income, long a point of concern, is currently benefiting from bioenergy development, and the forest products industry stands to realize gains from expanded product options, diversification, and increased profit potential.

In 2006 Minnesotans consumed an estimated 2.7 billion gallons of gasoline and additional fossil fuels such as aviation and diesel fuels. All of the petroleum from which this was produced was imported.

In 2006, Minnesota produced over 550 million gallons of ethanol, of which an estimated 287 million gallons were exported to other states. The economic impact of ethanol production within Minnesota is estimated at $1.72 billion annually, including 6,400 jobs, with much of this impact in rural areas. Recently enacted legislation sets a target within Minnesota for a 20 percent ethanol blend in all gasoline sold in Minnesota in 2010 and beyond. Meeting that target will require 574 million gallons of ethanol just to meet state consumption requirements. Using current technology and corn starch as a raw material, the 20 percent ethanol-lend requirement is expected to require the use of some 230 million bushels of corn, or assuming level production, about one-quarter of Minnesota's corn crop.

It is likely that wood will soon gain the attention of biodiesel producers, both within Minnesota and nationally. As an example, the Finnish-based paper manufacturer UPM-Kymmene, a corporation that operates a large mill in Grand Rapids, Minnesota, announced in October 2006 that it will "invest strongly" in second generation biodiesel production, using wood-based biomass as raw material, saying that it aims to become a major producer. UPM Chief Executive Jussi Pesonen was quoted as saying "If on a global scale (the biodiesel business) grows into the billions (of euros), then to begin with UPM's share would be in the hundreds of millions, and then even expanding into the billions" (Associated Press 2006). The company expects to make a decision on investing in the first commercial biodiesel production plant within the next few years.

The greatest likelihood of profitable biorefinery development based on woody biomass is in conjunction with pulp and paper operations. Minnesota, therefore, as a significant producer of paper is in a reasonably good position to capitalize on the biorefinery/bioenergy/biochemicals potential. Minnesota's proximity to the number-one paper producer, Wisconsin, is probably also a positive factor as it increases the likelihood of economies of developing critical mass. Also a favorable factor for wood-based biorefinery development is the presence in the region of leading agri-business companies and cooperatives that are currently leading the way in ethanol and biodiesel development.

Political leaders of many states, including Wisconsin and Michigan, and at least four other states, have publicly stated objectives of becoming the national leader in biochemicals development. Obviously, only one will succeed. Success will likely require an aggressive program of strategic planning and research, investment, collaboration with established energy and industrial chemical producers, and perhaps serendipity. Success may also require incentives in some form to encourage or jumpstart a fledgling industry.

What success will look like is not as yet clear, but one model would be a network of biorefineries across the landscape, coupled with a number of secondary manufacturers of chemical products including bio-plastics, lubricants, medicinal products, synthetic fibers, and so on. Ideally these new industries would generate significant local employment, taxes, and enhancement of quality of life (socially, environmentally, and economically), and would be sustainable over the long term.

Minnesota has several characteristics that support the state's potential to contribute to biomass energy developments. Minnesota's available biomass resources, biomass harvesting standards, and existing forest industry capacities all offer the state a strong starting position. However, the challenges and opportunities associated with biomass energy are larger than any single industry or state interests. For Minnesota to maximize its contribution to the emerging bio-economy and to maximize the benefits to the state's citizens and economy, our actions and strategies need to consider efforts by other public and private interests within and beyond Northern Minnesota.

As Minnesota considers how it might more extensively use its forest resources to increase its participation in the emerging bio-revolution, it is important that decision leaders understand fully what is potentially involved. The prospects for improved energy security, expanded economic activity, and new employment prospects are exciting. Careful thought and planning is needed to ensure that development is not haphazard and that development outcomes mesh with other state values and goals. Whatever is done, it is vitally important that efforts to bolster supplies of one critically important resource – energy – not result in depletion of other critically important resources – soil and clean water.

Introduction

One hundred fifty years ago more than 90 percent of U.S. energy and fuel needs were supplied by biomass. Subsequently, energy supplies in the U.S. and much of the rest of the world have been dominated by fossil fuels – petroleum, natural gas, and coal. Today, biomass supplies just 3 percent of U.S. energy consumption.

The principal fuel in the world today is petroleum, a substance that was largely unknown until the late 1850s when commercial production began more or less simultaneously in Romania and Canada, and several years later in the United States. By the early 1900s oil and the natural gas that often accompanied it in underground deposits were principal energy sources for the U.S. and other developed nations. Consumption was spurred by discoveries of major deposits in Iran in 1908, Iraq in 1927, and Saudi Arabia in 1938. In addition to serving as a source of energy, petroleum also increasingly served as a source of industrial chemicals and consumer goods such as plastics, synthetic fibers, and lubricants.

By the mid-1900s, however, there were already signs of possible supply problems. For example, in 1959, exactly 100 years after the first oil well began production in the U.S., domestic petroleum reserves peaked. Eleven years later, in 1970, U.S. petroleum production peaked, beginning a decline that continues today. Now there are indications that global production of petroleum may peak within the foreseeable future, creating an urgent need for development of alternative forms of energy. Appropriately, a shift back toward biomass as a significant source of energy and industrial chemicals now appears to be underway.

Potential petroleum demand/supply imbalances pose a significant challenge for the people and economies of all regions, but particularly those regions such as Minnesota and the Lake States that do not have petroleum or other fossil fuel reserves. On the other hand, regions rich in biomass such as Minnesota and the Lake States may have a substantial opportunity going forward to ensure future energy supplies while enhancing economic growth.

Current Energy Trends

Changes in Regional, National and Global Energy Markets

Petroleum Outlook Changing

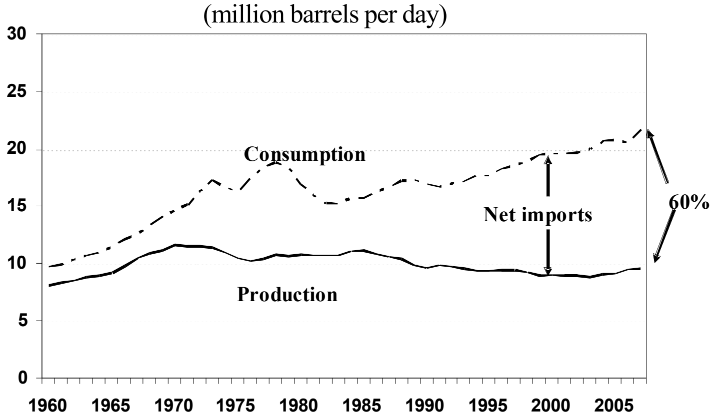
After decades of debate about how long the age of petroleum abundance might last, it now appears that the year of peak petroleum production worldwide may be in sight. With the peak now likely to occur within one to three decades, complacency is beginning to be replaced by a sense of urgency.

In the early 1970s a reduction of petroleum production and an embargo on energy shipments to the U.S. and other nations by a number of Arab nations created energy supply problems and chaos in world economies. Marked price increases by principal oil-exporting nations again caused economic problems only several years later.

Within the U.S. these developments helped to spur domestic energy conservation programs, development of nuclear energy, and the initiation of alternative energy research on a broad scale. Unfortunately, the obvious political maneuverings that led to the 1970s oil shortages also led to a widely held public view that shortages were not real, but only manufactured by governments and multinational corporations motivated by greed. After only a few years, interest in energy conservation and alternative energy research waned and robust growth of U.S. petroleum consumption resumed. The U.S. petroleum import reliance, which was 29 percent at the time of the oil embargo, has now grown to 60 percent (Figure 1). Growth in net imports combined with recent price increases have significantly impacted the U.S. trade deficit, with a large and growing imbalance (Figure 2).

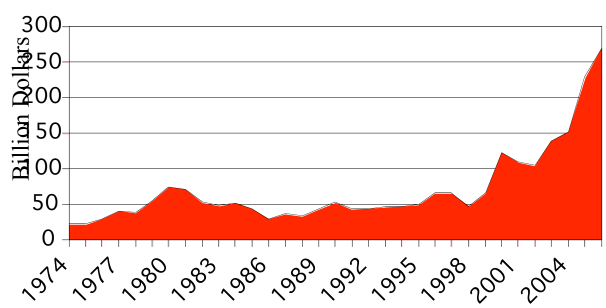
Numerous projections of petroleum reserves and depletion dates over the several decades following the 1970s oil shocks were mostly discounted by business and government leaders and by the general public.

Figure 1
U.S. Petroleum Supply, Consumption, and Imports, 1970-2007
(million barrels per day)



Source: EIA Annual Energy Outlook, 2007.

Figure 2
U.S. Trade Deficit, Energy Products, 1974 – 2006



Source: Energy Information Administration, 2007.

So too were rather sobering projections offered in the 1990s by several highly credible research organizations (Table 1). For example, the International Energy Agency forecast that peak production would occur sometime between 2010 and 2020. Dr. Jonathan Edwards of the Colorado School of Mines, put the peak globally at 2020. However, what began to draw the attention of doubters was a year 2000 study by the U.S. Geological Survey, done at the request of the U.S. Department of Energy. This was the most comprehensive petroleum forecast undertaken, and involved assessments of known reserves, estimation of original and remaining stocks, and predictions of future expansion of reserves resulting from discovery of new oil fields and new technology development (EIA, 2000). Using 2% annual growth in global consumption as the most likely scenario, the USGS study concluded that peak production would likely occur in 2037. It was the first time that an entity of the U.S. government had predicted that peak production would be reached within the relatively near term.

Table 1
Consensus is Emerging that Peak Petroleum Production in in Sight

International Energy Agency	2010-2020
World Resources Institute	2007-2014
J. Edwards, Colo. School of Mines	2020
U.S. Department of Energy	2037

Source: Kerr, R. 1998. The Next Oil Crisis Looms Large – and Perhaps Close. Science 281 (August 21), pp. 1128 -1131 .

Several forecasts in mid-2007 have accentuated the USGS findings. On July 10 the International Energy Agency (IEA) forecast increasing difficulty in supplying the rising demand for petroleum. While stopping short of revising its peak oil forecast of 2010-2020, the organization pegged 2012-2013 as a point at which rising demand may exceed the ability of producers to increase supply accordingly. The IEA also projected tight natural gas supplies going forward, limiting the ability of consumers to switch from oil to natural gas (Bahree 2007a). Less than a week later the U.S. petroleum industry, in a report commissioned by the Secretary of Energy, acknowledged the likelihood of supply constraints, indicating that oil and natural gas production is unlikely to keep pace with rising consumption over the next 25 years (National Petroleum Council 2007, Bahree 2007b).

Part of the reason for growing pessimism about longevity of petroleum supplies can be traced to the rapid emergence of China as an economic power. A net importer of fewer than 10,000 barrels of oil daily in 1970, China had net imports more than 200 times that by 2004. By 2025 China's daily net imports will approximate current U.S. net imports – more than 13 million barrels daily (Table 2). Increasing oil consumption is not, of course, limited to China; other growing economies, including those of India and other Asian nations, are exerting pressure on world oil supplies. India alone is expected to double its petroleum imports by 2030, from 2.6 million barrels daily at present to over 5 million barrels.

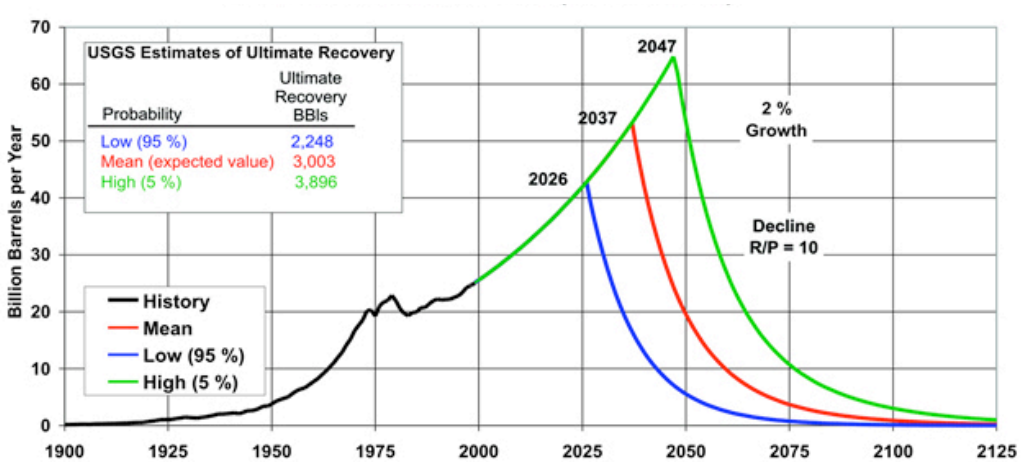
Table 2
China Petroleum Imports, 1990 -2030

Year	Average Daily Imports (barrels/day)
1990	net exporter
1995	240,000
2000	1,520,000
2006	3,600,000
2030 (est.)	10,900,000

Source: Energy Information Administration, 2006b and Congressional Budget Office, 2006.

As part of the USGS study, scenarios were developed regarding depletion of supply following peak production. That shown in Figure 3 is based on a rate of decline such that the reserve to annual production ratio remains constant at 10. All scenarios show a steep reduction as increasing consumption collides with a declining supply, suggesting chaotic conditions in world markets absent the development of energy alternatives.

Figure 3
Annual Production Scenarios with 2 Percent Demand Growth Rates and Different Resource Levels (Decline Reserves/Production=10)



Source: EIA 2000.

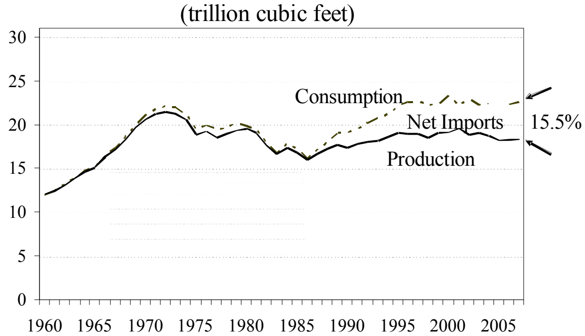
Outlook for Natural Gas Supplies Generally Positive, but Cloudy

In recent years as petroleum supplies have tightened, and as concerns about coal combustion-related environmental impacts have increased, the industrial sector in the U.S., including the commercial energy industry, has made a significant shift toward use of natural gas. At the same time, increases in population and a robust housing industry have translated to growing demand for natural gas for residential use.

The net effect has been the end of a long-standing natural gas demand/supply balance that existed in the United States through the late 1980s, and a growing import dependence since then. Currently about 16 percent of U.S. natural gas consumption is provided by imports, with an increase to 21 percent likely by 2030 (Figure 4). Through about 2020 the use of natural gas for electricity generation is expected to increase as a percentage of all forms of energy consumed for that purpose. Thereafter, the rate of increase in natural gas consumption is expected to slow (EIA Annual Energy Outlook 2007a).

As of January 1, 2007 world natural gas reserves were estimated at 6,183 trillion cubic feet, yielding a world natural gas reserves-to-production ratio of 65 years, a number that has changed little from a decade ago. In addition, the mean estimate for worldwide undiscovered natural gas is 4,136 trillion cubic feet, roughly double the world cumulative consumption forecast through 2025 (EIA Annual Energy Outlook 2007a). The bottom line is that global natural gas reserves are viewed by many experts as adequate for the foreseeable future, even given rapidly rising consumption. However, some, including the IEA, are beginning to question whether it will be possible to continue to increase production at a rate sufficient to keep pace with the rate of increase in consumption. The possibility that insufficiency of petroleum supplies may accentuate demand for natural gas clouds the future outlook.

Figure 4
U.S. Natural Gas Production, Consumption, and Net Imports, 1960-2007
(trillion cubic feet)



Source: EIA, Annual Energy Review 2006 (2007).

Coal Abundant but Greenhouse Gas Issues Raise Concerns

Coal accounted for 26 percent of total world energy consumption in 2006, with two-thirds of coal consumption used in production of electricity and most of the remainder used by industrial consumers. Only 4 percent of world coal consumption was attributable to the residential and commercial sectors.

Although coal consumption globally is expected to rise substantially in the decades ahead – from 6,512 million short tons in 2006 to 8,226 million short tons in 2025 - the relative share of global energy production that is provided by coal is expected to rise only slightly – to 28 percent by 2030. Total recoverable reserves globally are estimated at 998 billion tons, a supply sufficient to supply the current level of consumption for about 164 years. In the United States coal provides 49.6 percent of total energy generated. The U.S. has more coal reserves than any other country (27 percent of the world total), with recoverable reserves sufficient to meet the current level of consumption for over 240 years (EIA International Energy Outlook 2007f).

With increasing discussion about the possibility of gasifying coal and/or converting coal to liquid fuels and other products it is worth noting that the projected longevity of coal supplies are based on *current rates of use*. Actions that serve to markedly increase rates of consumption will also markedly reduce the projected supply period.

One factor that is likely to limit coal development in North America is growing concern about CO_2 emissions. Should discussions about carbon emissions reduction translate into an action plan, there are likely to be financial and other disincentives for use of all fossil fuels, but perhaps especially coal, since coal combustion emits almost twice as much carbon dioxide per unit of energy as does the combustion of natural gas, and half again more than combustion of petroleum (EIA 1993).

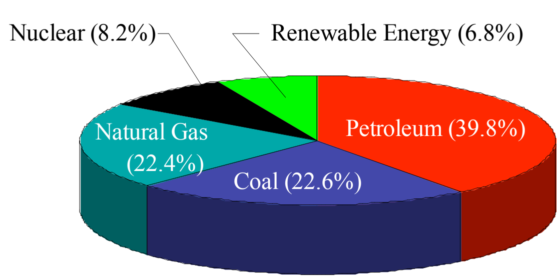
There is increasing evidence that governments across North America may act to reduce carbon dioxide emissions. For instance, although the US federal Government has not established targets for greenhouse gas emissions reduction, several states, and most notably a consortium of ten northeastern states, led by New York, established a mandatory carbon emissions stabilization and reduction program in early 2007 focused on public utilities. The net effect is immediate pressure on coal-using electric utilities to reduce emissions, pressure that is likely to reduce coal consumption in the long term, a reality that was underscored by a July 25, 2007 article in the Wall Street Journal. That article indicated that plans for a number of new coal-burning power plants are on hold largely because of concerns about carbon dioxide emissions (Smith 2007).

Renewable Energy

Today, biomass provides about 15 percent of energy globally, with biomass energy production concentrated in the developing countries (Research Reports International 2006). A large portion of biomass energy is used for home heating and cooking, and wood provides most of this. More than one-half the global harvest of wood in 2006 was used as fuel wood (FAO 2007).

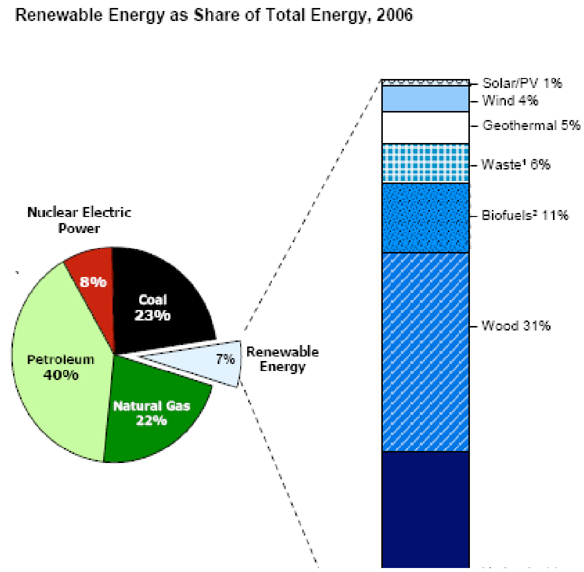
In the United States biomass currently provides less than 3% of energy needs, but almost one-half of energy from renewable energy sources (Figures 5, 6).

Figure 5
U.S. Energy Consumption by Fuel Type, 2006
(% of Btu)



Source: Perlack et al. 2005

Figure 6
The Role of Renewable Energy in U.S. Energy Supply, 2006



Source: EIA, Renewable Energy, 2007f.

Emergence of Bio-Energy Alternatives

Many Options Are Available

Current technology provides a number of options for conversion of biomass and other biomaterials to energy and these include direct firing for electrical generation, production of ethanol and bio-diesel, repackaging of biomass in the form of fuel pellets for use in home heating, and use as a fuel in steam generation for either large-scale district heating or for powering manufacturing operations.

Current interest in bio-energy is driven primarily by near and longer-term concerns vis-à-vis petroleum supplies and the impact of energy imports on the U.S. trade balance. Thus, while plant materials can be used in at least several ways to produce energy, it is the growing need to develop options for liquid transportation fuels that represents the greatest need, and not coincidentally the greatest opportunity.

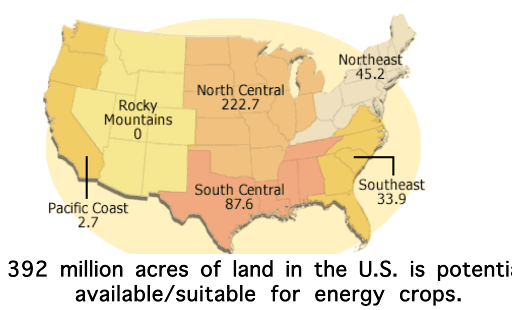
Bio-energy sources include such things as waste wood and cooking liquor from wood pulping operations, methane gas from old landfill sites or from manure collected at feedlot or dairy operations, organic materials recovered from wastewater, and municipal solid waste. The volume of manure alone, considering only the volume in excess of that which can be applied for on-farm soil improvement, is estimated at 106 million dry tons annually. In terms of volumes available, the bio-material with the greatest potential for use as an energy source is overwhelmingly biomass; a recent report suggests the annual availability of over 1.3 billion dry tons beyond that needed for food, livestock feed, fiber, and soil conservation (Perlack et al., 2005).

Biomass Alternatives

Today in the U.S., some 190 million tons of biomass is used annually for production of energy or bio-products that directly displace petroleum-based feedstocks. The potential contribution of biomass to domestic energy production is far greater than the current level. For instance, there are about 392 million acres in the continental U.S. that are not being used for food production that have the capacity of producing significant quantities of biomass without the need for irrigation (Figures 7, 8). Of these, some 55 million acres have been identified as available and having high potential for production of energy crops such as switchgrass, reed canary grass, poplar, eucalyptus, and other species.

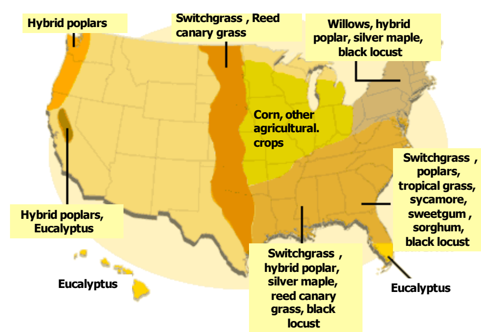
An estimated 377 million dry tons of biomass crops could be produced annually from these 55 million acres. In addition, an estimated 428 million dry tons of agricultural residues in excess of that needed for conservation tillage could be removed annually from U.S. farmland for production of bio-fuels (Perlack et al., 2005). Another 368 million dry tons of woody biomass could be sustainably removed annually from the nation's forest lands and gleaned from current waste streams; a part of the woody biomass would come from non-commercial forest thinnings conducted for the purpose of reducing wildfire danger.

Figure 7
Available Acreage for Energy Crops



(Source: Tuskan et al. 1994)

Figure 8
Geographic Suitability for Energy Crops



(Source: Tuskan et al. 1994).

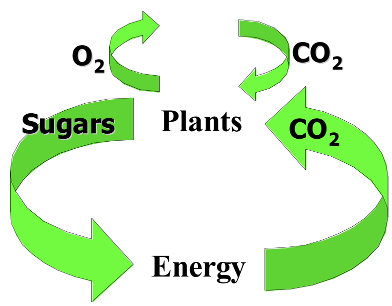
As noted by Perlack et. al. (2005), if considering only agricultural and forest land, the two largest potential biomass sources, there is potential for annual production of over 1.3 billion dry tons of biomass in the U.S., a volume more than seven times the current volume of biomass consumed for production of bio-energy and bio-based products.

Translating the potential for biomass production to the potential for production of biomass-derived energy, goals as set forth in the Perlack report indicate that by 2030 biomass will supply 5 percent of the nation's power, 20 percent of its transportation fuels, and 25 percent of its industrial chemicals and chemical feedstocks. This goal is equivalent to 30 percent of current petroleum consumption. Overall, the quantity of biomass identified as annually available in the United States is equivalent to a little over one-half of 2006 petroleum consumption.

In a more recent paper, Zerbe (2006) calculated that use of woody biomass alone could provide far more energy than is indicated in the Perlack report. Zerbe's figures show available woody biomass as capable of producing 6.7 exajoules (6.4 quads) of energy, and with increased access to forest biomass 10.5 exajoules (10 quads), or about 10 percent of U.S. energy needs.

Not only is the energy production potential from biomass substantial, but combustion of such material is close to carbon neutral (Haq, 2002). The growth of replacement crops following harvest sequesters atmospheric carbon in a quantity equivalent to that released when the harvested crop is burned; the result is that no net CO2 is produced in the cycle (Figure 9). This represents a substantial advantage over the combustion of fossil fuels.

Figure 9
Bio-Fuels Are Environmentally Attractive



No net CO_2 produced in the cycle.

Considerable potential exists for development of at least several forms of energy, and for a myriad of chemicals and chemical feedstocks currently produced from petroleum:

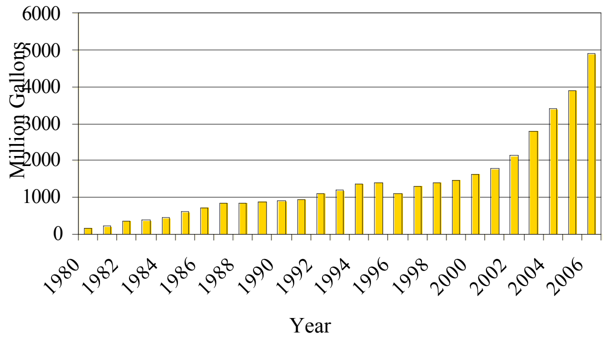
Bio-Energy Alternatives

Ethanol

In 2006, the annual production capacity of the U.S. corn ethanol industry reached about 4.9 billion gallons, continuing a pattern of accelerating growth. In June 2007 there were 119 operating plants in 26 states, and 86 plants under construction or undergoing expansion (Figure 10). The U.S. ethanol industry is currently centered in the Midwestern states (Figure 11), with Iowa, Illinois, Nebraska, Minnesota, and South Dakota the top five producers (Table 3). The vast majority of current ethanol production is based on corn starch, explaining the concentration of ethanol producers in the heart of the nation's corn-belt. The top five producing states currently account for about 75 percent of ethanol production capacity nationwide.

There is considerable room for growth of the U.S. ethanol industry. It is estimated that production from biomass could eventually reach about 50 billion gallons annually (Smith et al., 2004), a sizeable quantity when compared to current annual gasoline consumption of about 140 billion gallons (EIA, 2007c). Using current technology, production of 50 billion gallons of ethanol would require the consumption of the equivalent of approximately 30 billion gallons of gasoline, giving a net gain of some 20 billion gallons.

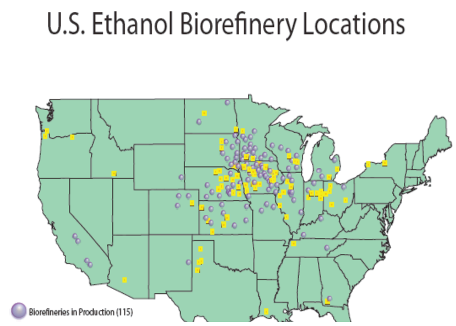
Figure 10
U.S. Ethanol Production, 1980 – 2006



Source: Renewable Fuels Association 2007a.

Although current U.S. ethanol production is almost totally based on corn starch, technology is emerging that will allow economic production of ethanol from the cellulose component of plants.[2,3] When this technology is commercialized, all forms of biomass will become potential raw materials for ethanol production. Beyond that point, future expansion of ethanol production is expected to be based on a cellulose-to-ethanol processing technology. In part this expectation is based on the view that the production of ethanol from corn is a mature technology that is unlikely to yield significant future reductions in production costs (DiPardo 2002). A larger part of the equation is the expectation that cellulose-based processes will yield more gallons of ethanol per dry ton of material produced, leading to substantial improvements in the net energy balance realized in conversion. For instance, corn-based ethanol is reported to have a net energy balance of 20,000 – 25,000 Btu/gallon whereas the balance for cellulose-derived ethanol is expected to exceed 60,000 Btu/gallon (Wang et al. 1999).

Figure 11
Geographic Location of U.S. Ethanol Production Facilities, 2006



Source: Renewable Fuels Association, 2007b.

[2] Wood ethanol technology is not new; wood ethanol was used extensively, for example, in the U.S. during World War I to fuel vehicles. What is currently holding back the commercialization of cellulosic ethanol is the cost of production.

[3] Production of cellulosic ethanol is technically feasible, but production costs are about $2.73 per gallon. As reported by Dr. Arvizu, Director of the National Renewable Energy Laboratory, a goal of reducing production costs to $1.07 by 2020 has been set, which is viewed as attainable within that time frame.

Table 3
U.S. Ethanol Production Capacity by State, June 2007

State	Annual Ethanol Production Capacity (million gal.)	Percent of U.S. Production Capacity	Capacity Currently Under Construction (million gal.)
Iowa	1861.5	29.4	1570.0
Illinois	921.0	14.5	291.0
Nebraska	729.5	11.5	731.0
Minnesota	606.6	9.6	497.5
South Dakota	582.0	9.2	328.0
Wisconsin	278.0	4.4	220.0
Indiana	252.0	4.0	556.0
Kansas	212.5	3.4	295.0
Michigan	155.0	2.4	107.0
Missouri	155.0	2.4	--
North Dakota	133.5	2.1	100.0
Colorado	85.0	1.3	40.0
California	68.0	1.1	--
Tennessee	67.0	1.1	138.0
Kentucky	35.4	0.6	--
New Mexico	30.0	0.5	--
Texas	--	--	385.0
Wyoming	5.0	0.1	--
Ohio	3.0	0.1	384.0
Georgia	0.4	--	100.0
Washington	--	--	55.0
New York	--	--	164.0
Oregon	--	--	143.0
Arizona	--	--	55.0
Louisiana	--	--	1.5
	6332.4* **	97.7*	6245.9* **

Source: State of Nebraska, 2007.

* The sum of values reported by state do not equal sum of columns.

** The Renewable Fuels Association reported production capacity nationwide as 6,444 million gallons, and total capacity under construction at 6,374 gallons as of July 23, 2007.

In accordance with values shown in Table 4, expectations are based on a near-term ethanol yield of 76-77 gallons/dry ton of hardwood biomass (such as from aspen), and a yield figure that will reach 98 gallons/dry ton by 2010 (Wang et al. 1999), and perhaps 110 gallons per dry ton in the longer term; both of these numbers are well above the 66.5 gallons per dry ton near term yield assumed for forest thinnings estimated by NREL (Mann and Bryan 2001).

Table 4
Estimated Near, Mid/Long Term, and Theoretical Ethanol Yields
from Various Forms of Biomass

Waste/Residual Biomass Resource Category	Theoretical Yield*, (gal/BDT)	Near-Term Yield**, (gal/BDT)	Mid/Long-Term Yield*** (gal/BDT)
Paper (landfill)	127.8	63	95.3
Field and Seed Crop Residues	102.0	55.1	85.5
Lumber Mill Waste	112.8	59.5	82.5
Forest Slash/Thinnings	112.8	66.5	94.8
Urban Wood Waste	108.2	45.6	66.6
Urban Yard Waste	91.8	45.6	66.6
Food Processing Waste	?	43.6	64.4
Wheat Straw	114.1	57.6	84.2
Corn Stover	113.3	57.2	83.6
Aspen	131.0	77.3	110.0
Ponderosa Pine	112.9	66.6	94.8
Poplar	111.4	65.7	93.6
Switch Grass	97.4	43.6	64.4

Source: National Renewable Energy Laboratory as reported by Mann and Bryan (2001).

* Data compiled by Quang Nguyen, NREL.

** Near-term yields are based on current NREL 2-stage dilute acid experiments and models. See Table 2.4 for yield assumptions.

*** Mid/long-term yields are based on NREL projections for performance of the Simultaneous Saccharification and CoFermentation (SSCF) (1-dilute stage acid/1-stage enzymatic hydrolysis) process. It should be noted that the U.S. Forest Products Laboratory estimates long-term potential for ethanol production from wood at 120 gallons/bone dry ton.

In addition to the data reported in Table 4, some current research indicates additional opportunities with mixed grass and native prairie systems that may have low energy and water input requirements, biodiversity benefits, and carbon sequestration potentials. Data for these types of systems are not fully developed at this time but are likely to be a continued area of research. These systems may present additional energy development opportunities for Minnesota.

While the billion-ton report cited earlier (Perlack et al 2005) clearly indicate that bio-energy is largely an opportunity for the agricultural sector, there is an important aspect of woody plants that makes them particularly attractive as a raw material for cellulosic ethanol production: the quantity of fossil fuel energy needed to deliver 1,000,000 Btu to the automobile gas tank is far lower than for the same product made from agricultural crops. Whereas a 4:1 to 5:1 gain of energy delivered vs. fossil fuel consumed is estimated in production of cellulosic ethanol from corn stover, recent estimates suggest a 100:1 gain when using wood as a raw material (Table 5).

The commercialization of cellulose-to-ethanol technologies will markedly reduce the need for fossil fuel inputs. Cellulosic ethanol production from corn will require less than 40 percent of the fossil energy now needed per unit of output. Cellulosic production from wood, on the other hand, will require only about 10,000 Btu of fossil fuel per 1,000,000 Btu delivered to the fuel tank, giving a 100:1 gain for petroleum use to fuel gain through ethanol production. Total energy required to produce cellulosic ethanol from wood are higher than for any other raw material source only because of the relatively long growth period and resulting consumption of solar energy.

Low fossil fuel requirements for ethanol production from wood are certain to stimulate interest in woody biomass on the part of policy makers. Low fossil inputs will also translate to increasing economic advantages for the landowner or fiber producer, especially if prices of fossil fuels continue to rise. Increased interest in establishment of tree plantations is also likely. In the future, conversion of existing pulp and paper mills to integrated biorefineries will be driven in part by the availability of cost effective technologies for producing cellulosic ethanol.

Table 5
Energy Required to Deliver 1,000,000 Btu to a Vehicle Fuel Tank

Fuel	Total Energy Required (Btu)	Fossil Energy Required (Btu)
Gasoline	1,241,000	1,241,000
Ethanol (corn -starch)	1,587,000	600,000
Ethanol (corn cellulose)	1,250,000	230,000
Ethanol (wood)	2,600,000	10,000

Source: Oregon Department of Energy, 2005.
(http:// egov.oregon.gov/ENERGY/RENEW/Biomass/forum.shtml)

Despite the widely shared positive outlook for cellulosic ethanol it is worth noting that the technology is currently not commercially viable, with production thus far only within laboratories and several pilot plants. As reported by BioCycle (Greer 2005), a major limitation has been the high cost of cellulase enzymes. One enzyme producer, Genencor, who received DOE funding to study the problem announced in October 2004 a 30-fold reduction in the cost of enzymes, to a range of \$0.10 to \$0.20 per gallon of ethanol. Additional research efforts are focused on biomass pretreatment to allow improved yields of sugars without material degradation. Thus, progress is being made to bring cellulose-to-ethanol production from the laboratory and pilot plant to commercial production. Until commercialization becomes reality, however, projections of future production are highly speculative and must be kept in perspective (California Energy Commission 2004). In addition, in the short run at least, ethanol development is projected based on an assumption of continued federal subsidies, which at this writing extend only through December 2007.

A recent study of ethanol costs by the Congressional Research Service (Table 6) found ethanol to cost significantly more than gasoline, both on an absolute and an equivalent energy basis. Large differences, unfavorable to ethanol, are also shown in a recent comparison of market prices for ethanol and gasoline Figure 11. However, researchers at the National Renewable Energy Laboratory estimate that once cellulosic ethanol technology is adopted, it should be possible to reduce production costs for ethanol to under $1.10 within 15 years, and eventually to about $0.70/gallon.

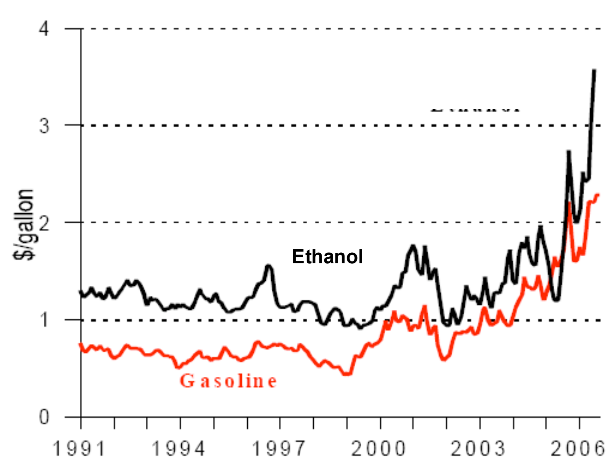
Table 6
Wholesale Price of Pure Ethanol Relative to Gasoline
(October to December 2006)

	Relative price by volume	Relative price on an equiv. energy basis
Ethanol wholesale price	170-250¢/gal.	258-379¢ equivalent gal.
Alcohol fuel tax incentive	51¢/gal.	77¢/equiv. gal.
Effective price of ethanol	119-199¢/gal.	181-302¢/gal.
Gasoline wholesale price	148-179¢/gal.	148-179¢/gal.
Wholesale price difference	-29- +20¢/gal	33-123¢/gal.

Source: Yacobucci 2007

Regarding the relative prices in Figure 12, it has been noted by several analysts that a large portion of ethanol is sold under forward contracts, and that relatively limited supplies can translate to large price changes with fluctuations in demand. This happened in late 2005 and 2006 when MTBE phase-out demand across the U.S. exceeded available supply. Thus, price reductions and relative price stability are likely as domestic ethanol production capacity rises.

Figure 12
Wholesale Prices of Ethanol vs. Gasoline, 1991 -2006



Source: Prices are monthly averages: gasoline prices are national wholesale DOE, EIA;. Ethanol are rack, f.o.b. Omaha, Nebraska Ethanol Board, Lincoln, NE. Nebraska Energy Office, Lincoln, NE.

Biobutanol

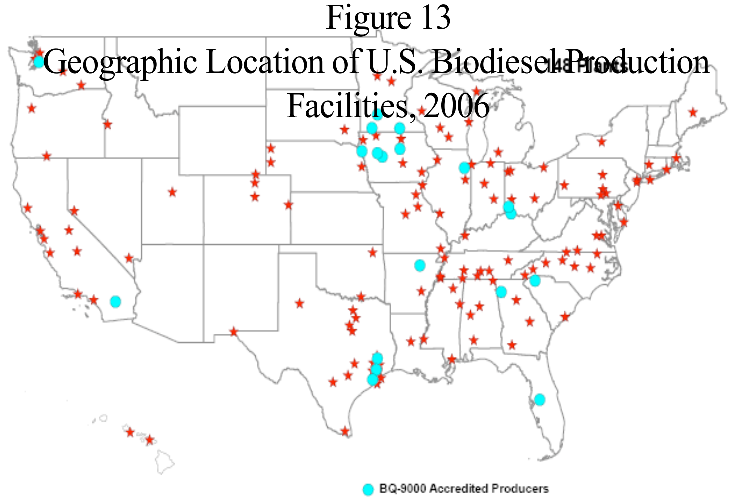
Butanol is a platform chemical with several large volume derivatives, used as a solvent and in plasticizers, amino resins, and butylamines. Butanol can also be used as a bio-based transportation fuel and is more fuel efficient than ethanol on a volume basis in this application. A very attractive feature of butanol is that its energy content is about 105,000 Btu/gallon, much higher than ethanol (75,000 Btu/gal), and only slightly lower than gasoline (114,000 Btu/gal). Butanol is also less volatile than ethanol and can be mixed with motor fuels without modification of engines.

Biodiesel

As described by the U.S. Department of Energy Office of Biomass(USDOE 2007), biodiesel is made by transforming animal fat or vegetable oil with alcohol and can be directly substituted for diesel either as neat fuel (B100) or as an oxygenate additive. In Europe, the largest producer and user of biodiesel, the fuel is usually made from rapeseed (canola) oil. In the United States, the second largest producer and user of biodiesel, the fuel is usually made from soybean oil or recycled restaurant grease. Biodiesel can also be produced from wood.

As of June 2007 there were 148 biodiesel plants in the nation spread across 37 states, with an annual production capacity of 1.39 billion gallons per year (Figure 13). Production in 2006 was about 250 million gallons, more than triple 2005 production. That dramatic increases in biodiesel production are likely in coming years is evidenced by the large difference between installed capacity and production and the fact that in mid-2007 some 96 plants were under construction with an additional 1.89 billion gallon capacity scheduled to go on-line within the next 18 months (National Biodiesel Board 2007).

Figure 13
Geographic Location of U.S. Biodiesel Production Facilities, 2006



Source: National Biodiesel Board, 2007.

Electricity from Biomass

Sampson et al. 2001, citing a DOE database, reported a U.S. biomass electrical generating capacity of about 7,800 megawatts in 2000, with 350 plants spread across 39 of the 50 states. Another 650 generators in the nation's industrial plants were in operation. Overall, the biomass electricity industry is estimated to have employed over 66,000 people in 1999, with an investment base of about $15 billion. A biomass electricity generating capacity of some 50,000 megawatts was said to be a possibility by as early as 2010. The report noted that if all available biomass were converted to electricity, a capacity of over 70,000 average MW could be supported, a large number when compared to U.S. electric consumption of 425,000 MW in 2004. Based on the 2006 EIA Annual Energy Outlook (EIA, 2006a), these earlier predictions appear to mesh with current expectations. With current biomass electrical generating capacity at 9,490 megawatts, this number is projected to grow to 45,000 MW by 2010 and to 58,000 MW by 2030, with biomass generation capacity divided more or less equally between dedicated and co-generation facilities.

Electricity generation from biomass is expected to increase from 1.0 percent of total generation to 1.8 percent in 2030. Almost half of the increase is expected to be from biomass co-firing (with coal), 29 percent from dedicated biomass power plants, and 25 percent from new combined heat and power facilities (EIA 2007d).

Interest in biomass as a raw material for direct electricity generation is stimulated primarily by environmental concerns and in particular the carbon neutrality (or near neutrality) of a biomass-to-energy system. Use of biomass for industrial electricity generation via spent liquor as byproduct is discussed under a separate section.

Syngas

Syngas or synthesis gas is produced through gasification of a carbon-containing fuel such as coal, municipal solid waste, or wood to a gaseous product. Gasification of biomass produces a mixture of gases (so called synthesis gas) mainly consisting of H_2, CO, CO_2, CH_4 and higher hydrocarbons, solids (char) and liquids (aromatic hydrocarbons) known as 'tars'. The relative proportion of each of the constituent in the products depends on the operating conditions such as temperature, pressure, type of gasifying medium, biomass type and composition, biomass feed rate, heating rate, flow rate of gasifying medium, physical characteristics of biomass such as particle size, shape, surface area to volume ratio and the gasifier design. Among all the variables, the gasifying medium (i.e. steam, air and CO_2) strongly influences the product gas composition. Syngas has about one-half the energy density of natural gas. Syngas is combustible and can be used as a fuel source or as an intermediate for the production of other chemicals. There is considerable potential for production of synthesis gas from gasification of black liquor, a by-product of pulping in the papermaking process.

Hydrogen

Another possibility for producing fuels from biomass involves the production of hydrogen using gasification or other technologies in combination with steam reforming and what is referred to as the water-gas shift reaction. The reaction taking place in the gasifier can be written as follows:

$$\text{biomass} + \text{heat} \xrightarrow[\text{air}]{\text{steam or}} H_2 + CO + CO_2 + CH_4 + C_nH_m + \text{tars}$$

The following reaction known as the water gas shift reaction (WGS), describes the equilibrium between CO and H_2 in the presence of water:

$$CO + H_2O \leftrightarrow CO_2 + H_2$$

The maximum amount of hydrogen that can be produced at equilibrium in pure air gasification with no steam and at about 1100°K is small – about 0.7 mol. However, in the presence of steam, hydrogen production can be increased to about 1.3 mol at T =1100°K. The additional hydrogen in the output stream is due to the water gas shift reaction (WGS). Steam not only influences the WGS but also reforms the hydrocarbons, solid char and tars and thereby produces more hydrogen (Melgar et al. 2007, Mahishi et al. 2007). Despite low levels of hydrogen within biomass (about 6 percent by weight) the process of biomass conversion in the presence of water/steam provides a yield of approximately 9 percent by weight dry biomass. Biomass-derived hydrogen is not yet economically feasible, but it is estimated that in the long-term, biomass may provide an economically viable source of hydrogen fuels (Czernik et al. 2004). Accordingly, a goal of economic competitiveness with gasoline by 2015 has been established by NREL scientists. Parallel development of hydrogen fueling stations and vehicles equipped to use hydrogen fuel will be needed to achieve commercialization.

Industrial Energy Generation

In 1998 of the 190 million tons of biomass used annually for production of energy or bio-products that directly displaced petroleum-based feedstocks, some 96 million tons, or slightly more than 50 percent of energy from biomass was produced by the forest products industry for use in powering manufacturing operations. Then, as now, this industry had a high degree of energy self-sufficiency, with over one-half of all energy used in the primary forest products industry self-generated (EIA 1998a, b, Mayes 2003).

Today, approximately 60 percent of biomass energy consumption occurs in the forest products industry, with the majority of this in the form of process heat and steam. When *industrial* biomass energy consumption in the U.S. is considered, the contribution of the U.S. forest products industry is even more impressive. The paper and allied products industry accounts for 75 percent of biomass energy consumption by all of industry (Murray et al. 2006).

In recent years rising costs of traditional fuels and rising market prices for energy, combined with improved technologies for energy production from biomass has stimulated interest in gasification and other approaches to energy production. As a result, the forest products industry is providing more and more of its own energy needs from biomass, and is increasingly providing electricity to local and regional energy grids from combined heat and power (CHP) operations.

District Heating

District heating involves production of steam or hot water for use in heating and cooling a cluster of buildings connected by an energy core. Long a common feature of rural communities of northern Europe, district heating has come to North America much more recently. The St. Paul district heating facility that provides energy for much of the downtown, and the Energy Park project, also located in St. Paul, are prime examples of this concept. The availability of biomass in northern Minnesota may provide opportunities for municipalities to increase their energy independence.

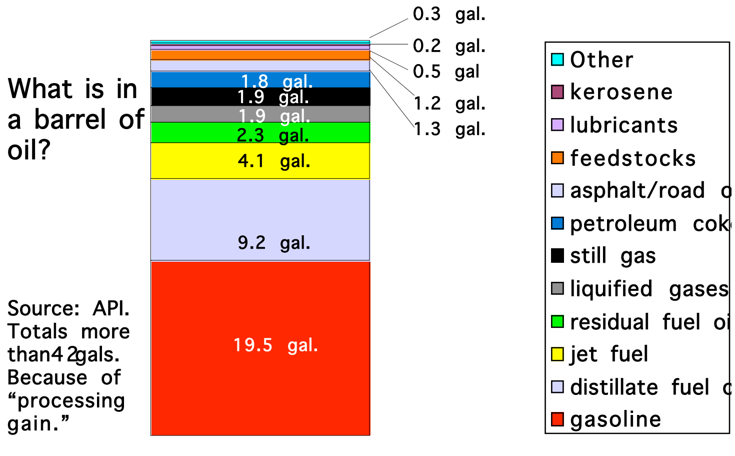
Fuel Pellets

Fuel pellets are made from various forms of biomass (corn stalks, straw, wood) and are used as a clean fuel for production of heat within a closed combustion stove used for heating. These have been in common use in some regions of Europe for a number of decades. Market growth occurred in the United States in the 1970s and ‘80s following the energy shocks of that period. Today, wood fuel pellets enjoy only limited regional markets in the US and Canada, with a significant portion of annual production (1.56 million tons in 2006) exported to Europe. Nonetheless, recent energy market trends are bringing renewed interest in fuel pellets. Fuel pellet production in the United States rose by about 25% in 2006 over the previous year.

Changing Fossil Fuel Markets Bring Bio-Chemical Opportunities

Bioresources are one potential source of energy and chemicals. In a period in which a great deal of attention has been focused on development of cost-effective means of capturing and using solar energy, bio-materials as a source of energy have, until fairly recently, remained below the radar of policy-makers. However, biomass produced by plants through solar-energy-driven photosynthesis and subsequent growth processes has the potential to provide significant quantities of energy, as well as a wide array of industrial chemicals. Because many such chemicals today are derived from petroleum (Figure 14), the prospect of a petroleum peak within the relatively near term provides both a need and an opportunity for production of industrial chemicals and chemical feedstocks from biomass.

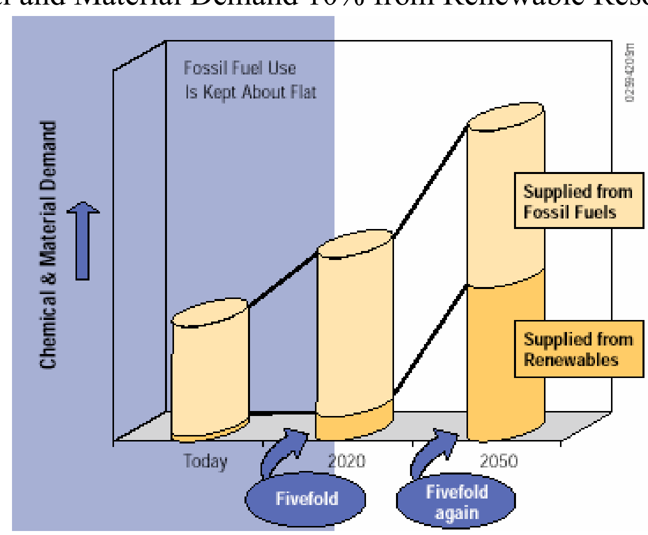
Figure 14
A Myriad of Industrial Chemicals are Derived from Petroleum



(Source: American Petroleum Institute)

The Department of Energy has forecast that some 10 percent of industrial chemicals and materials will be produced from renewable resources by as early as 2020, with this number approaching 50 percent by 2050 (Figure 15). Even at a 10 percent share, such chemicals would have an annual value of about $400 billion (1999 dollars), or about twice the value of all forest products produced in the U.S. in that year. The opportunities would appear to be substantial.

Figure 15
Chemical and Material Demand 10% from Renewable Resources by 2020.



Source: US Department of Energy 1999.

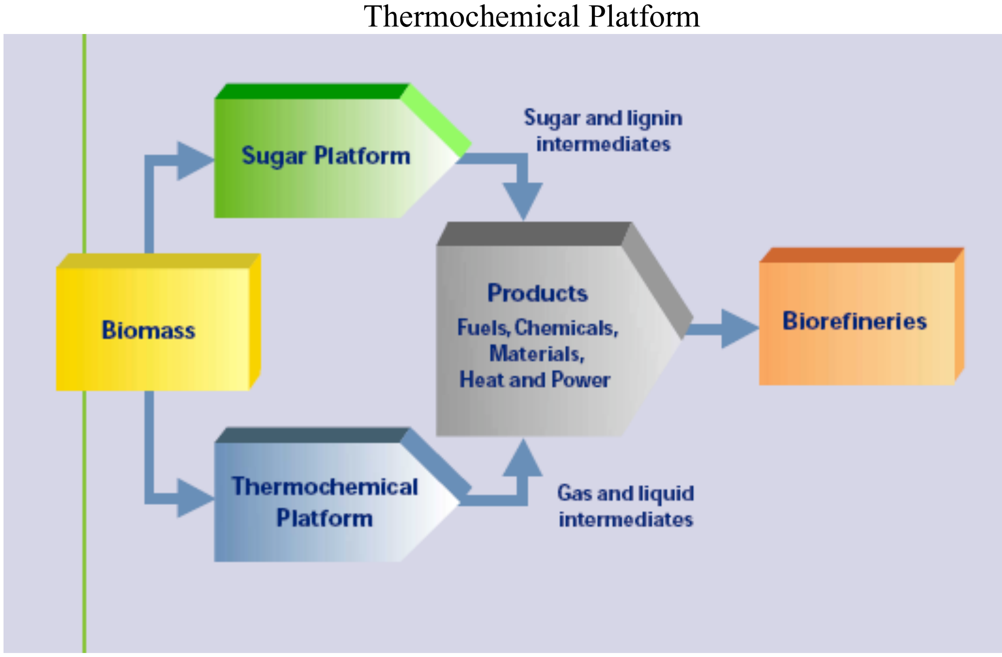
The Biorefinery Concept

Fundamentals

There are many processes for converting biomass components to value-added products, fuels, and power. They can be broadly classified as thermochemical or biochemical conversion processes.

Biochemical technologies use enzymes or microorganisms to convert biomass feedstocks to desired products (e.g., through fermentation). These kinds of technologies may be used alone, or may augment more traditional thermochemical technologies such as those used to remove wood extractives or separate fiber. Fermentation processes are most commonly used for the production of organic acids and ethanol. Thermochemical technologies may utilize catalysts (acid, metal, or a combination) and/or high pressure and temperature to convert biomass components to the desired product. For example, oils from woody resources are typically processed using thermochemical methods. Thermochemical processes such as gasification and pyrolysis have been explored to some degree for the production of energy products and biochemicals but are not in widespread commercial use. Products (e.g., sugars) can be derived from more than one conversion technology such as through a series of steps that involve both thermochemical and biochemical processes. Biochemical technologies (sugar platform) and thermochemical technologies (thermochemical platform) are depicted in Figure 16.

Figure 16
US DOE's Biomass Program – Multi-year Technical Plan – Sugar Platform and Thermochemical Platform



Source: U.S. Department of Energy, Biomass Program (2007).

Biochemical Conversion Technologies

Through biochemical conversion technologies, products are derived from constituent sugars. Biomass sugars represent the most abundant renewable resource available. There are many ways to transform sugars into bioproducts. Many common products (citric acid, ethanol, lactic acid) are produced through fermentation. With a vast range of microorganisms and enzymes currently available and investigation ongoing, the fermentation of sugars holds great potential for new bioproducts. Two types of sugars are present in biomass:

- 6- carbon sugars or hexoses, of which glucose is the most common.
- 5-carbon sugars or pentoses, of which xylose is most common.

The most promising glucose derivatives include:

- **lactic acid -** There are many potential derivatives of lactic acid, some of which are new chemical products, and others that represent bio-based routes to chemicals currently produced from petroleum. Lactic acid derivatives include ethyl lactate, acrylic acid, propylene glycol, and pyruvic acid.

- **succinic acid -** At current production costs of succinic acid, derivatives such as THF (tetrahydrofuran), BDO, GBL (gamma butyrolactone), NMP (n methylpyrolidone) , 2-pyrrolidone, and succinate salts are either cost-competitive or nearly cost competitive.

- **butanol -** Butanol is a platform chemical with several large volume derivatives, used as a solvent and in plasticizers, amino resins, and butylamines. Butanol can also be used as a bio-based transportation fuel and is more fuel efficient than ethanol on a volume basis in this application.

  1,4-Butanediol (BDO) and its derivatives (THF, GBL, NMP, 2-pyrrolidone) represent a market ripe for the introduction of a competitive bio-based route. Demand and growth are high (5-6% annually), supply is tight, and raw material costs for fossil-derived butanediol have increased sharply over the past two years.

- **3-hydroxypropionic acid** - 3-hydroxypropionic acid (3-HP) is just now being actively investigated by Cargill, Inc. Many high volume products can be made from 3-HP creating the potential for a platform intermediate similar to lactic acid and succinic acid. The synthesis of acrylic acid, and the process for obtaining the salts and esters of acrylic acid from 3-HP have been demonstrated in the laboratory. Other derivatives under consideration include acrylamide, 1,3- propanediol, malonic acid esters, and acrylonitrile. As with polylactide, there is no commercially-viable production route of 3-HP from fossil fuel feedstocks. The conversion of 3-HP to acrylic acid is expected to be "easier" and may require less energy than the oxidation of propylene to acrylic acid that is currently practiced from petroleum. As new conversion technologies are developed, the challenge will be to make them cost competitive with the current fossil-based routes to acrylic acid.

- **1,3-propanediol** - 1,3-propanediol, together with terephthalic acid, is used to produce polytrimethylene terephthalate (PTT). PTT is a polymer with remarkable "stretch-recovery" properties, and is used in apparel, upholstery, specialty resins, and other applications where properties such as softness, comfort-stretch and recovery, dyeability, and easy-care are desired. It is currently manufactured by Shell Chemical (CORTERRA Polymers) and DuPont (Sorona® 3GT). Studies have shown that the properties of DuPont's Sorona® surpass nylon and polyethylene terephthalate (PET) in fiber applications and polybutylene terephthalate and PET in resin applications such as sealable closures, connectors, extrusion coatings, and blister packs. PTT polymers currently on the market are made using fossil-based 1,3-propanediol. However, Genencor International and DuPont have been collaborating to develop the metabolic pathway in E. coli to produce 1,3-propanediol directly from glucose at a lower cost. Commercial production of bio-based 1,3-propanediol has been successfully practiced by DuPont.

- **polyhydroxyalkanoates (PHAs)** - PHAs are a family of natural polymers produced by many bacterial species for carbon and energy storage. They are extremely versatile and can be used in a broad range of applications. Their performance exceeds that of PLA, and PHAs could capture a large share of the plastics market if they could be produced at a competitive cost. Bacterial fermentation of PHAs, specifically poly-3-hydroxybutyrate-co-3- hydroxyvalerate) (PHBV), has been performed commercially by Zeneca and then Monsanto and under the trade name Biopol™ in the 1990s. PHBV has been used to make plastic bottles and coated paper.

- **L-lysine -** L-Lysine is a bio-based animal feed additive typically produced from corn starch and molasses using fermentation. This is also used as raw material for pharmaceutical salts, peptide drugs and as diagnostic aids. An improved economically competitive biochemical process is necessary to successfully compete with currently imported bio-based chemicals.

Thermochemical Conversion Technologies

Thermochemical conversion processes involve use of elevated temperature to convert biomass or biomass-derived biorefinery residues to intermediates that may be used directly as raw fuels or products, or that may be further refined to produce fuels and products that are interchangeable with existing commercial commodities. Intermediate products include clean syngas, pyrolysis oil, hydrothermal oils, and gases rich in hydrogen or methane. These intermediate products can be used directly for heat and electric power generation, or may be upgraded by various processing technologies to products such as crude oil, gasoline, diesel, alcohols, olefins, oxo chemicals, synthetic natural gas, and high-purity hydrogen.

Thermochemical conversion provides an efficient approach for producing fuels and products from biomass. Thermal processes readily convert all major components of biomass including lignin, which is currently resistant to biological conversion, to intermediate building blocks. Use of the lignin, that comprises 25%-35% of biomass, is essential to achieve high efficiencies in the conversion process. Thermal processes are "omnivorous" and can convert most biomass feedstocks or residues to a raw synthesis gas. Clean-up and conditioning of the raw gas results in a clean synthesis gas. It is then possible to access and leverage the extensive process technology developed in the petroleum and chemicals industry to produce a wide range of liquid fuels and chemicals from this synthesis gas.

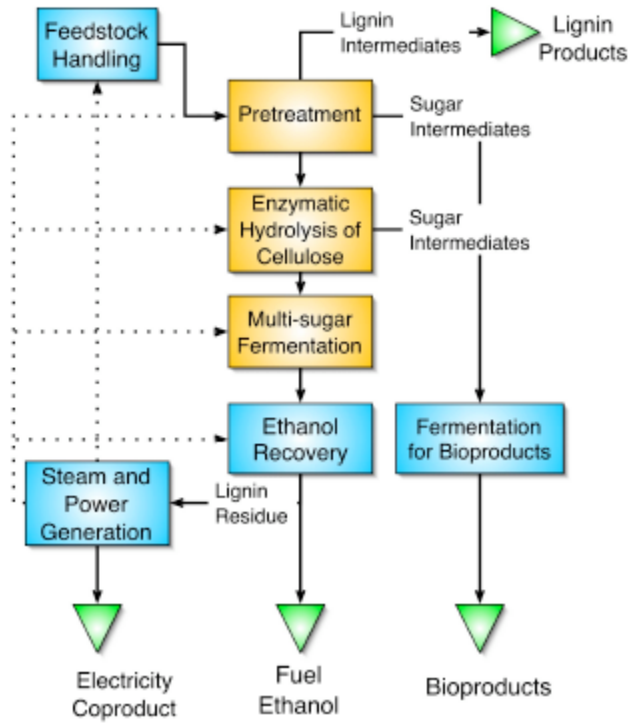
The development of a second generation of biofuels is receiving interest by the pulp and paper industry globally. Of particular interest currently is further conversion of synthesis gas to a number of products such as methanol, dimethyl ether, and Fischer-Tropsch diesel. The goal is to develop commercially viable second-generation biofuels that can compete in the marketplace without subsidies. According to reports by STFI-Packforsk AB, the production costs for the second generation biofuels could be considerably less than for ethanol today. This is but one example of emerging biofuels technologies that do not rely on the use of enzymatic reactions – a current limiting factor in cellulosic ethanol commercialization.

The Integrated Biorefinery

The integrated biorefinery is a conceptual framework that capitalizes on the synergies of integrating technologies as opposed to the previous concept of separate biomass-related programs. Under the separate biofuels, bio-power, and bioproducts concept, energy production from biomass had to compete head-to-head with very mature technology that uses non-renewable sources of feedstock such as coal, petroleum, or natural gas. Under these paradigms bioproducts by themselves offered only small impact to reducing fossil energy dependence. Alternatively, combining higher value products with higher volume energy production and employing any combination of conversion technologies has the greatest potential for making fuels, chemicals and materials, and power from biomass competitive.

Figure 17 illustrates the integrated biorefinery concept that represents a generic integration of all aspects of biomass conversion technology. In this figure, the biorefinery concept is not confined to only a biochemical conversion–based biorefinery or a thermochemical conversion–based biorefinery. In fact, the combined use of both conversion platforms offers the greatest opportunity for optimizing the conversion of biomass into a variety of different fuels, chemicals, and energy products. Not all biorefineries will be this complex, but some may have even greater complexity. The biorefinery should benefit from lessons learned during the evolution of modern-day petroleum refineries. The concept is analogous to a combined use of fluid catalytic cracking, thermal cracking, and hydro-cracking technology to convert the higher-boiling-range fractions of crude oil into more useful lower-boiling-range products. Just as few petroleum refineries use all available conversion technologies, integrated biorefineries of the future will use only those technology platforms most cost effective for converting a certain type of biomass into a certain collection of desired end products.

Figure 17
Schematic of an Integrated Biorefinery



Source: U.S. Department of Energy, Biomass Program (2007).

The primary technology platforms for the manufacture of bioproducts – gasification, hydrolysis, and hydrothermal processing – are briefly discussed below as are the specific bioproducts that can be produced, and current markets and technical challenges.

Gasification and pyrolysis involve the conversion of solid or liquid organic matter to gases (CO, CO_2, H_2, and CH_4), organic vapors, water, and residual solids at elevated temperatures. A strict technical definition is that pyrolysis takes place through the application of elevated temperatures in the absence of any reactive compounds or oxidants. Gasification is the reaction of any carbonaceous feedstocks with air, oxygen, steam, carbon dioxide, or mixtures of these, to yield a gaseous product that is suitable for use either as a source of energy or as a raw material for the synthesis of chemicals, liquid fuels, or other gaseous fuels.

A practical definition that covers most biomass conversion processes states that the primary difference between pyrolysis and gasification is that pyrolysis takes place at temperatures in the range of 750–1,200ºF (400–650°C) at which the primary product is a liquid (pyrolysis oil), whereas gasification takes place at higher temperatures (1,200–1,650ºF; 650–900°C;) at which the primary products are permanent gases (CO, CO_2, H_2, CH_4).

Hydrothermal processing involves lower temperatures (570–660ºF; 300–350°C) and excess water and/or organic solvent and sufficient pressure (2,300 psia; 16 MPa) to maintain the water or solvent in the liquid phase. The primary products are complex hydrocarbon liquids including long aliphatic chains, some cyclic compounds containing carbonyl groups, and a few hydroxyl groups, ether linkages, and carboxylic acid groups.

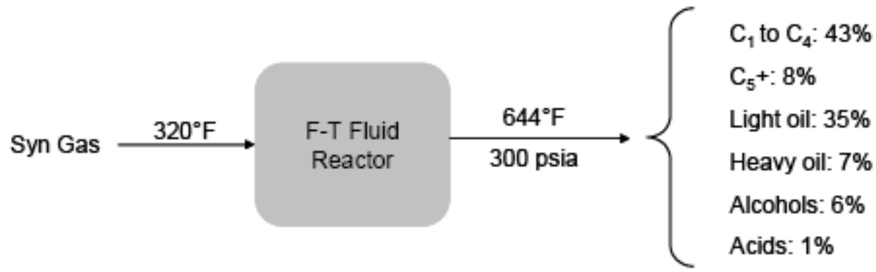
Gasification

Biomass gasification is important in providing a source of fuel for electricity and heat generation for an integrated biorefinery. Virtually all other conversion processes, whether physical, chemical, or biological, produce residue that cannot currently be converted to primary products. To avoid a waste stream from the refinery and to maximize biorefinery efficiency, residues can be used for combined heat and power production (CHP). In existing facilities, these residues are combusted to produce steam for power generation. Gasification offers the potential to use higher-efficiency power generation technologies such as combined cycle gas turbines or, in the future, fuel cells. Gas turbine systems offer potential electrical conversion efficiencies approximately double that of steam-cycle processes, with fuels cells being nearly three times as efficient.

Gasification is the use of high temperatures and oxygen to transform solid carbonaceous material into a mixture of mostly gas and a small amount of liquid for use as fuels, chemical feedstocks, and power. Used since the early 1800s to gasify coal, and used to gasify biomass in the mid-1940s to power over a million vehicles in Europe (Huber it al. 2006), the application of the technology to biomass has been studied extensively since the 1970s. It is now a matter of economics to commercialize biomass gasification systems. If oil prices remain high or increase and/or improved technologies significantly reduce costs, biomass gasification will be commercially viable. The gas produced through gasification is synthesis gas (syn gas), a mixture of carbon monoxide (CO), carbon dioxide (CO_2), hydrogen (H_2), and methane (CH_4). Syn gas can serve as a fuel to produce power and/or it may serve as one source of hydrogen for hydrogen fuel cells. Syn gas can also be converted to valuable chemicals and fuel. Current methanol production is based on syngas derived from natural gas, naphtha, or refinery light gas.

An increase in natural gas prices may encourage the development of alternative processes such as biomass gasification to syn gas and subsequent conversion to methanol. Ethanol can also be produced from syn gas. Research is ongoing in this area and bio-based ethanol via syn gas could be as cost effective as the sugars fermentation route. Fischer-Tropsch chemistry is another approach for converting syngas to valuable chemicals and fuels. Fischer-Tropsch technology was first developed in the early 1900s and used by Germany in the 1930s and '40s to produce liquid chemicals from syn-gas-derived coal (Huber et al. 2006). The chemicals that can be produced include paraffins, mono-olefins, aromatics, alcohols, aldehydes, ketones, and fatty acids. These molecules can contain from 1 to 35 carbons. Fischer-Tropsch chemistry utilizes either cobalt (fixed-bed) or iron (fixed- and fluid-bed) catalysts with high temperature and pressure to convert syngas to chemicals and fuels. Yield, catalyst selectivity, and product composition depend on the catalyst, reaction conditions, and reactor type. The process is highly exothermic and the principal problem in designing the reactor is heat removal. A schematic of the Fischer-Tropsch (F-T) process with product composition is shown in Figure 18.

Figure 18
An Example of Fischer-Tropsch Product Stream Composition



Source: Mangold 1982

Potential F-T products from syngas include methane, propane, butane, methanol, ethanol, isobutaol, dimethly ether, methyl acetate, dimethly carbonate, gasoline, diesel, and paraffin waxes. The lighter hydrocarbons, C1 and C2, can be used to generate the hydrogen used downstream to refine the heavier hydrocarbons. In the future, hydrogen may instead be recovered and purified for use as a transportation fuel. The alcohols can be recovered, purified, and sold without further processing. The rest of the product stream is subjected to fractionation and processing to recover and upgrade the various products.

Other technologies utilizing syn gas include the biological conversion of syn gas to acetic acid or methanol. Formation of formaldehyde, another valuable chemical, is an intermediate step of the metabolic pathway. This could serve as another avenue from gasification products to industrial chemicals.

Pyrolysis

Pyrolysis is the direct thermal decomposition of organic components in biomass in the absence of oxygen to yield an array of useful products such as liquid and solid derivatives and fuel gases. It is similar to gasification except that the mixture produced by the high temperature and pressure conditions consists mostly of liquid with some gas and solids. The gas could be used for its fuel value to produce power. The solids, on the other hand, are very similar to powdered coal. The liquid could be used as a fuel to replace petroleum in applications such as home or commercial heating. Depending on pyrolysis conditions and feedstock, the liquid derived from biomass pyrolysis could also contain many valuable chemicals and chemical intermediates. The technical challenge is developing separation technologies capable of cost-effectively isolating these chemicals. The technology closest to commercialization is pyrolysis of high lignin-containing lignocellulosics which yields a replacement for phenol in phenol-formaldehyde resins.

Hydrothermal Processing

A third alternative (apart from gasification and pyrolysis) is hydrothermal processing with excess water and/or organic solvent at medium temperatures (570–660ºF; 300–350°C) and sufficient pressure (2,300 psia; 16 MPa) to maintain the water or solvent in the liquid phase. The primary products are complex hydrocarbon liquids including long aliphatic chains, some cyclic compounds containing carbonyl groups, and a few hydroxyl groups, ether linkages, and carboxylic acid groups. Hydrothermal processing in the presence of a heterogeneous catalyst (e.g. Ni-Ru) produces primarily methane or hydrogen and is referred to as wet gasification.

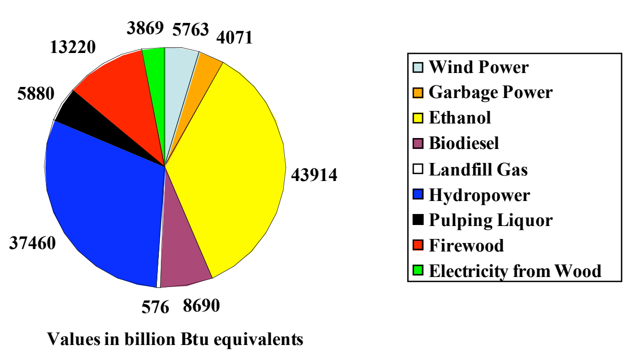
Production of bio-oils by fast pyrolysis, currently a commercial technology, is another possibility. In this case, bio-oils are generally used as an intermediate in chemicals production rather than for production of liquid fuels (Huber et al. 2006).

Renewable Energy in Minnesota

Minnesotans consumed about 1,795,768 billion Btu in 2003. Transportation fuels (gasoline, diesel, jet fuel) accounted for the greatest quantity of energy consumed, followed by coal and natural gas used primarily for electrical generation and home heating. Energy expenditures were approximately $13.3 billion.

Renewable sources of energy, though still accounting for a relatively small proportion of total energy requirements, are growing. In 2005 renewables accounted for about 86 trillion Btu of Minnesota's energy production (Figure 19), or about 7.1 percent of total energy consumption (compared to 6 percent nationwide); renewable energy production included about 11 percent of electricity, 10 percent of gasoline, and 2 percent of diesel. The state ranks 4th in production of wind energy, 4th in production of ethanol, and 8th in production of biodiesel.

Figure 19
Renewable Energy Produced in Minnesota, 2005



Source: Derived from Jordan and Taff (2005), with hydropower and energy from pulping liquor (listed in Jordan and Taff as conventional sources of energy) and firewood (from Mouelle et al. (2003) added.

Bio-Energy Status and Trends

Current and Potential Biomass Availability Within Minnesota

The majority of renewable energy produced in Minnesota in 2005 came from biomass – about 80 trillion Btu in the form of ethanol from corn starch, biodiesel from soybeans; heat from burning of firewood; and electricity and heat from spent pulping liquor and waste wood. This was equivalent to about 6 percent of the total non-transportation energy consumed in the state and about 15 percent of all industrial energy consumed.

While corn is today by far the leading raw material for bioenergy production in Minnesota, emerging technology is likely to expand bio-fuels options to include energy crops such as switchgrass, agricultural crop residues, and broader applications of woody biomass. Such materials will also become important as a source of industrial chemicals and industrial feedstocks.

Increasing importance of biomass as a source of energy and chemicals translates to substantial opportunity for Minnesota's farm economy, as well as potential for revitalization of the State's forestry and wood products sector. Farm income, long a point of concern, is likely to receive a significant boost, and the forest products industry stands to benefit from expanded product options, diversification, and increased profit potential.

Minnesota Bio-Energy Development

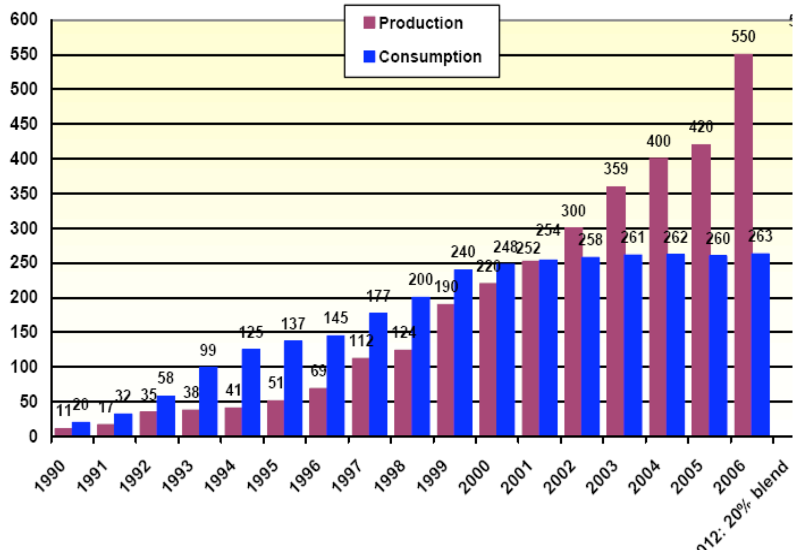
Ethanol

It is clear that there is considerable potential for generating electricity from agricultural and other forms of biomass in Minnesota given the right economic conditions. However, the potential payoff from production of liquid fuels from biomass is far greater, with the caveat that the technology needed to bring about that payoff is as yet unproven from a commercial standpoint.

In 2006 Minnesotans consumed an estimated 2.7 billion gallons of gasoline and additional fossil fuels such as aviation and diesel fuels. All of the petroleum from which this was produced was imported. Also in 2006, Minnesota produced over 550 million gallons of ethanol, of which an estimated 287 million gallons were exported to other states (Figure 20). The economic impact of ethanol production within Minnesota is estimated at $1.72 billion annually, including 6,400 jobs, with much of this impact in rural areas.

Recently enacted legislation sets a target within Minnesota for a 20 percent ethanol blend in all gasoline sold in Minnesota in 2010 and beyond. Meeting that target will require 574 million gallons of ethanol just to meet state consumption requirements. Using current technology and corn starch as a raw material, the 20 percent ethanol-lend requirement is expected to require the use of some 230 million bushels of corn, or assuming level production, about one-quarter of Minnesota's corn crop.

Figure 20
Ethanol Production in Minnesota, 1990 -2006

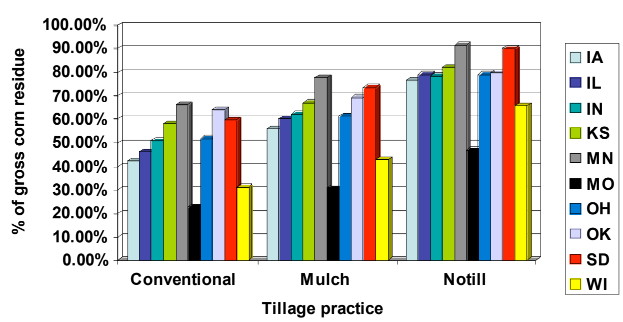


Source: Minnesota Department of Administration (2007)

As in the rest of the United States, the production of ethanol in Minnesota is completely corn-starch-based. Implementation of cellulosic technology will allow the use of corn stalks, wheat straw, switch grass, wood, and other cellulosic materials as raw materials for ethanol production.

Corn stalks alone represent a large potential fuel resource. Studies of the percentage of agricultural crop residues that can be removed from the land on a sustainable basis have generally shown acceptable removal rates of 60 to 80 percent. A study of corn stover showed permissible removal rates of 65 to 91 percent in Minnesota, depending upon the tillage practices used (Figure 21).

Figure 21
Geographic Variation in Percent of Gross Corn Stover Supply that Can Be Harvested with "Acceptable" Erosion Rates



Source: Graham, R. Oak Ridge National Laboratory (2003)

There are significant cellulosic resources potentially available other than corn stalks. As shown in Table 7, it has been estimated in several studies that substantial volumes of biomass are available beyond current needs for food, fiber, and conservation tillage.

Table 7
Biomass Resources in Minnesota by Three Studies

Source of Biomass	Biomass in Resources from ORNL database (tons/year at < $50/ton)	Biomass Resources from NREL GIS Group (tons/year)	Biomass Resource from 1997 ILSR Inventory (tons/year)	Average of All Biomass Resource Data (tons/year)
Forest residue	874,900	-	-	874,900
Mill residue	1,121,000	1,017,688	571,960	903,549
Agricultural residue	11,935,896	40,709,527	22,040,438	24,895,287
Energy crops	5,783,002	-	-	5,783,002
Urban wood waste	1,532,529	-	-	1,532,529
Total	21,247,327	41,727,215	22,612,398	33,989,267

Source: NREL (2005)

This biomass, in turn, could be used to produce as much as an additional 1.1 billion gallons of ethanol using cellulose-to-ethanol technology (Table 8), assuming conversion yields as shown in the center column of Table 4 (page 14). If the more optimistic biomass availability figures are used in determining ethanol production potential (from the far right column of Table 4), then additional ethanol production potential in Minnesota rises to 1.8 billion gallons annually.

Table 8
Ethanol Production Potential from Minnesota Biomass, Based on ONRL 1999 Study* and NREL Near-Term Conversion Factors

Resource	Quantity Available @ (000 dry tons/year)			Ethanol Potential (million gallons)		
	<$30/t	<$40/t	<$50/t	<$30/t	<$40/t	<$50/t
Forest residues	468	682	875	31	45	58
Mill residues (wd)	71	916	1,121	3	42	51
Ag. residues	0	11,936	11,936	0	597	597
Energy crop pot.	0	427	5,783	0	26	347
Urban wd waste	1533	1,533	1,533	70	70	70
Total	2917	15,494	21,348	104	779	1,122

* Walsh et al. 1999.

Over the long term the 1.1 and 1.8 billion gallon figures as indicated above are probably conservative, as yields are likely to improve as technology develops.

Biodiesel

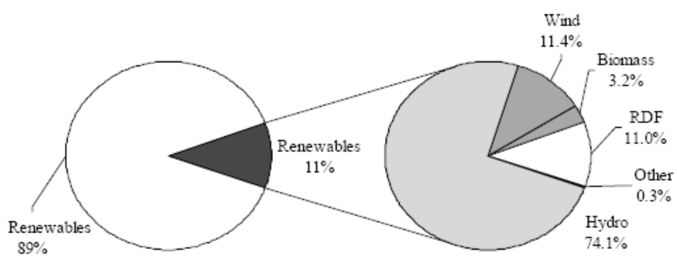
In Minnesota, the nation's eighth largest producer of biodiesel, production approximated 60 million gallons in 2006, consuming 13 percent of the State's soybean crop. Overall consumption of diesel fuel within the State approximated 1.1 billion gallons, meaning that biodiesel was produced in a quantity about three times greater than that needed to meet the state's 2 percent biodiesel requirement.

It is likely that wood will soon gain the attention of biodiesel producers, both within Minnesota and nationally. As an example, the Finnish-based paper manufacturer UPM-Kymmene, a corporation that operates a large mill in Grand Rapids, Minnesota, announced in October 2006 that it will "invest strongly" in second generation biodiesel production, using wood-based biomass as raw material, saying that it aims to become a major producer. UPM Chief Executive Jussi Pesonen was quoted as saying "If on a global scale (the biodiesel business) grows into the billions (of euros), then to begin with UPM's share would be in the hundreds of millions, and then even expanding into the billions" (Associated Press 2006) The company expects to make a decision on investing in the first commercial biodiesel production plant within the next few years.

Electricity from Biomass

Biomass accounted for 200,000 MWh, or 3.2 percent of the electricity produced in Minnesota from renewables in 2005 (Figure 22). This figure is expected to rise to 5.5 percent of renewable electricity production by 2015, when renewable electricity will account for about 20 percent of total electricity produced.

Figure 22
Profile of Renewable Electricity Production in Minnesota, 2003



Non-Renewables	50,100,000 MWh
Renewables	6,200,000 MWh
Total Energy	56,300,000 MWh

Minnesota Department of Commerce 2004.

Beyond what is now produced, there is considerable potential for additional production of electricity from biomass. For instance, a 2005 report by the National Renewable Energy Laboratory (NREL) at the request of the Minnesota Department of Commerce and the Minnesota Office of Environmental Assistance concluded that available biomass (Table 7) could produce 80 percent of Minnesota's electricity needs assuming energy generation in direct-fired power plants and 99 percent if combusted in plants employing state-of-the-art technology (Table 9).

Table 9
Power Potential from Minnesota Biomass

Source of Biomass	Average of All Biomass Resource Data from Table 1 (tons/year)	Power Potential from the Use of Direct-Fired Biomass Power Plants (aMW)	Power Potential from the Use of Integrated Gasification/Combined Cycle Power Plants (aMW)
Forest residue	874,900	176	220
Mill residue	903,549	182	227
Agricultural residue	24,895,287	5,009	6,252
Energy crops	5,783,002	1,164	1,452
Urban wood waste	1,532,529	308	385
Total	33,989,267	6,389	8,536

Source: NREL (2005)

Again referring to Table 7, if instead of using averaged estimates of biomass availability as in the NREL study, only data from the 1999 Oak Ridge National Laboratory (ORNL) study of biomass is used, more conservative, but nonetheless impressive, estimates of electric production capacity are obtained (Table 10). The electric generating potential shown in the far right column of Table 10 (<$50/ton) is equivalent to over 40 percent of current generating capacity. The difference in electric generating potential between the two studies is due to a more conservative estimate of agricultural crop residue availability.

Table 10
Potential Power Obtainable from Minnesota's Plant-Based Bio-Resources, Based on ONRL 1999 Study and NREL Conversion Factors

Resource	Quantity Available @ (000 dry tons/year)			Electric Potential (aMW)		
	<$30/t	<$40/t	<$50/t	<$30/t	<$40/t	<$50/t
Forest residues	468	682	875	94	137	176
Mill residues (wd)	71	916	1,121	12	149	182
Ag. residues	0	11,936	11,936	0	2,401	2,401
Energy crop pot.	0	427	5,783	0	86	1,164
Urban wd waste	1533	1,533	1,533	308	308	308
Total	2917	15,494	21,348	414	3,081	4,231

Source: National Renewable Energy Laboratory, 2004.

While generation of a large portion of Minnesota's electricity from biomass appears to be technically feasible, economic feasibility appears doubtful, at least given current prices and technology levels. The Minnesota Center for Rural Policy and Development concluded in a 2005 report (Jordan and Taff 2005) that electricity production from wood was not economically feasible, except perhaps in specific locations and situations, unless wood could be obtained for less than prevailing prices or if wood-generated electricity would be sold at above-market rates. Wood generated electricity was, in fact, identified, as the least economically attractive option of six alternative energy production systems.

The finding that production of electricity from wood biomass is not economically feasible was underscored by a December 2005 report for the American Forest and Paper Association that examined costs of biomass- vs. coal- generated energy nationwide. Estimated national average costs of producing electricity from wood in 50 and 100 MW plants were estimated to be 80 to 90 percent higher than current retail electricity costs in Minnesota and 26 percent higher than electricity production in new coal facilities.

The nationwide averages were similar to electricity production costs in Wisconsin. Nonetheless, because differences between wood and coal-generated electricity generally fall in the range of 1.4-2.2 cents/KWh and far less than that in several southern states, there is concern that energy demand may soon threaten pulpwood supplies; subsidies for biomass could bring about an immediate threat.

Because of the relatively high costs associated with production of biomass electricity, the U.S. Department of Energy forecasts little to no growth in the biomass generating industry through at least 2020. Current projections are for about 15.3 billion KWh of biomass generation in 2020, or only 0.3 percent of electric generation nationally. Biomass energy, including cogeneration of electricity, is likely to continue to provide a major portion of energy consumed by the forest products industry – over one-half at present.

Hydrogen

Another possibility for producing fuels from biomass involves the production of hydrogen using gasification or other technologies in combination with steam reforming and what is referred to as the water-gas shift reaction. Despite low levels of hydrogen within biomass (about 6 percent by weight) the National Renewable Energy Laboratory recently (NREL 2005) estimated that hydrogen from Minnesota biomass could replace as much as 89 percent of current gasoline consumption in the State, while also dramatically reducing transportation related CO_2 emissions. As discussed earlier, biomass-derived hydrogen is not yet economically feasible, but a goal of economic competitiveness with gasoline by 2015 has been established by NREL scientists. Parallel development of hydrogen fueling stations and vehicles equipped to use hydrogen fuel will be needed to achieve commercialization.

Wood-Based Bio-Energy and Bio-Chemicals Potential in Minnesota

The greatest likelihood of profitable biorefinery development based on woody biomass is in conjunction with pulp and paper operations. Minnesota, therefore, as a significant producer of paper in the U.S., with eight operating paper mills, is in a reasonably good position to capitalize on the biorefinery/bioenergy/biochemicals potential. Minnesota's proximity to the number-one paper producer, Wisconsin, is probably also a positive factor as it increases the likelihood of economies of developing critical mass. Also a favorable factor of wood-based biorefinery development is the presence in the region of leading agri-business companies and cooperatives that are currently leading the way in ethanol and biodiesel development.

Political leaders of many states, including Wisconsin and Michigan, and at least four other states, have publicly stated objectives of becoming the national leader in biochemicals development. Obviously, only one will succeed. Success will likely require an aggressive program of strategic planning and research, investment, collaboration with established energy and industrial chemical producers, and perhaps serendipity. Success may also require incentives in some form to encourage or jumpstart a fledgling industry.

What success will look like is not as yet clear, but one model would be a network of biorefineries across the landscape, coupled with a number of secondary manufacturers of chemical products including bio-plastics, lubricants, medicinal products, synthetic fibers, and so on. Ideally these new industries would generate significant local employment, taxes, and enhancement of quality of life (socially, environmentally, and economically), and would be sustainable over the long term.

Public Policy Considerations Related to Biorefinery and Bioproducts Development

As Minnesota considers how it might more extensively use its forest resources to increase its participation in the emerging bio-revolution, it is important that decision leaders understand fully what is potentially involved. As exciting as the prospects for improved energy security, expanded economic activity, and new employment prospects are, what is under consideration is establishment of several or an extensive network of biorefineries and associated enterprises across Minnesota. Careful thought and planning is needed to ensure that development is not haphazard and that development outcomes mesh with other state values and goals. That care is needed is exemplified by a region such as that surrounding Charleston, West Virginia, long a poster child for environmental degradation linked to chemical industry activity. Whatever is done, it is vitally important that efforts to bolster supplies of one critically important resource – energy, not result in depletion of other critically important resources – soil and clean water.

Areas requiring thorough discussion are the following:

1) Are there things that might be done to increase the likelihood of local control and community participation in economic returns from bio-based industries?

2) Will additional regulatory oversight be needed to ensure rational, sustainable use of resources?
   a. With regard to forest resources?
      1. Ongoing monitoring of biomass harvesting?

    2. Continued work to refine biomass harvesting guidelines?
    3. Additional mechanisms to foster discussion of broader forest management goals in the context of increased biomass use?
  b. With regard to surface and ground water use?
  c. With regard to allowances for citizen input on siting of refinery operations?

3) Are there things that the State might do to avoid the possibility that bioenergy development will provide a disincentive to conserve energy?

4) What can be done to take maximum advantage of developing carbon markets in conjunction with forest management and forest-based activity (including forest-based bioenergy/biochemicals development)?

5) Might government incentives increase the likelihood of success in bioenergy development? If so, how can incentives be structured so as to not disadvantage or penalize current users of forest biomass?

6) What needs to be done to inform the population at large about potential developments and the rationale for them. A proactive rather than reactive strategy might be a key to rational development.

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