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# U.S. Biobased Products Market Potential and Projections Through 2025



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**U.S. Biobased Products: Market Potential and Projections Through 2025.** Office of the Chief Economist, Office of Energy Policy and New Uses, U.S. Department of Agriculture. Prepared jointly by the Office of Energy Policy and New Uses, the Center for Industrial Research and Service of Iowa State University, Informa Economics, Michigan Biotechnology Institute, and The Windmill Group. OCE-2008-1, 293 pp.

## Abstract

This study is based upon data and assumptions as of 2006 which are not reflective of recent market developments. These assumptions were used to identify the market potential for biobased products - their production volumes and applications - through the year 2025. Market penetration was assessed based on information available through April 2006 and benchmark assumptions with respect to factors such as policy, biobased feedstock prices, and energy prices. Recent results of the benchmark assumptions have not materialized; corn prices have increased, the market prices for biofuels are lower, and the infrastructure costs continue to increase. If such trends that lead to low profit margins continue there will be a slowing effect on the biofuels industry. With the dynamic nature of the biobased industry affecting short term developments, the long term trends toward 2025 could vary widely based upon future policy, research, and market developments. Development of the biobased products industry can be expected to spur increased investment in processing and manufacturing facilities in rural America. This investment will both expand employment opportunities for rural residents and spur demand for farm products. Substantial growth is to be expected, especially in a high-priced oil and natural gas environment. For example, the global chemical industry is projected to grow 3 - 6 percent per year through 2025, with biobased chemicals' share of that market rising from 2 percent currently to 22 percent or more by 2025. The science and technology for producing biobased products have advanced to the point that a wide array of products such as fuels, chemicals, and materials currently produced from petroleum feedstocks can now be produced from biobased feedstocks. Moreover, these products can compete on a performance basis with products made from petrochemical feedstocks. The shift toward greater use of biobased products will be linked to the development of biorefineries capable of producing both liquid fuels and streams of feedstocks for a wide range of biobased products. But to achieve the forecast growth, a number of scientific and processing impediments must be cleared including the development of improved fermentation processes, improved biocatalysts and integration of biomass conversion into large-scale biorefineries. Currently and for the next 10 years, grains will be one of the primary feedstocks for biobased product production, corn being the primary feedstock and oilseed crops playing a growing role. However for biobased products and biofuels to achieve expected targets, it will be necessary to develop processes for utilizing a broad range of plant and animal material and animal waste. Economically viable cellulosic conversion of plant material will be critical. Public sector investments in research and product development have played and will continue to play an important role in developing and deploying biobased products.

**Keywords:** biobased products, ethanol, biodiesel, biomass, energy, fuels, chemicals, biorefinery.

## Preface

The Energy Policy Act of 2005 (Public Law 109-58) required the Secretary of Agriculture to issue a report that describes the economic potential in the United States for the widespread production and use of commercial biobased products through calendar year 2025 and, to the extent practicable, identifies the economic potential by product area.

This study was prepared under the direction of the Office of Energy Policy and New Uses of the Office of the Chief Economist, in cooperation with the Center for Industrial Research and Service of Iowa State University; Informa Economics; the Michigan Biotechnology Institute; and The Windmill Group. Principal authors are Dr. Marvin Duncan and Dr. Irene M. Xiarchos of the Office of Energy Policy and New Uses; Dr. John Whims and Tom Scott of Informa Economics; Dr. Mark Stowers and Dr. Bernie Steele of the Michigan Biotechnology Institute and; Don Senechal of The Windmill Group. Dr. Ron Cox and Steve Devlin of Iowa State University coordinated the project.

The analysis and projections in this report were based on data current as of April 1, 2006. During the preparation of the report a significant expansion in the biofuels sector has occurred, as a result of record oil prices, strong demand for ethanol by blenders, as methyl tertiary-butyl ether was being phased out, and relatively low corn prices. Because of the lag created during the preparation of the report, the analysis has not included this information. However, even if biofuels' production increases more rapidly than described in the report, the projected market penetration of the non-fuel biobased products remains valid.

Dr. Roger Conway, Director, Office of Energy Policy and New Uses

For updates on Biobased Products, please visit:  
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## I. Executive Summary

The production of industrial and consumer products from biomass is not a new idea. Worldwide, over \$400 billion in products are currently produced annually from biomass in conventional manufacturing (Informa Economics et al., Biobased Multi-Client Study, March 2006). These products include inorganic and organic chemicals, pharmaceuticals, soaps and detergents, pulp and paper, lumber, fuels, lubricants and greases, and paints. The emerging biobased economy will drive the production of nontraditional products from biomass, such as fuels, chemicals, and materials currently produced from petroleum feedstocks. At present, industrial biobased products in the United States use an estimated 12 billion pounds of biomass per year (Informa Economics et al.).

The U.S. biobased industry is poised for substantial growth between 2007 and 2025. The science and technology for producing biobased products have advanced to the point that a wide array of products can be produced from biobased feedstocks. These products can compete on a performance basis with products made from petrochemical feedstocks. Volatile prices and price spikes for oil and natural gas have spurred new interest on the part of chemical and other product manufacturers in the use of biobased feedstocks. In addition, in some cases, the manufacturing processes may be less costly and involve fewer steps than is the case for petrochemical feedstocks.

A number of factors will affect the rate of growth of the biobased industry. These factors include, but are not limited to, federal and state policy, technology, prices of feedstock such as corn, oilseeds, energy crops, and other forms of biomass (i.e., crop residues, wood chips and forest residues, and solid municipal waste), prices of petroleum based fuels and chemicals, and consumer acceptance of biobased products. The analysis and projections included in this document are based on information available and assumptions (of the factors affecting growth) as of April 2006. In a perfect world, assumptions made apriori would reflect what actually occurs. But that is not the case in the real world. The political environment, technological developments and market dynamics will not evolve as assumed (as of April 2006), and, as a consequence, development of the biobased industry may be accelerated or inhibited, depending on what actually occurs. The robust and rapid expansion of both the ethanol and biodiesel capacity, since this analysis was originally completed and draft finalized, suggests that the biobased industry will grow faster in the near term than originally anticipated.

### Benefits

Replacing fossil sources of fuel and other products with renewable energy and biobased products can provide an opportunity to reduce air pollutants and greenhouse gas emissions. The growth of the biobased economy can enhance national security and strengthen the U.S. economy. The economic impacts will be widespread but especially noticeable in the rural sector. Farmers and suppliers of production inputs (such as seeds, fertilizer, and equipment) will earn more revenue as the demand for corn, soybeans, and other agricultural feedstocks intensifies. Increased investment in processing and manufacturing facilities in the rural United States is also expected which could grow employment opportunities for rural residents.

### Public Policy

Public sector investments in research and product development have played an important role in developing biobased products, and will likely continue to do so. Federal government mandates U.S. fuel use to include a minimum amount of renewable fuel each year with the Renewable Fuels Standard (RFS) and provides tax credits to producers of ethanol and biodiesel. The most important credits are \$0.51 cents per gallon of ethanol and up to \$1.00 per gallon of biodiesel blended with gasoline and diesel, respectively. Furthermore, state programs supporting the development of the biofuels market have been numerous and diverse.

### The Importance of Biofuels

Biofuels are perhaps the most widely recognized of the biobased products. The two most prominent biofuels produced in the United States are ethanol and biodiesel, with corn and soybeans as respective feedstocks. As the biofuel industries continue to develop and mature, the concept and potential for biorefineries is also emerging. Similar to petroleum refineries that divide crude oil into numerous products, biorefineries would convert biobased renewable feedstocks into multiple streams of outputs.

It is expected that the shift toward greater use of biobased products will be strongly linked to the development of biorefineries capable of producing both liquid fuels and streams of feedstocks for a wide range of biobased products.

### Feedstocks

Currently, in the United States, corn and soybeans are the primary feedstocks for biobased production. Corn will continue to be the primary feedstock for the biorefinery platform for the next decade, with oilseed crops playing a growing role. Yet, it is well understood that if biobased fuel and biobased production are to achieve expected targets, it will be necessary to develop processes for utilizing a broad range of plant and animal material and animal waste, commonly referred to as biomass. Economically viable cellulosic conversion will be crucial for the expansion of the industry.

### *The Biobased Potential*

Biobased products include biobased chemicals, plastics, polymers, films, packaging and cellulose fiber products. Based on the feedstocks used, biobased products can be divided into oil and lipid-based products, sugar and starch products, cellulose derivatives, fibers, plastics, and gum and wood chemicals.

Biotechnology has offered the potential for new bioprocesses and innovating biobased products, especially in the speciality and fine chemicals markets. The integration of chemicals production with fuel production (ethanol or biodiesel) will help drive chemical costs down and generate new feedstocks in which biobased platforms replace petrochemical platforms. A biorefinery of the future, in which renewable resources are used as feedstocks, would include biological or enzymatic conversions, chemical conversions, and thermochemical conversions to enable the production of multiple products with utility in a variety of markets.

Many biobased products are far from market maturity. The development stage of the various biobased products ranges from research to early development, and from the path towards commercialization to adoption by the marketplace, with sales steadily expanding.

### *Market Analysis of Biobased End Products*

The categories for biobased products, as well as the available information, are very diverse. They can range from motor oils and fuel in our cars, to the clothes we wear, to the products we use to wash our hands and clean our homes. To provide an overview of the biobased end product markets, this study - in addition to ethanol and biodiesel - focuses on 19 biobased end product categories representing products with the largest market potential and commercial viability in the U.S. economy.

The stage of development and the market forecasts for biobased end products are based on industry reviews by Informa Economics. Clothing, pharmaceuticals, plastic films, carpeting, containers, composite panels, sorbents, solvents, adhesives, and insulation are at a well-established stage of development. Pharmaceuticals, coatings, plastic films, containers, adhesives, insulation, wood waste products, and composite panels are expected to represent a substantial share in the biobased industry. The importance of the biopharmaceutical industry is recognized by the magnitude of its value relative to other biobased industries; it also rests in the biotechnology potential and increased consumption of nutraceuticals.

### *Market Forecasts*

The global chemical market was estimated at \$1.2 trillion in 2005. Commodity chemicals and polymers contributed 60 percent to the total; followed by specialty chemicals, 30 percent; and fine chemicals, 10 percent. The next 2 decades are likely to see significant growth of the global chemistry industry. The global chemical industry is projected to grow 3 - 6 percent per year through 2025. Biobased chemicals are expected to grow from 2 percent of the total chemical market to at least 10 percent by 2010 and 22 percent by 2025. Excluding pharmaceuticals, the

global chemical industry is expected to grow to over \$2 trillion per year by 2025, with biobased products replacing existing products and providing new revenue sources amounting to more than \$500 billion per year (Table 1).

Substitution of biobased resins for petrochemical products will be determined by the cost of oil and energy and the performance of biobased resins relative to their petrochemical competitors. The global polymer market is estimated at \$250 billion and is predicted to exceed \$450 billion by 2025; the biobased share is expected to increase from the current 0.1 percent to 10 - 20 percent by 2025. The maximum substitution potential has been estimated to be about 33 percent of total polymer production, though diminishing supplies and higher prices for petroleum feedstocks could elevate that share.

In the medium term, biobased raw materials can increase modestly in cost (based on corn starch as the primary feedstock). Over the long term, the cost of biobased raw materials may even decrease as cellulosic and plant-oil feedstocks come on line. However, processing remains the dominant cost of making biomaterials. Industrial biotechnology will be a dominant driver in reducing processing costs during the next decade according to the Michigan Biology Institute (MBI).

**Table 1: Projected Global Markets of Chemical Sectors: 2005, 2010, and 2025 \***

(Billion U.S. dollars)

Chemical Sector	2005		2010		2025	
	Total	Biobased	Total	Biobased	Total	Biobased
Commodity	475	0.9	550	5-11	857	50-86
Specialty	375	5	435	87-110	679	300-340
Fine	100	15	125	25-32	195	88-98
Polymer	250	0.3	290	15-30	452	45-90
<b>Total</b>	<b>1,200</b>	<b>21.2</b>	<b>1,400</b>	<b>132-183</b>	<b>2,183</b>	<b>483-614</b>

\* The value of pharmaceuticals is excluded.

Sources: Bachmann, 2005; Cygnus Business Consulting & Research; Informa Economics et al.

New biobased chemicals and materials most likely will be concentrated in the fine chemicals sector and biotechnology's contribution to value in this segment will be driven by new revenue growth, as opposed to cost savings in the processing of existing products (MBI). Biobased building blocks or platform chemicals are critical for biobased products to penetrate the market for polymers, chiral drugs, resins, fine chemicals, high-performance chemicals, and commodity chemicals. Significant growth in biobased chemicals and materials will come from new platform chemicals like succinic acid, as well as new fine and specialty chemicals.



Platform Chemicals

The U.S. Department of Energy (USDOE, 2004) identified 12 chemicals or chemical classes as potential building blocks or platform chemicals from which many value-added chemicals may be derived. For example, succinic acid could be used to produce a biobased butanediol, expanding the utility of this compound.

The USDOE projects that these chemicals and chemical classes could be produced from biobased feedstocks, and that these chemicals could in turn serve as platforms for the creation of other existing chemicals. However as Table 2 shows even though many of these chemicals are already in the market as specialty or fine chemicals, such as xylitol and glutamic acid, they have not been yet developed as commodity chemicals. The development of platform chemicals from biobased feedstocks has advanced for only a few chemicals, and none are used commercially as platform chemicals at present. The 1, 4 diacids (specifically succinic acid), 3 hydroxypropionic acid, and levulinic acid are the only chemicals in this group with near-term potential as platform chemicals. The others have significant technical barriers to overcome before commercial production is feasible.

**Table 2: USDOE Top Value-Added Chemicals from Biomass Feedstocks**

<b>Chemicals</b>	<b>Carbon Number</b>	<b>Base Technology Stage</b>	<b>Platform Chemical Stage</b>
1,4 diacids succinic, fumaric and malic	4	Commercial	Development
3 hydroxypropionic acid	3	Development	Development
levulinic acid	5	Commercial	Development
glutamic acid/MSG	5	Commercial	Detailed Investigation
sorbitol	6	Commercial	Detailed Investigation
xylitol/arabinol	5	Commercial	Detailed Investigation
2,5 furan dicarboxylic acid	6	Preliminary Investigation	Preliminary Investigation
aspartic acid	4	Detailed Investigation	Preliminary Investigation
glucaric acid	6	Preliminary Investigation	Preliminary Investigation
itaconic acid	5	Commercial	Preliminary Investigation
3-hydroxybutyrolactone	4	Commercial	Preliminary Investigation
glycerol	3	Commercial	Preliminary Investigation

Base Technology Stage = current technology status; commercial production is for low volume specialty or fine chemicals.

Platform Chemical Stage = status with regard to production as a high volume commodity or platform chemical with potential for further production of multiple products.

Source: U.S. Department of Energy, 2004.

Biocatalysts

The development of biocatalysts (whole-cell microorganisms or specific enzymes derived from microorganisms) is one of the primary drivers for development of biobased chemicals and fuels. Industry experts have predicted that by 2020, the development time for new whole-cell biocatalysts will be reduced from 10 years to 2 years and that the product cycle for biocatalysts created by protein engineering will be reduced to less than 6 months (Energetics, Inc., 1999).

*Barriers to Overcome*

A number of scientific and processing hurdles must be cleared to achieve the forecast growth in biobased production and use. These include development of improved batch and continuous flow fermentation processes and improved biocatalysts. The economically feasible use of thermochemical conversion techniques awaits integration of biomass conversion into large-scale biorefineries. Economically viable cellulosic conversion of biomass will open up a large and diverse array of feedstocks ranging from crop residues to forest resources to dedicated grass production. Finally, more effective pretreatment processes for biomass are needed to support economically viable cellulosic conversion.

## II. Introduction

This study fulfills Section 948 of the Energy Policy Act of 2005 (Public Law 109-58), which requires the Secretary of Agriculture to examine the biobased economy. Its purpose is to describe the current range of biobased products and to assess the market potential for these products through the year 2025. This study was prepared jointly by the Office of Energy Policy and New Uses of the U.S. Department of Agriculture, the Center for Industrial Research and Service (CIRAS), Iowa State University; Informa Economics; Michigan Biotechnology Institute (MBI); and The Windmill Group.

Many industry participants and technical experts were consulted in order to understand the full scope and potential of the biobased economy, and their assessments are incorporated in the report. Sources of forecasts and projections are also noted in the text and tables.

The analyses and projections were based on data available as of April 1, 2006. Between April and the publication of this report a number of factors influenced the U.S. biofuels industry, such as record oil prices, strong demand for ethanol by blenders, as methyl tertiary-butyl ether was being phased out, and relatively low corn prices. In retrospect, these factors have accelerated investment in the biofuels sector.

Actual U.S. biofuels' production increases in the near term will exceed projections reported in this study. At the end of December 2006, the Renewable Fuels Association reported that there were 110 plants operating with a capacity of 5.4 billion gallons. In addition, there are another 73 plants under construction and 8 expansion projects with a reported capacity of 6.0 billion gallons per year for a total capacity of 11.4 billion gallons by early 2008. The National Biodiesel Board reports that as of September 13, 2006, that there were 86 operating facilities with a capacity of 581 million gallons, another 65 plants under construction, and 13 expansion projects that will add 1.4 billion gallons to biodiesel capacity for a total of 2 billion gallons by early 2008.

Furthermore, projections of the addition of cellulosic ethanol to total ethanol capacity were based on cellulosic conversion becoming commercially viable within six to ten years. However, according to some industry sources cellulosic ethanol could make a significant contribution to total biofuels supply within the next 2 to 3 years. Thus, biofuels production could increase more rapidly than projections in this report, leading to greater quantities of feedstocks used in the production of non-fuel biobased products. Nonetheless, the report's projected market penetration of the non-fuel biobased products remains valid.

## A. Overview

The introduction frames biofuels within the larger petroleum and energy industries and highlights the developing role of renewable resources.

- Chapter III looks at the forces and policies that launched biofuels and explores present and future dimensions of the ethanol and biodiesel industries.
- Chapter IV analyzes the markets and prospects for a broad array of other products that are or could be biobased, ranging from pharmaceuticals to paneling, and projects the outlook for chemicals derived from biobased feedstocks.
- Chapter V focuses on biobased technologies and discusses the present and potential uses of fermentation, biocatalysis, and thermochemical conversion. It also looks at the chemical building blocks of plants and pretreatment technologies to unlock them.
- Chapter VI previews the emerging biorefinery concept and required technologies. Like an oil refinery, a biorefinery can process a feedstock into a number of useful commodities.
- Chapter VII maps the distribution and concentration of crops and infrastructure that supply the raw materials for biorefining in the United States.
- In chapter VIII the potential for growth of the biobased sector is projected and impacts are considered.
- Chapter IX reviews the developments shaping public policies that led to expanding production and use of biofuels in the United States.
- Chapter X presents the major report findings and conclusions.
- Appendices provide background information on biofuel policies at the state level, policies adopted by other countries, and the distribution of U.S. bio-product firms by industry.
- References and sources, and a glossary follow.

### **What is a biobased product?**

The term “biobased product,” as defined in the Farm Security and Rural Investment Act of 2002, is “a commercial or industrial product (other than food or feed) that is composed, in whole or in significant part, of biological products or renewable domestic agricultural materials (including plant, animal, and marine material) or forestry material.”

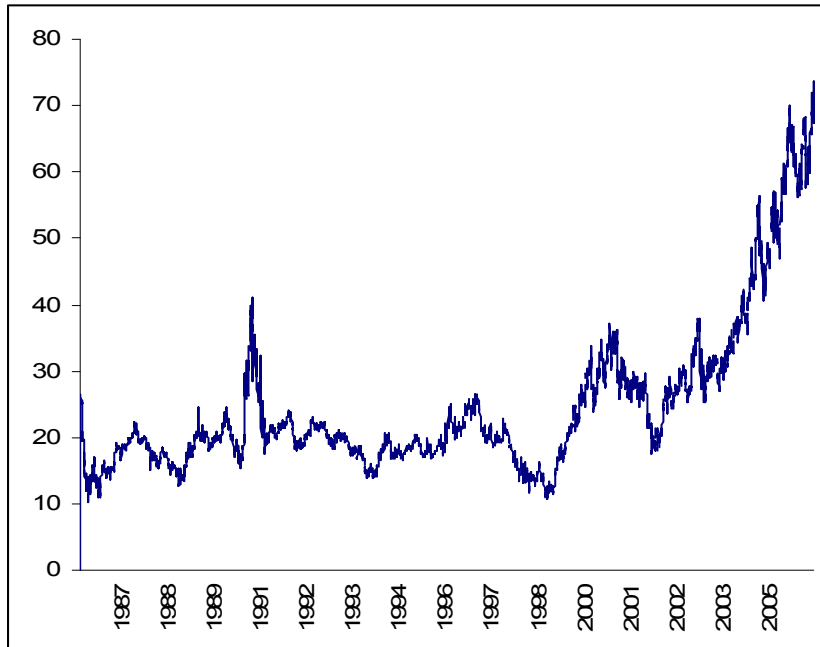
The United States is positioned to use its vast renewable resource base in arable land and its infrastructure (such as human capital, investment capital, transportation network, and agricultural production practices) to pursue biobased product opportunities. In the near term (1 to 3 years), product development will continue to primarily be derived from corn and soybean economies; however cellulosic conversion technologies are expected to grow more practical and emerge as a significant contributor in the U.S. biobased economy. This would unlock vast renewable resources from U.S. forests and from agricultural lands (for example, corn stover and switchgrass feedstocks).

## **B. Energy Sources, Supplies and Demand**

The key to understanding the present state of biobased products and their future potential is their role in the U.S. energy economy. Reliance on energy sources, whether hydrocarbon fossil fuels (such as petroleum and coal) or renewable supplies (such as hydroelectric and wind), underpins the composition of every economy. Unlocking and utilizing these energy resources efficiently helps sustain a nation’s transportation, industrial, residential, and commercial sectors. Any significant change in the price of natural energy resources is quickly felt throughout the economy.

Nominal oil prices for West Texas Intermediate (WTI) crude were \$73.71 a barrel on April 21, 2006 (Figure 1). Oil prices at \$73.71 a barrel are a contrast to an average of \$19.09 a barrel from 1986 to 1999, and a range from \$10.25/barrel to \$41.07. Adjusted for inflation, gasoline prices have actually been in a long-run decline since 1919 (Figure 2), with only brief price spikes. The jump in oil prices in recent years has elevated real gasoline prices to levels not experienced since the late 1970s and early 1980s. The longer high real prices persist, the greater the negative impact as the “cost of doing business” increases for all economic sectors.

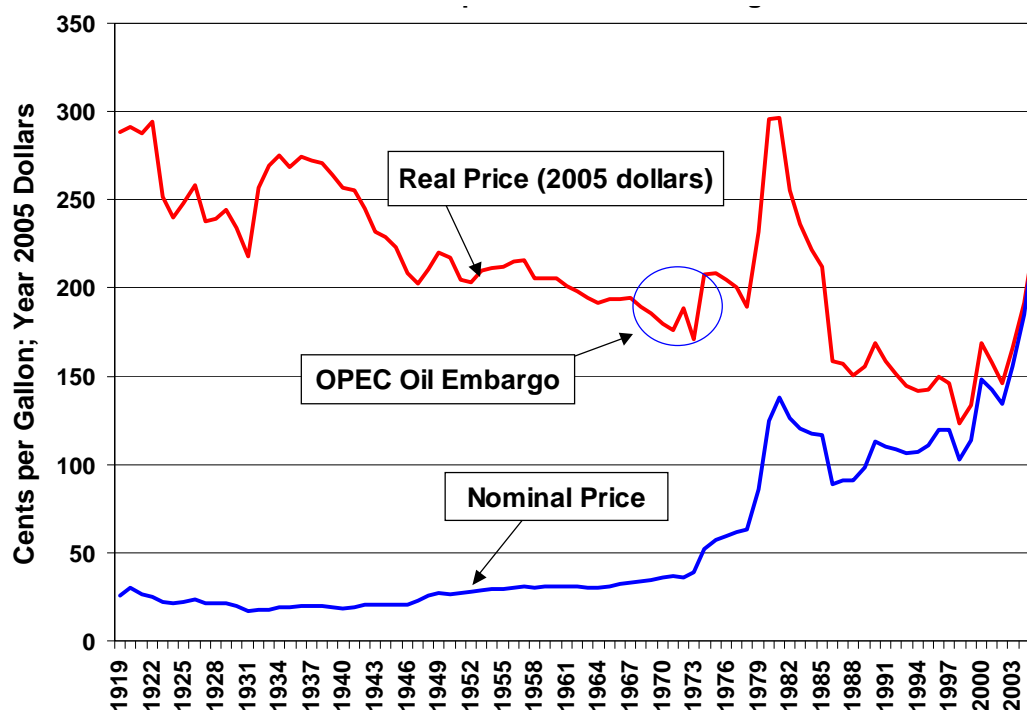
**Figure 1: Crude Oil Price, West Texas Intermediate: 1986 to April 28, 2006  
(Nominal Dollars per Barrel)**



Source: U.S. Department of Energy, Energy Information Administration.

Higher real petroleum prices have renewed interest in reducing U.S. dependence on foreign imports of petroleum. The current Administration has acknowledged the need to find alternative, and preferably renewable, sources of energy. In his 2006 State of the Union Address, President Bush outlined an advanced energy initiative, designed to help break America's dependence on foreign sources of energy (Bush). It set a national goal to replace the equivalent of 75 percent of the oil imports from the Middle East by 2025. The initiative provides for a 22 percent increase in clean-energy research at the U.S. Department of Energy. The intent of the funding increase is to accelerate breakthroughs in two critical areas: how we power homes and businesses, and how we power vehicles.

Since the 1950s, the United States has imported more energy than it has exported. Consumption of petroleum, the most prominent energy resource, expanded from 6.2 million barrels daily in 1950 to almost 20 million barrels a day in 2003 (Figure 3). During this period, petroleum imports grew, surpassing U.S. domestic supplies.

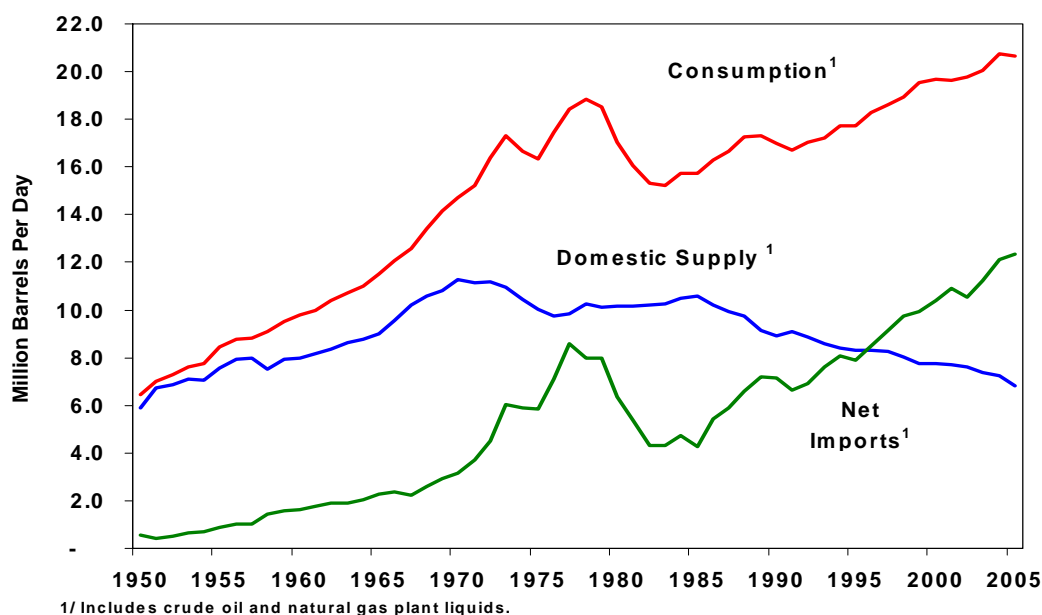
**Figure 2: Real Gasoline Pump Price: Annual Average, 1919 - 2005**

Source: U.S. Department of Energy, Energy Information Administration.

North American neighbors Canada and Mexico supplied more than 31 percent of U.S. petroleum import needs during 2005 (Table 3). The concern is the consistent availability of future supplies from regions such as the Middle East and from countries such as Nigeria, Iraq, and Venezuela, which together accounted for one-fourth of U.S. imports in 2005.

Oil sands are considered a key source of oil in the future if oil prices rise to levels that make the extraction of oil sands broadly economical<sup>1</sup>. Oil sands are being currently rapidly developed in Northern Alberta, Canada. Oil sands (also known as bitumen) can change the distribution of future imports of oil. Oil sands are found mostly in Alberta, Canada, and Venezuela. Canadian reserves are estimated to hold 175 billion barrels of recoverable oil from oil sands (as much as Saudi Arabia's reserves). Geologists think that another 315 billion barrels will be accessible when new technologies are full developed. Venezuelan heavy oil sand reserves are currently believed to be even larger than Canada's reserves, an estimated 270 billion barrels (Figure 4).

<sup>1</sup> The National Energy Board of Canada (NEB) estimates that with current technology the breakeven level for operating and extraction (including capital cost of equipment) of a new mining operation in the Athabasca, Alberta region is \$18 to \$20 a barrel. In order to process and upgrade the crude bitumen into synthetic crude oil, however, the final breakeven cost for a barrel of heavy oil climbs to \$36 to \$40 a barrel for a new mining operation.

**Figure 3: U.S. Petroleum Situation: 1950 - 2005**

Source: U.S. Department of Energy, Energy Information Administration.

**Table 3: U.S. Imports of Crude Oil by Country of Origin, 2005**

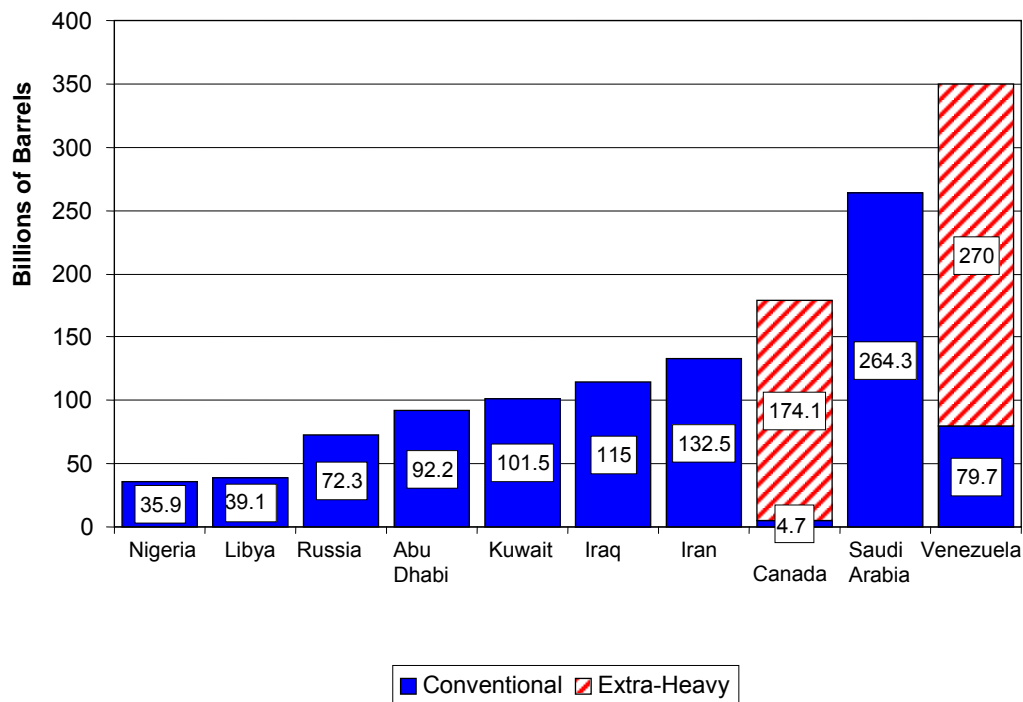
	Country of Origin	Thousand Barrels	Percent Total
1	Canada	599,681	16.3%
2	Mexico	565,919	15.4%
3	Saudi Arabia	524,714	14.3%
4	Venezuela	449,196	12.2%
5	Nigeria	386,872	10.5%
6	Iraq	189,657	5.2%
7	Angola	164,183	4.5%
8	Ecuador	100,681	2.7%
9	Algeria	83,359	2.3%
10	United Kingdom	80,055	2.2%
	Rest of World		14.3%
<b>Total</b>		<b>3,670,403</b>	<b>100.0%</b>
	<b>Non OPEC Countries</b>	<b>1,932,132</b>	<b>52.6%</b>
	<b>Persian Gulf</b>	<b>796,094</b>	<b>21.7%</b>
	<b>Total OPEC Countries</b>	<b>1,738,271</b>	<b>47.4%</b>

Source: U.S. Department of Energy, Energy Information Administration.



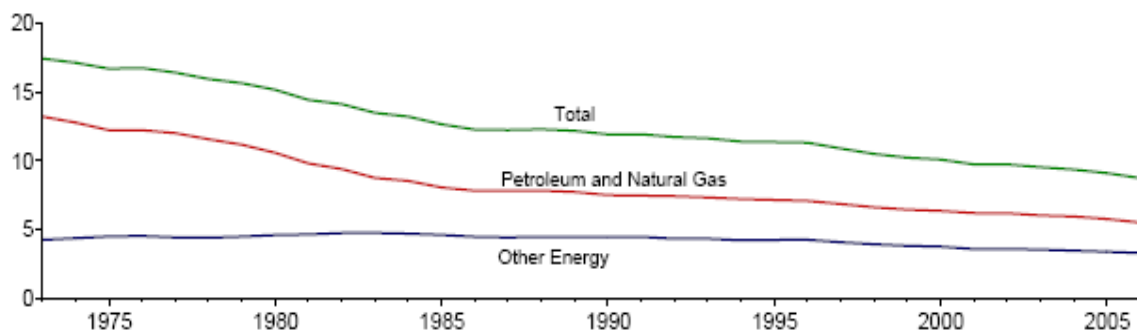
**Figure 4: Reserves of Conventional Oil and Extra-Heavy Oil (Oil Sands)**

Reserves of Conventional Oil and Extra-Heavy Oil (oil sands)



Source: Informa Economics et al., Biobased Multi-Client Study, March 2006.

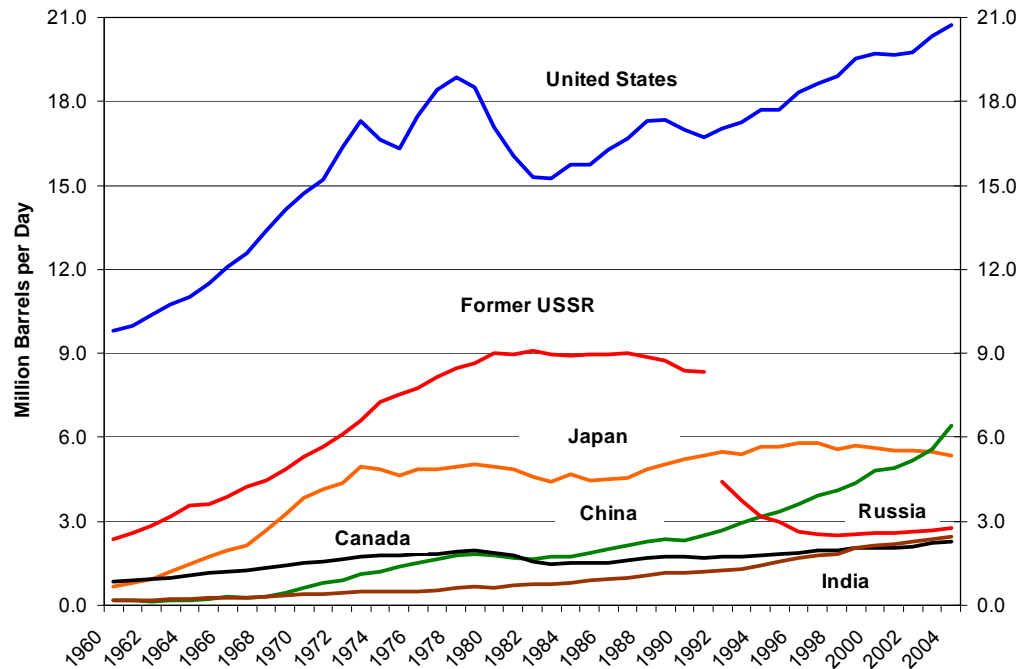
Despite the greater dependence on imports for the Nation's energy needs, the energy consumption per dollar of real gross domestic product (GDP) has fallen consistently from the 1970s to the present (Figure 5). There has been a shift in the U.S. economy from manufacturing to services and many of the "heavy industry" sectors such as steel, pulp and paper mills, and automobile manufacturing have moved offshore, thus reducing U.S. energy use.

**Figure 5: Energy Consumption per Real Dollar of Gross Domestic Product (Thousand Btu per chained (2000) Dollar)**

Source: U.S. Department of Energy, Energy Information Administration.

The United States is the top petroleum-consuming country (Figure 6). The former Soviet Union was second until its breakup in the early 1990s. Now China ranks second.

**Figure 6: Leading Petroleum Consuming Countries, Average Daily Consumption, 1960 - 2004**

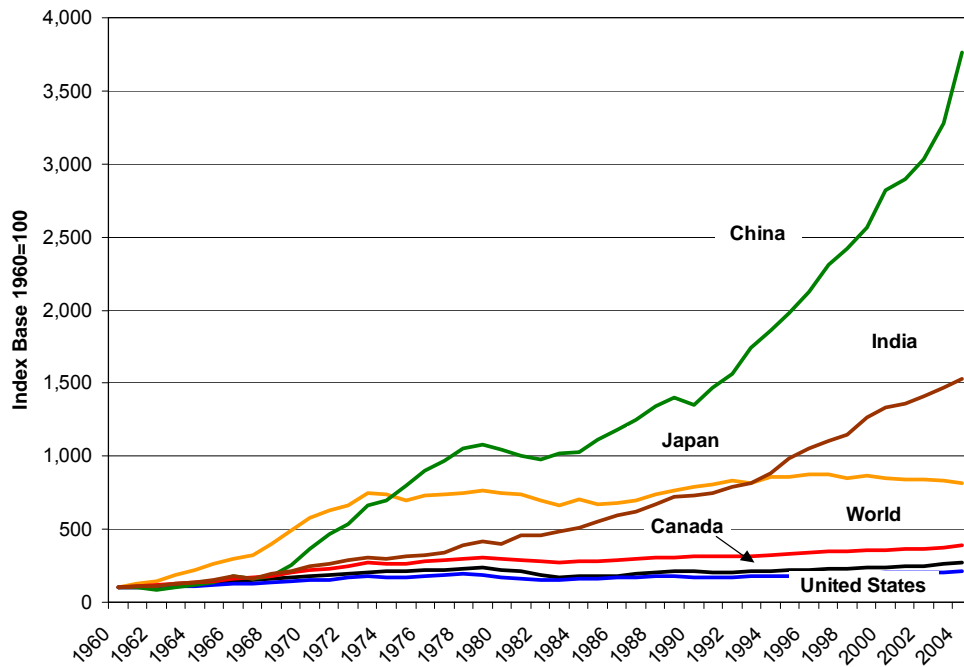


Source: U.S. Department of Energy, Energy Information Administration, Annual Energy Review 2006.

Since 1960, China has increased its consumption of petroleum faster than any country (over 3,000 percent), while India has increased consumption by almost 1,500 percent (Figure 7). Interestingly, both the United States and Canada exhibit long-run growth below the world trend. From 1960 to 1969, the United States used, on average, 37.6 percent of global petroleum supplies. Between 1990 and 2004, this share was 25.4 percent (Energy Information Administration [EIA]).

European Union countries have generally dropped in their rankings for petroleum consumption as emerging economies have rapidly increased their share of total petroleum demand. Often overshadowed by China and India, South Korea has also experienced rapid growth in petroleum use, with annual growth exceeding 5 percent over the last 20 years (EIA).

**Figure 7: Indexed Growth of Petroleum Consumption for Key Countries, 1960 - 2004**



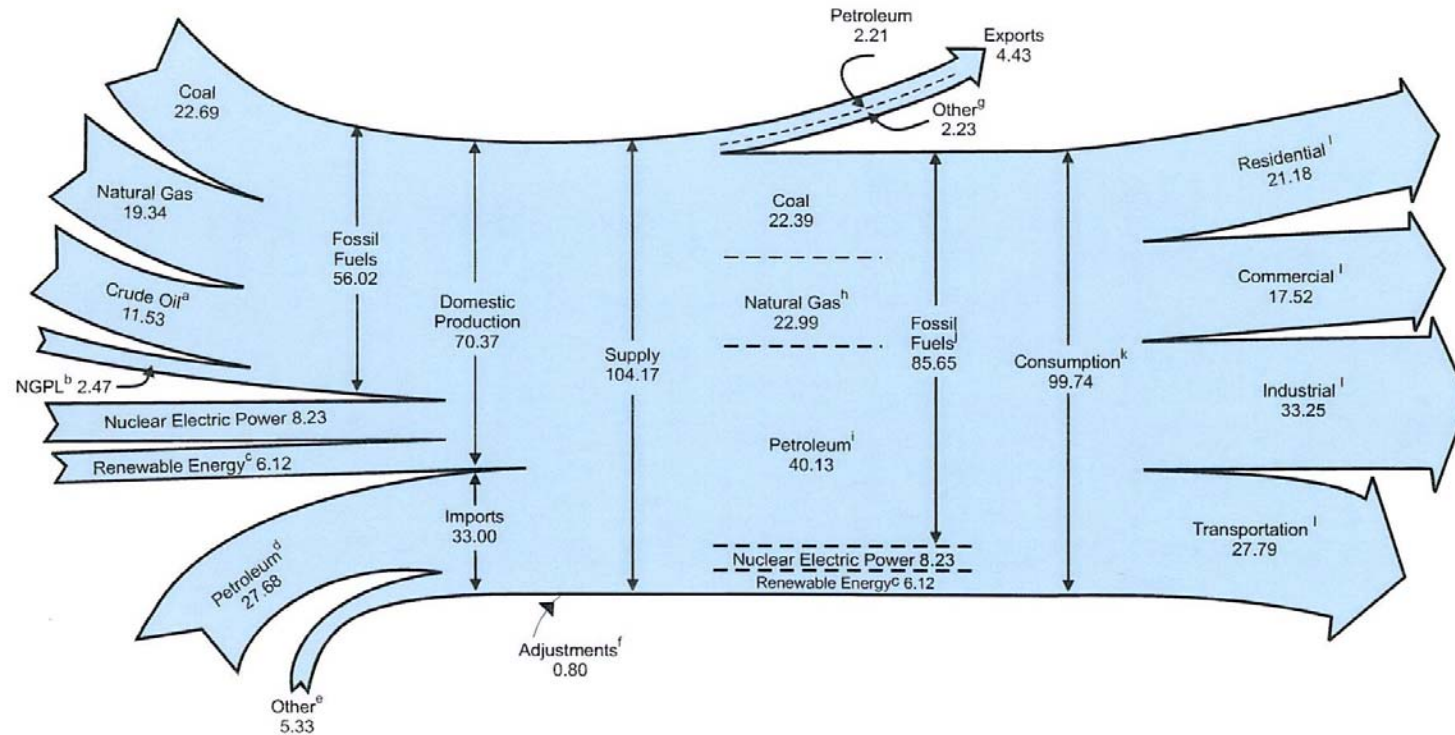
Source: U.S. Department of Energy, Energy Information Administration, Annual Energy Review 2006.

While petroleum is the primary source of energy, other sources play a significant role in the U.S.'s intricate energy balance (Figure 9). Fossil fuel based energy sources (coal, natural gas and petroleum) accounted for 85.8 percent of energy consumed in 2005, with the remainder provided by nuclear electric power (8.1 percent) and renewable energy (6.1 percent) (Figure 9).

Since 1949, fossil fuel as a share of total energy consumption has risen dramatically relative to nuclear electric power and renewable energy sources (Figure 10).

U.S. energy is consumed by four basic sectors: residential, 21.9 percent; commercial, 17.9 percent; industrial, 32.1 percent; and transportation, 28.1 percent (Figure 11).

Figure 8: U.S. Energy Flow, 2004 (Quadrillion Btu)



<sup>a</sup> Includes lease condensate.

<sup>b</sup> Natural gas plant liquids.

<sup>c</sup> Conventional hydroelectric power, wood, waste, ethanol blended into motor gasoline, geothermal, solar, and wind.

<sup>d</sup> Crude oil and petroleum products. Includes imports into the Strategic Petroleum Reserve.

<sup>e</sup> Natural gas, coal, coal coke, and electricity.

<sup>f</sup> Stock changes, losses, gains, miscellaneous blending components, and unaccounted-for supply.

<sup>g</sup> Coal, natural gas, coal coke, and electricity.

<sup>h</sup> Includes supplemental gaseous fuels.

<sup>i</sup> Petroleum products, including natural gas plant liquids.

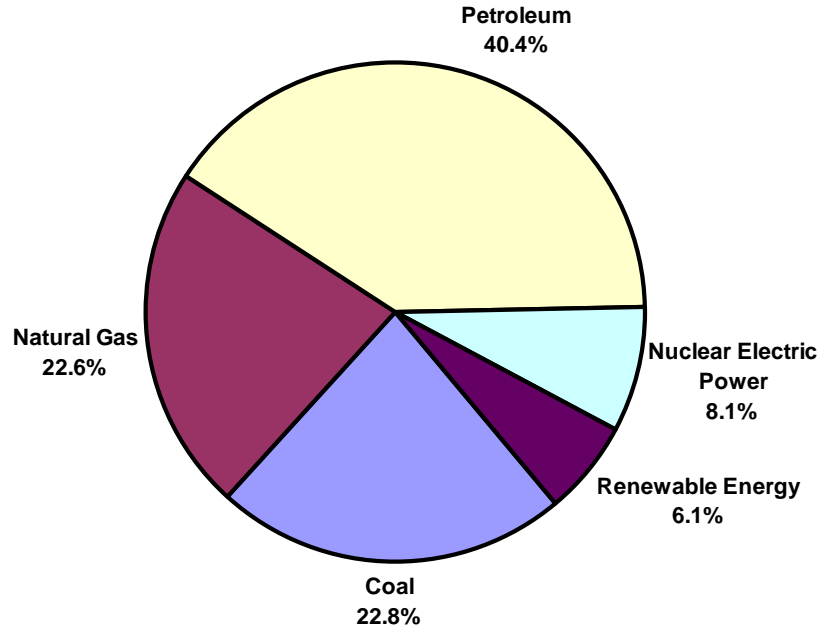
<sup>j</sup> Includes 0.14 quadrillion Btu of coal coke net imports.

<sup>k</sup> Includes, in quadrillion Btu, 0.30 ethanol blended into motor gasoline, which is accounted for in both fossil fuels and renewable energy but counted only once in total consumption; and 0.04 electricity net imports.

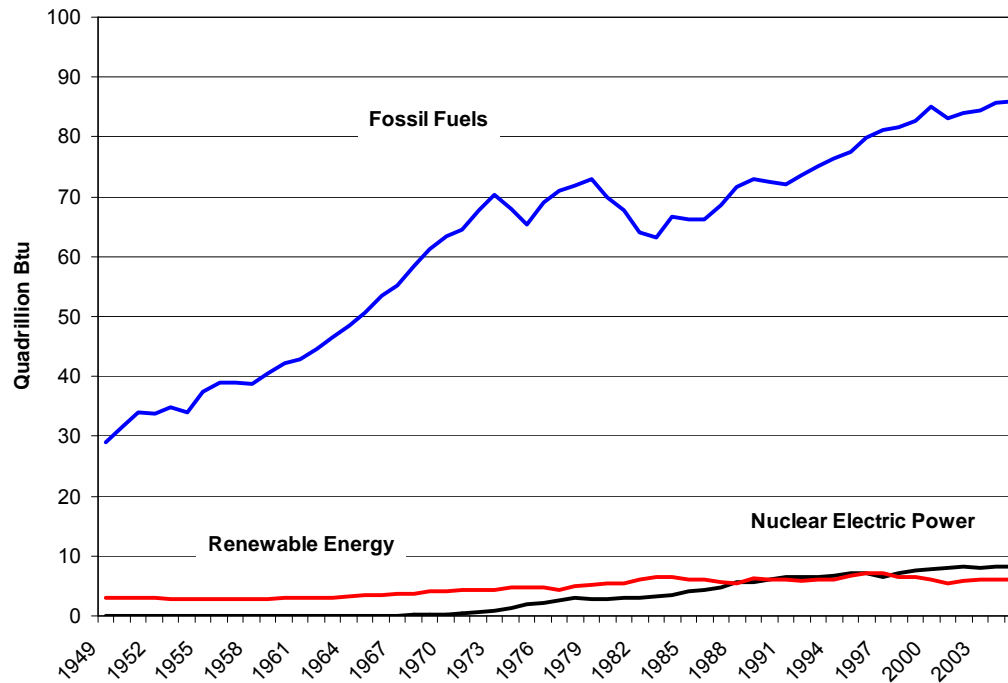
<sup>l</sup> Primary consumption, electricity retail sales, and electrical system energy losses, which are allocated to the end-use sectors in proportion to each sector's share of total electricity retail sales. See Note, "Electrical Systems Energy Losses," at end of Section 2.

Notes: • Data are preliminary. • Totals may not equal sum of components due to independent rounding.

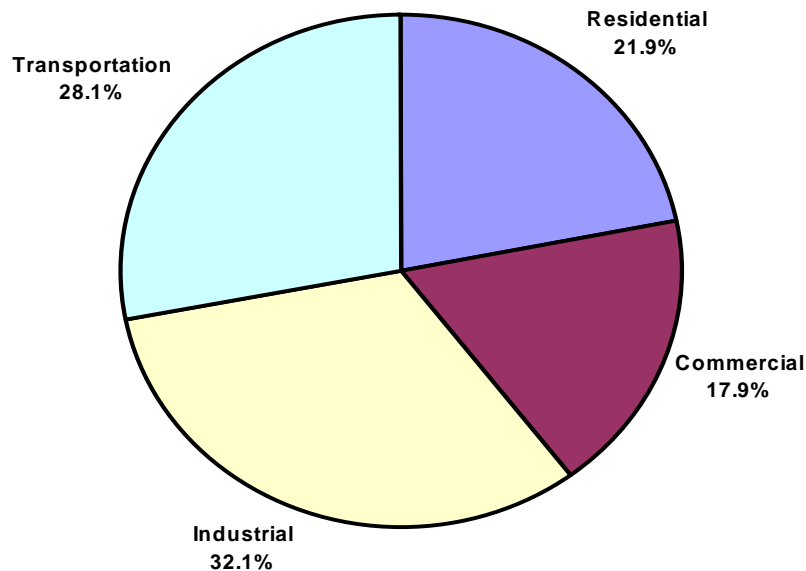
Source: U.S. Department of Energy, Energy Information Administration, Energy Flow.

**Figure 9: U.S. Sources of Energy Consumed, 2005**

Source: U.S. Department of Energy, Energy Information Administration, Monthly Energy Review, April 2006.

**Figure 10: Energy Consumption by Source, 1949 - 2005**

Source: U.S. Department of Energy, Energy Information Administration, Annual Energy Review

**Figure 11: U.S. Consumption of Energy by Sector, 2005**

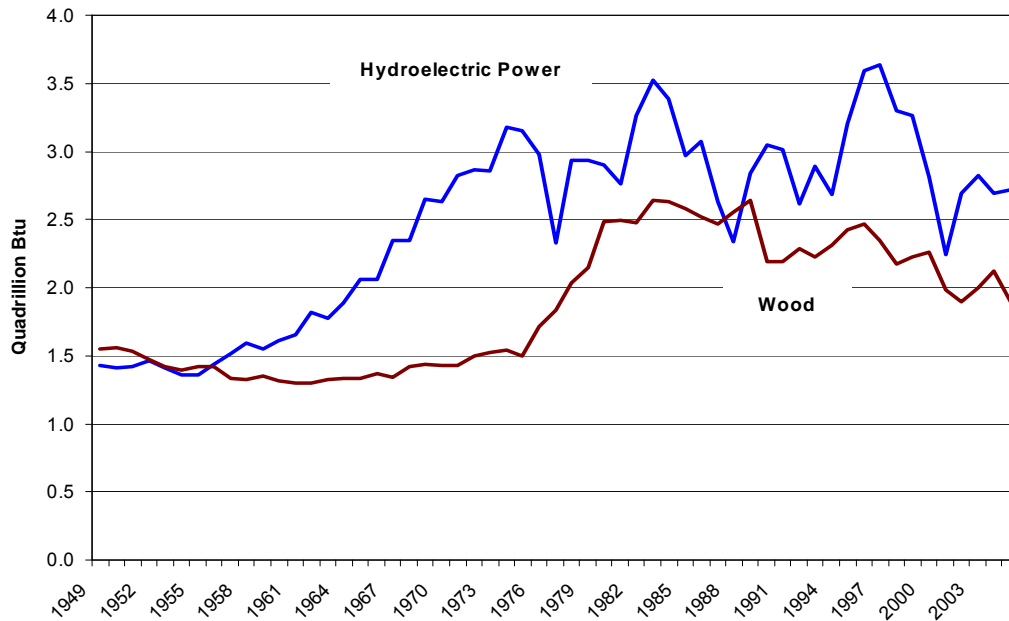
Source: U.S. Department of Energy, Energy Information Administration, Monthly Energy Review, April 2006.

Renewable energy comes from a half-dozen sources:

- Hydroelectric: Renewable energy from hydroelectricity.
- Wood: Wood, black liquor, and other wood waste.
- Waste: Municipal solid waste, landfill gas, sludge waste, tires, and agricultural byproducts - including animal waste - and other biomass (plant material and residue).
- Alcohol: Ethanol blended into motor gasoline.
- Geothermal: Geothermal electricity net generation, heat pump, and direct use energy.
- Solar: Solar thermal and photovoltaic electricity net generation, and solar thermal direct use energy.

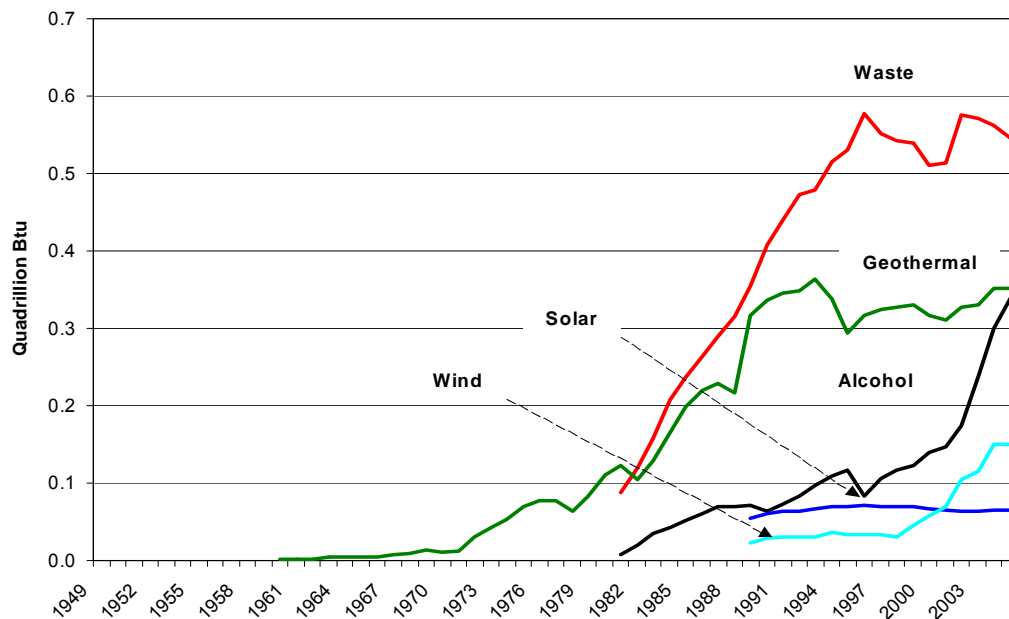
Hydroelectric power and wood-based power contribute the largest amount of renewable energy by a wide margin (Figure 12). However, their growth has remained flat since the 1980s. In general, other renewable energy sources have shown greater increases in their rate of adoption (Figure 13). Alcohol (ethanol) and wind-based renewables have grown most quickly, with compound annual growth rates of 11.9 percent and 11.6 percent from 1990 to 2005 (EIA). Still, they account for less than 3 percent of total renewable energy consumption (EIA).

**Figure 12: U.S. Renewable Energy Consumption by Source, 1949 - 2005, Part 1**



Source: U.S. Department of Energy, Energy Information Administration, Annual Energy Review.

**Figure 13: U.S. Renewable Energy Consumption by Source, 1949 - 2005, Part 2**



Source: U.S. Department of Energy, Energy Information Administration, Annual Energy Review.

### **III. Biofuels**

The U.S. biofuels industry has its origins in the economic and political shocks of the 1973 and 1979 oil embargoes by the Organization of Petroleum Exporting Countries (OPEC), which generated political pressure to reduce dependence on imported petroleum. The OPEC oil embargoes and subsequent price shocks of the 1970s stimulated a worldwide movement to find alternatives to petroleum based fuels. The United States established a series of programs to encourage production of biobased fuels. However, low petroleum prices in the late 1980s slowed growth in biofuels production during that period, despite the research efforts and incentive programs put in place.

In the 1990s, demand for ethanol in the United States was primarily driven by provisions in the Clean Air Act of 1990, which mandated the use of oxygenates in the reformulated gasoline and winter oxygenate programs that it created. Much of the current interest in biofuels has been driven by high petroleum prices. In August 2005, oil prices reached \$70 a barrel, and the EIA forecasted that oil prices would move down from that level to the \$ 40-50 range a barrel (inflation adjusted) level for the next 25 years.

Many states were early leaders in laws and programs to encourage the production and use of biofuels, and today, all 50 states have at least one such program<sup>2</sup>.

Today, biofuels production is growing rapidly for several reasons:

- Biobased fuels like ethanol contain more oxygen than gasoline, so blended fuels burn cleaner and reduce air pollution.
- High oil prices.
- Use of biofuels is seen as a way to reduce dependence on foreign oil and increase reliability of energy supplies.
- Shifting to biobased fuels to replace petroleum can cut net emissions of greenhouse gases.
- Public policy incentives have reduced the investment risk in the industry.

#### **A. Ethanol**

##### **1. Policy Environment**

While petroleum costs were high in the 1970s and early 1980s, enthusiasm for programs to find and develop new energy sources was high; however, as petroleum prices declined during the remainder of the 1980s and 1990s, public support for, and the perceived need for, alternative energy receded. Against this trend, the funding of ethanol incentives and implementation of demand-enhancing programs continued,

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<sup>2</sup> Appendix 1 presents State policies and lists individual State programs.



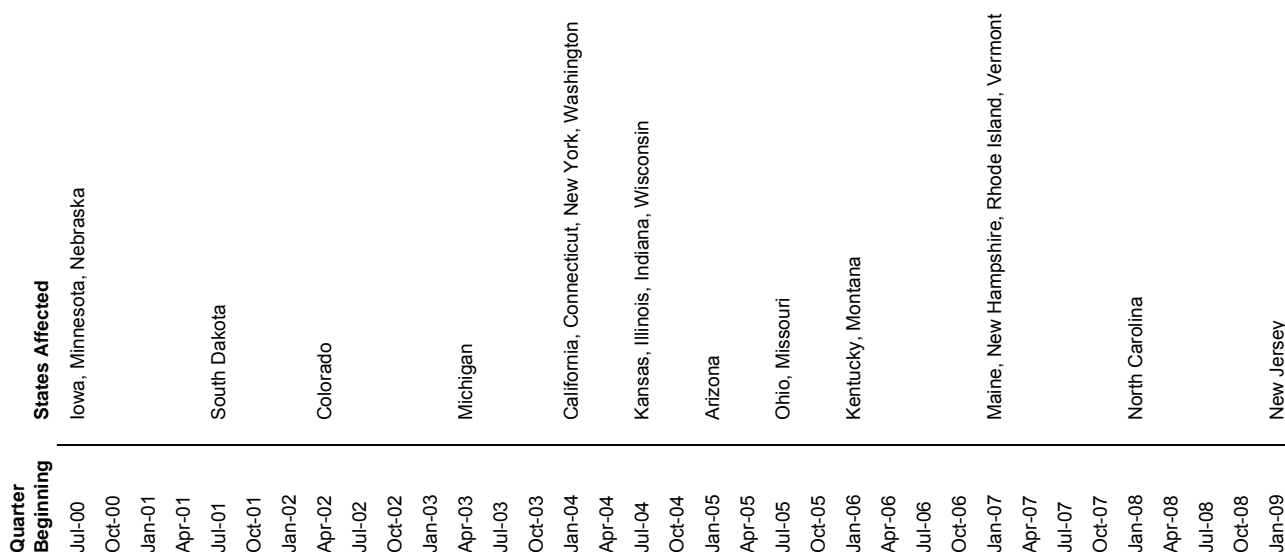
mainly through support from and the efforts of special interest groups representing agriculture and the environment and organizations promoting alternative fuels.

In 1990, a new source of demand for ethanol was created when the Congress passed amendments to the Clean Air Act (referred to as CAA90), establishing two programs to reduce automotive pollution by mandating specifications for “cleaner” fuel. The Oxygenated Fuels Program (OXY Program) was targeted at reducing carbon monoxide emissions, whereas the Reformulated Gasoline Program (RFG Program), implemented in 1995, was intended to reduce smog-forming emissions.

Methyl tertiary butyl ether (MTBE) was the predominant oxygenate used in the RFG Program prior to 2003. However, MTBE caused long lasting contamination of water supplies, particularly in metropolitan areas participating in the RFG Program. The health effects of low levels of MTBE in water are subject to debate, but it is thought to be carcinogenic when ingested at high doses. The 2005 Energy Policy Act (EPACT) did not include a nationwide ban on the use of MTBE, but it did remove the oxygenate requirement in the RFG Program in May 2006. Additionally, many states have banned the use of MTBE, most notably California, New York, and Pennsylvania - making ethanol the only alternative for use in reformulated gasoline. Bans and other severe restrictions in the use of MTBE have been applied in 25 states (Figure 14).

State MTBE bans has been encouraging production and consumption of ethanol, and oil companies’ decisions to remove MTBE from their supply chains have caused a surge in ethanol demand. As the MTBE was successively banned by states, the demand for ethanol grew until it reached approximately 3.9 billion gallons in 2005.

**Figure 14: Timetable for Implementation of Methyl Tertiary Butyl Ether State Bans**

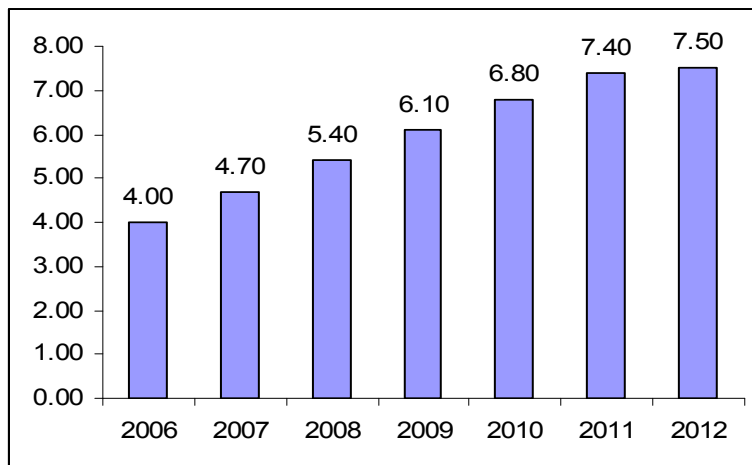


Sources: Informa Economics et al., Biobased Multi-Client Study, March 2006.

Historically, the primary Federal incentive for ethanol use was the exemption of ethanol-containing blends from a portion of the Federal excise tax on motor fuels. Through late 2004, blends containing 10 percent ethanol (from renewable resources) were exempt from \$0.052 of the \$0.184 federal excise tax on each gallon of motor fuel. To streamline the management of the ethanol incentive and to avoid depleting the Highway Trust Fund, the JOBS Act, signed on October 22, 2004, contained a provision replacing the Federal excise tax exemption with an equivalent tax credit paid out of general government revenues. This arrangement, known as the Volumetric Ethanol Excise Tax Credit (VEETC), involves an excise tax credit of \$0.51 per gallon of ethanol blended into the gasoline. Small ethanol producers (production capacity less than 60 million gallons) receive an additional 10 cents per gallon tax credit on the first 15 million gallons of production annually.

The growth in ethanol demand after 1993 led to concerns over supply shortfalls. The Bioenergy Program initiated by USDA in 2000 encouraged new biofuel production by compensating ethanol (and biodiesel) producers for feedstocks used for increasing biofuel production in comparison to the previous year on a ratio of 1 feedstock unit for every 2.5 used<sup>3</sup>. The 2005 Energy Policy Act (EPACT) included a number of incentives to encourage ethanol (and biodiesel) production and use, as well as research on new biofuel technologies to encourage the use of alternative feedstocks such as switchgrass, wood chips, and municipal and animal waste. A significant research agenda now focuses basically on conversion of biomass to ethanol. The most important provision for ethanol in the EPACT is a new renewable fuel standard (RFS) that requires motor fuels sold in the U.S. to contain certain volumes of renewable fuels in future years (Figure 15).

**Figure 15: Renewable Fuels Standard Timetable (in Billion Gallons)**



Source: EPACT 2005

<sup>3</sup> Large facilities (over 65 million gallons of annual production capacity) were reimbursed on a ratio of 1 to 3.5.

The vast majority of the renewable fuel used to meet this mandate will be ethanol, resulting in a possible doubling of the domestic ethanol industry in the next 6 years. With current ethanol production capacity above the 2006 standard of 4 billion gallons and substantial new capacity under construction, the domestic ethanol industry should have no problem meeting the 2012 mandate of the RFS.

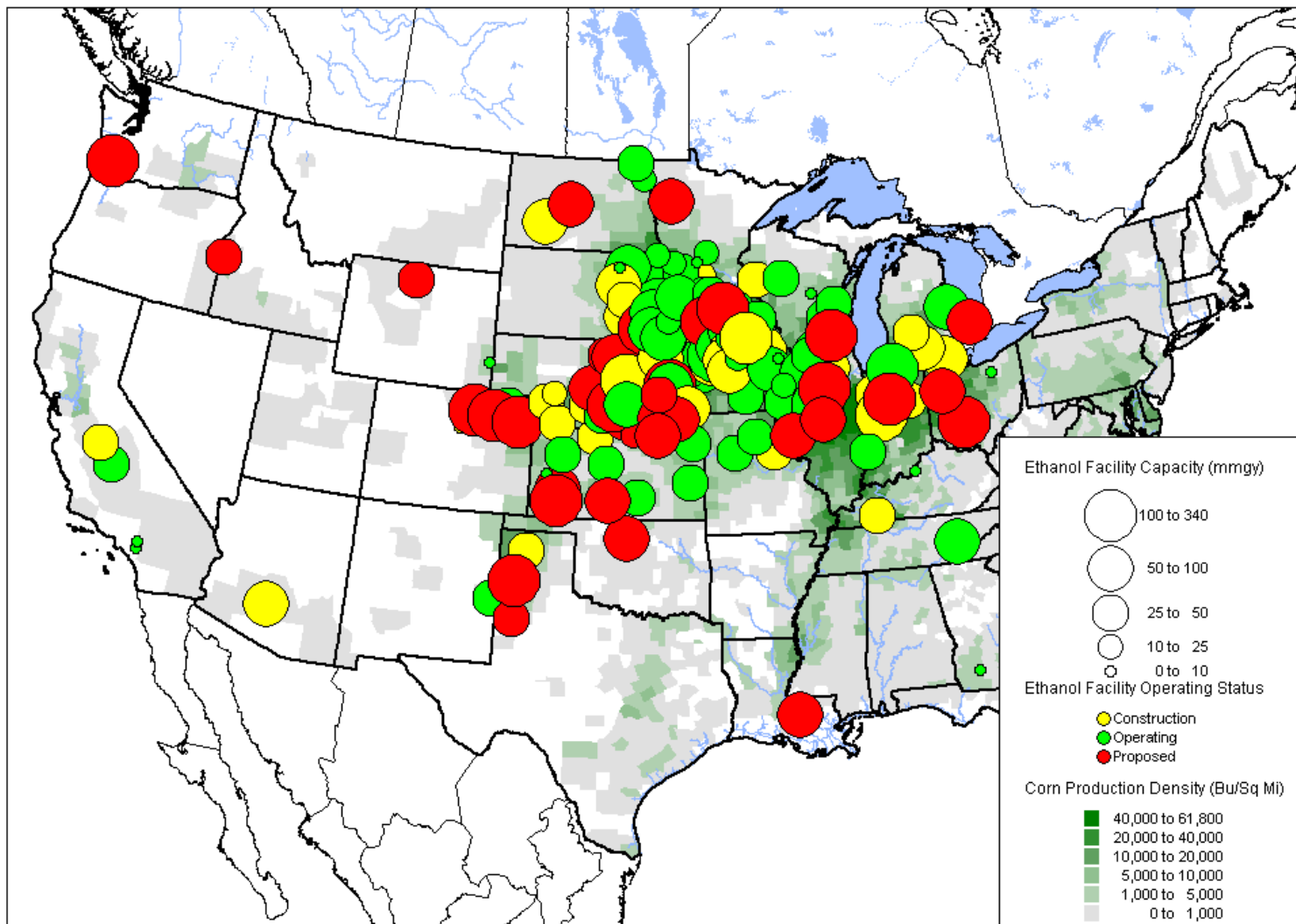
## **2. Ethanol Supply and Demand**

The CAA90 stimulated ethanol demand, and ethanol production capacity has grown dramatically since 1990. The economics of ethanol production have been particularly strong during the last 5 years, due to long stretches when low corn prices coincided with high gasoline prices. These high margins, as well as bans on MTBE use in California, New York, and other states, prompted industry capacity to more than double. As of April 2006, ethanol production capacity had reached 4.8 billion gallons, with another 2.2 billion gallons under construction, according to the Renewable Fuels Association (Map 1). Most existing facilities are in the middle of the Corn Belt, but new facilities are being proposed both on the edges of the Corn Belt and, to a lesser extent, in destination markets such as California and New York.

The U.S. renewable fuels market is in the midst of profound changes on both the supply and demand side. The RFS included in the 2005 Energy Bill will serve a floor for the future trajectory of renewable fuels consumption, including ethanol, while the clean air programs that drove the doubling of ethanol use in the 1990s will recede in importance, with the elimination of the oxygenate requirement in the RFG Program as of May 2006.

From 2000 to 2005, ethanol production and use more than doubled (Table 4 and Table 5). U.S. exports have been relatively flat, but imports have increased significantly since May 2004 (Figure 16). Driven by the stable policy environment provided by the Energy Bill and VEETC passage, as well as high margins for producers, Informa estimates that ethanol production and use are expected to grow even more rapidly through 2007, at an estimated 27 percent a year.

**Map 1: Existing, Under Construction, and Proposed U.S. Ethanol Facilities  
Relative to Corn Production, April 2006**



Source: Renewable Fuels Association (plants existing and under construction as of February 2006), Informa Economics (proposed facilities).

**Table 4: Ethanol Supply/Demand Balance, 2000 - 2007**

Million Gallons

	2000	2001	2002	2003	2004	2005	2006	2007
Beginning Inventories	151	140	169	259	221	252	<b>240</b>	<b>341</b>
Production	1,630	1,766	2,140	2,804	3,402	3,904	<b>4,773</b>	<b>6,432</b>
Imports	63	50	52	61	164	138	<b>257</b>	<b>360</b>
Total Supply	1,844	1,955	2,360	3,125	3,787	4,294	<b>5,270</b>	<b>7,133</b>
Domestic Usage	1,649	1,712	2,054	2,841	3,488	3,991	<b>4,871</b>	<b>6,615</b>
Exports	55	75	47	63	47	63	<b>58</b>	<b>58</b>
Total Disappearance	1,704	1,786	2,101	2,904	3,536	<b>4,054</b>	<b>4,929</b>	<b>6,674</b>
Ending Inventories	140	169	259	221	252	<b>240</b>	<b>341</b>	<b>459</b>

**Bold** numbers represent Informa Economics forecasts.

Sources: U.S. Department of Energy (historical production and inventory data), International Trade Commission (historical import data), Informa Economics (calculations and forecasts).

**Table 5: Ethanol Supply/Demand Balance, Crop Year (Sept. - Aug.) 1999/00 - 2006/07**

Million Gallons

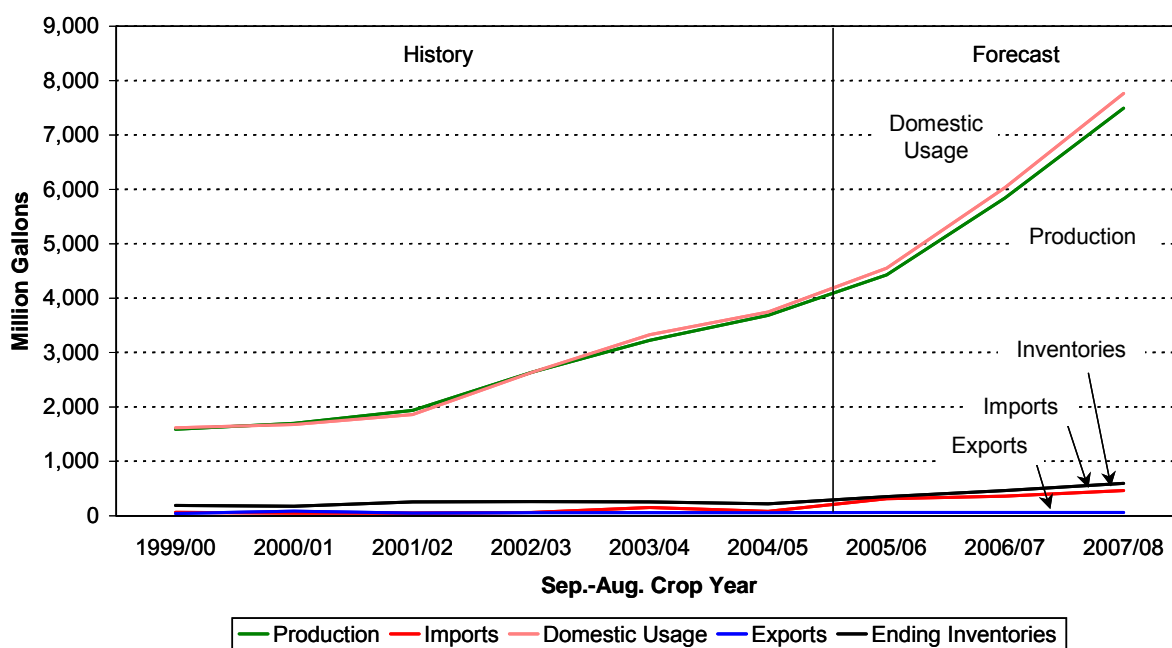
	1999/00	2000/01	2001/02	2002/03	2003/04	2004/05	2005/06	2006/07
Beginning Inventories	195	191	177	253	261	255	220	<b>351</b>
Production	1,590	1,699	1,936	2,634	3,228	3,685	<b>4,430</b>	<b>5,844</b>
Imports	62	48	50	61	153	82	<b>313</b>	<b>360</b>
Total Supply	1,846	1,938	2,163	2,949	3,642	4,022	<b>4,963</b>	<b>6,555</b>
Domestic Usage	1,614	1,677	1,862	2,632	3,330	3,745	<b>4,553</b>	<b>6,033</b>
Exports	41	83	48	56	57	57	<b>58</b>	<b>58</b>
Total Disappearance	1,655	1,760	1,910	2,688	3,387	3,801	<b>4,612</b>	<b>6,091</b>
Ending Inventories	191	177	253	261	255	220	<b>351</b>	<b>463</b>

**Bold** numbers represent Informa Economics forecasts.

Sources: U.S. Department of Energy (historical production and inventory data), International Trade Commission (historical import data), Informa Economics (calculations and forecasts).

To forecast industry capacity and production through 2008, Informa reviewed information about facilities that were under construction or had been proposed as of February 2006 (Map 1). Map 1 also highlights the heavy concentration of ethanol production in the United States near areas with high corn production density. For facilities under construction (or existing facilities that were expanding), Informa reviewed the dates when construction began, applied typical timelines for construction, and drew conclusions about when the incremental capacity would be online. Informa also developed a proposed plant list, conducted an informal review of the status of their progress with respect to key milestones (e.g., air permit applications, financing, negotiations with design and building companies), and drew conclusions about whether individual plants were likely to come to fruition and, if so, over what time period. This review was used to forecast ethanol capacity and production through 2008, the end of the “visible horizon” for plants that are currently being organized. In April 2006, Informa estimated 2008 ethanol production to be 7.9 billion gallons, which exceeds the 7.5 billion gallon level of the Renewable Fuel Standard for 2012. Given that ethanol would account for roughly 6 percent of the U.S. gasoline supply and that crude oil prices are expected to remain firm and corn prices moderate (assuming normal weather), this rapid growth likely will not result in low or negative margins - at least through 2008.

**Figure 16: Ethanol Supply/Demand Balance, Sep. - Aug. Crop - Year**



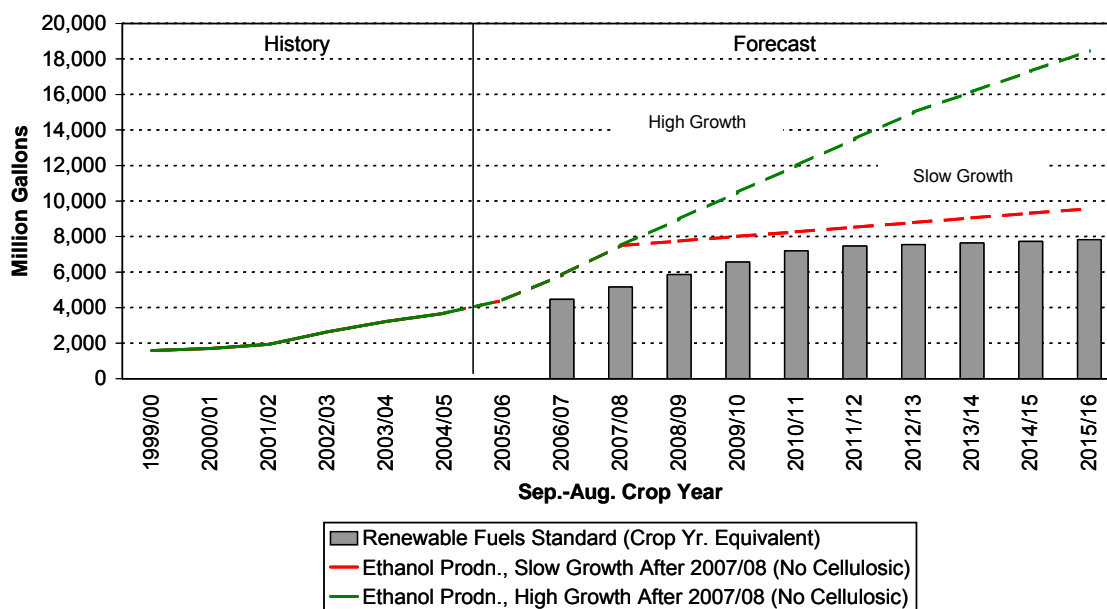
Sources: U.S. Department of Energy, International Trade Commission, and Informa Economics.

Capacity forecasts cannot be made much beyond 2008 by assessing the set of plants that are under construction or proposed as of mid-2006. Rather, long-term forecasts must be made based on expected industry responses to the macroeconomic and policy environment that is forecast to occur. After 2008, crude

oil prices are expected to recede toward a long-run equilibrium level of \$40-\$50 a barrel (inflation adjusted) [EIA], which in Informa's view will result in lower ethanol prices. Additionally, production will significantly exceed the RFS, and the Federal excise tax credit is scheduled to expire in 2010. The probability that the credit will be extended is judged by Informa to be high, although it is also possible the incentive will be extended at a lower level. Given this environment, capacity additions are expected to slow after 2008, with production approaching 10 billion gallons per year by 2015 under the slow growth scenario (Figure 17).

However, if oil prices are still significantly above their long-term average and given that there appears to be considerable political support for ethanol, a more aggressive long-run growth scenario is possible (Figure 17). In 2006, the pace of new facility announcements was brisk. Moreover, there are efforts underway in Congress to increase the RFS levels, given that production is expected to continue to exceed the RFS for the foreseeable future. This scenario assumes that the rate of annual capacity additions will be essentially the same during the 2008 - 2015 period as during 2006 - 2008.

**Figure 17: Ethanol Production and the Renewable Fuels Standard through 2015; High Growth and Slow Growth Scenarios**



Sources: U.S. Department of Energy (history), Informa Economics (forecasts).

Under both growth scenarios, ethanol production is expected to be greater than the RFS requirement for every year of the outlook, unless the RFS is increased through legislation, but both scenarios developed by Informa Economics assume that cellulosic ethanol will not yet be viable on a large scale by 2015. If cellulosic conversion becomes economically viable earlier, as some industry sources believe, ethanol production increases would be more rapid than projected here.

### 3. Ethanol Coproducts

Virtually all of the ethanol facilities built during the last decade have been dry mills, which grind and then directly process corn, as opposed to wet mills, which separate the corn kernel into its component parts. In the dry-mill process, the starch portion of the kernel is largely converted to ethanol, while the remaining material - mainly fiber and protein - referred to as distillers grains, is usually sold as livestock feed.

“Usually, distillers’ grains is dried to yield dried distillers grains (DDG), or dried distillers’ grains with solubles (DDGS) if solubles in the thin stillage are added back to the grains at drying. The solubles in the thin stillage may also be partially or totally dried to make condensed distillers solubles (CDS) or dried distillers solubles (DDS), respectively. Of these co-products, DDG and DDGS are the most commonly used, probably because of ease of handling, storage, and shipping.” (Akayezu et al.)

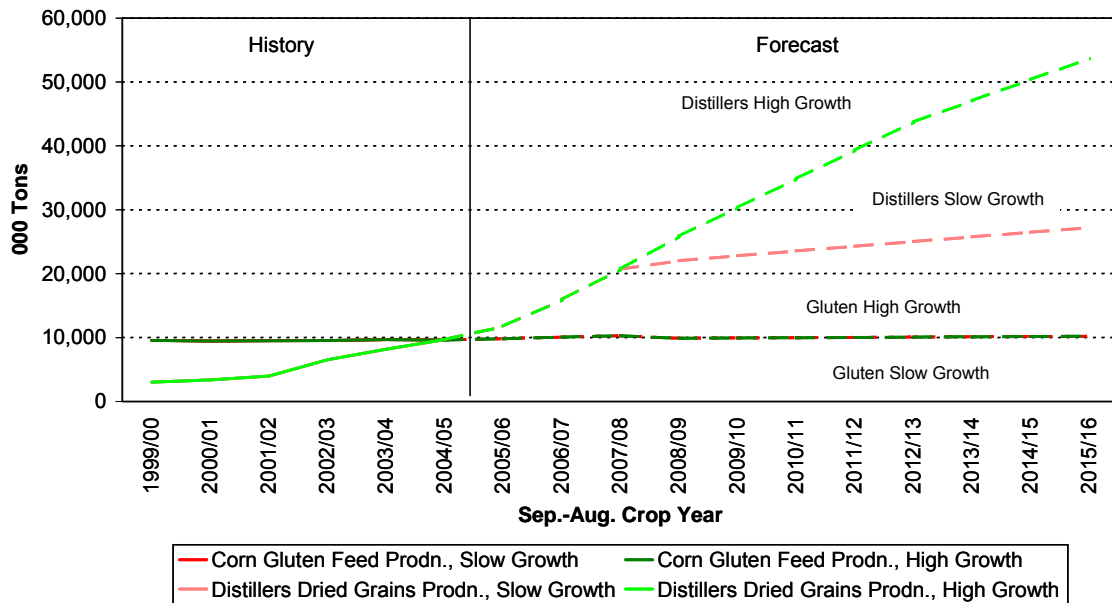
Since DDGS is becoming the most common form in the market, it will be used in this section as the “common denominator” of this group of coproducts.

DDGS is a middle-protein feed with a minimum crude protein content of roughly 27 percent, although this can vary significantly among facilities and is typically over 30 percent for newer facilities. DDGS is predominantly used in feed for ruminants (mainly cattle), as its composition limits the inclusion rate in feed for monogastric animals (e.g., hogs and poultry). Both domestic consumption and exports of DDGS have risen along with the expansion of the ethanol industry. Still, the volumes involved remain modest compared with the overall size of the markets for feed grains, protein meals, and nongrain feed ingredients.

Figure 18 shows production estimates for coproducts from all corn processing activities, excluding cereal and other dry food products; volume is shown under both ethanol output scenarios. Coproducts from the wet milling process (corn gluten feed and corn gluten meal) are expected to remain essentially flat in the high and low growth scenarios as few, if any, of the new facilities will be wet mills. Output of DDGS is expected to increase along with the increase in ethanol production. Under both scenarios, 20.7 million short tons of distiller’s grains will be produced in 2007/08 double the DDGS output in 2004/05. In the low-growth scenario, DDGS production increases to 27.2 million tons by 2015/16. In the high-growth scenario, it increases to 53.7 million tons. These forecasts are based on the ethanol volume outlooks discussed previously, a yield of 17.5 lbs. of DDGS per bushel of feed grain consumed and the expectation that ethanol yields per bushel of feed grain used will continue to increase, with new facilities achieving yields of 2.9 gallons/bushel in 2015 compared to 2.8 gallons/bushel in 2006.



**Figure 18: Coproduct Output from All Corn Processing**



Note: Excludes cereal and other dry food product processing.  
 Source: Informa Economics (estimates and forecasts).

DDGS can only be included in limited quantities in livestock rations. The total potential size of the domestic DDGS market is approximately 53 million tons a year, or about 2.5 times the estimated DDGS production in 2007/08 (Table 6). This ignores smaller markets for DDGS, such as in feed for layers, turkeys, and aquaculture, as well as in pet food. However, typical inclusion rates in livestock rations are lower than the maximum recommended rates, and some operations might choose not to use DDGS, especially if their location makes it impractical, and/or transportation costs make it uneconomical. Of course, animal production is expected to continue to trend higher over the next decade, increasing the potential size of the DDGS market. As production reaches such levels - especially in the high-growth scenario - it would likely be necessary to increase exports of DDGS.

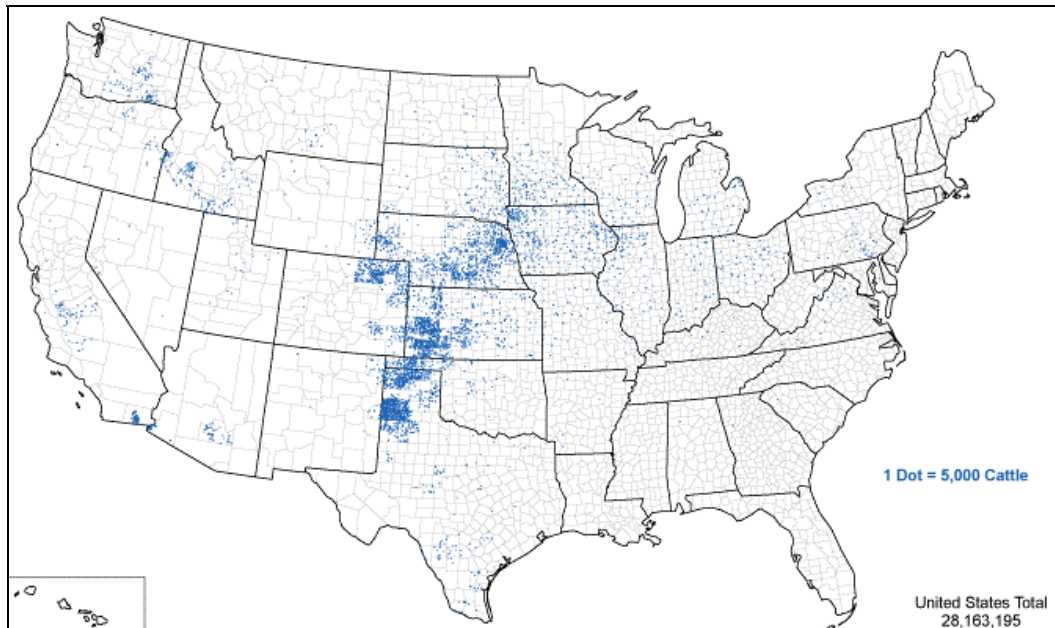
The largest potential markets for DDGS are in areas with large milk cow and cattle-on-feed (feedlot) inventories, which account for 41 million tons of maximum potential DDGS demand, based on animal inventories as of 2005. The largest cattle-on-feed inventories are in the Central and Southern Plains (Map 2), while the largest milk cow inventories are in the Upper Midwest, California, upstate New York, and Pennsylvania (Map 3). While not nearly as large as the potential market in cattle feeding, hogs and poultry together account for 12 million tons of maximum potential DDGS demand. Large hog inventories exist in the Mideast and in North Carolina (Map 4). Broiler production is spread throughout the Southeast, with Georgia and Arkansas each producing 1.2 billion birds/year (Map 5).

**Table 6: Distillers' Dried Grains: Maximum Potential Consumption by the Major U.S. Livestock Sectors, 2005**

<b>Animal/Growth Stage</b>	<b>Maximum Inclusion Rate</b>	<b>Quantity co- Total feed/day products /day (lbs)</b>	<b>Animal Quantity 2005 (000's head)</b>	<b>Maximum DDGS Consumption (tons)</b>
<b><u>Hogs and Pigs</u></b>				
Nursery pigs, under 60 lbs	5.0%	1.15	0.06	206,601
Grower pigs, 60-119 lbs	15.0%	4.77	0.72	1,704,575
Finish pigs, 120-179 lbs	20.0%	5.06	1.01	2,005,918
Hogs and pigs 180 lbs and over	22.0%	6.00	1.32	1,472,863
Hogs and pigs for breeding	35.0%	5.00	1.75	1,920,083
Developing gilts	20.0%	6.62	1.32	170,591
<b>Total maximum swine DDGS use</b>				<b>7,480,630</b>
<b><u>Cattle and Calves</u></b>				
Milk cows	30.0%	50.00	15.00	24,651,188
Cattle on feed	35.0%	18.30	6.41	16,518,955
<b>Total maximum cattle DDGS use</b>				<b>41,170,142</b>
<b><u>Broilers</u></b>				
Total broiler production	10%	Total feed/pound produced 2.00	Liveweight pounds Produced 2004 (000's) 44,635,400	Maximum DDGS Consumption (tons) 4,463,540
<b>Total maximum broiler DDGS use</b>				<b>4,463,540</b>
<b>Total maximum DDGS use (all species)</b>				<b>53,114,312</b>

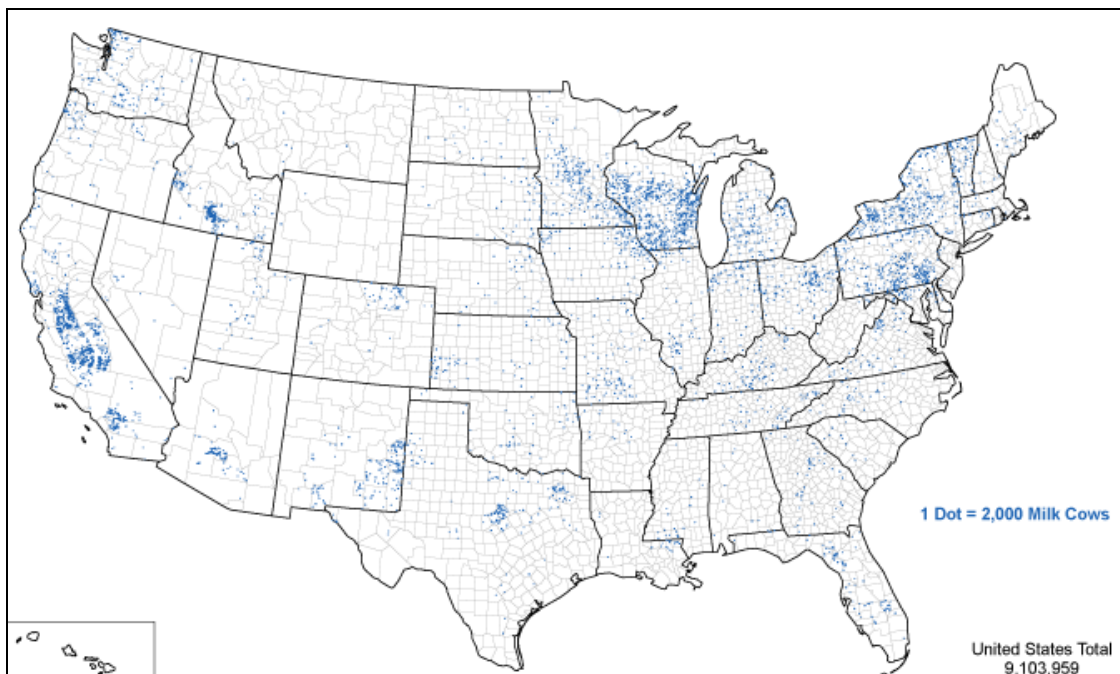
Source: Informa Economics et al., Biobased Multi-Client Study, March 2006.

**Map 2: U.S. Marketings of Cattle on Feed, 2002**



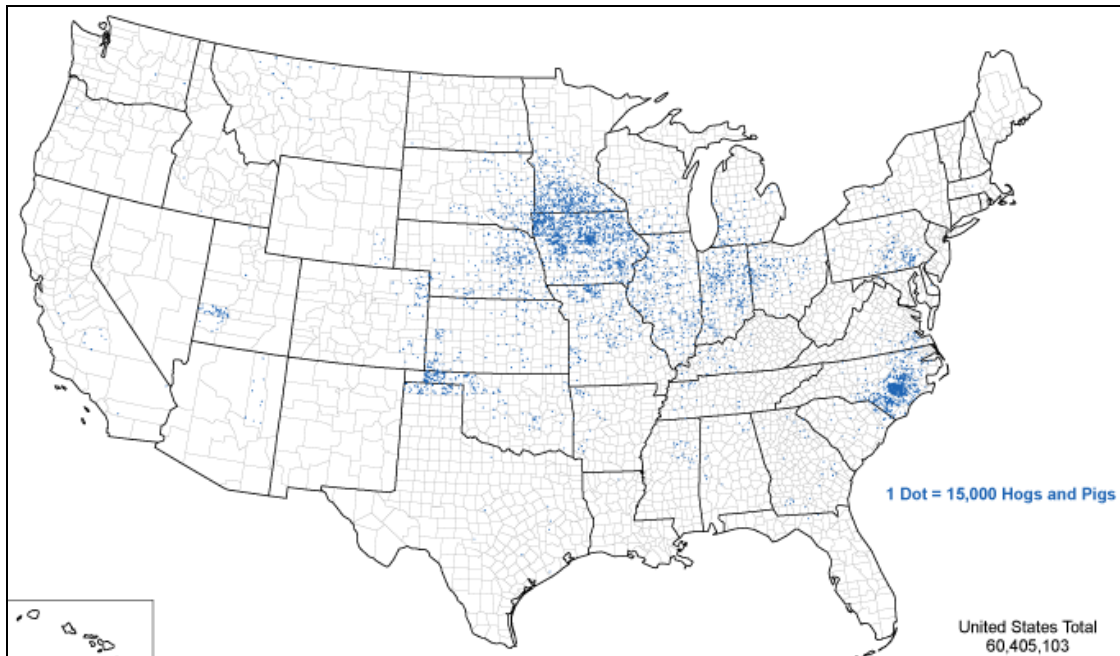
Source: U.S. Department of Agriculture, National Agricultural Statistics Service, 2002 Census of Agriculture.

**Map 3: U.S. Milk Cow Inventories, 2002**



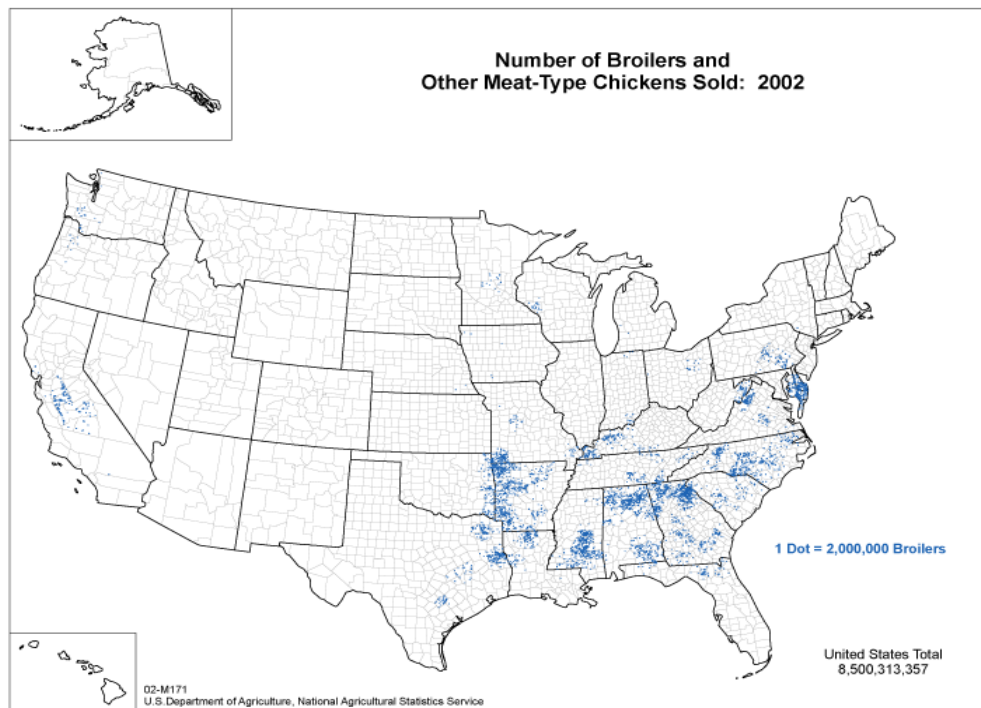
Source: U.S. Department of Agriculture, National Agricultural Statistics Service, 2002 Census of Agriculture.

**Map 4: U.S. Inventories of Hogs and Pigs, 2002**



Source: U.S. Department of Agriculture, National Agricultural Statistics Service, 2002 Census of Agriculture.

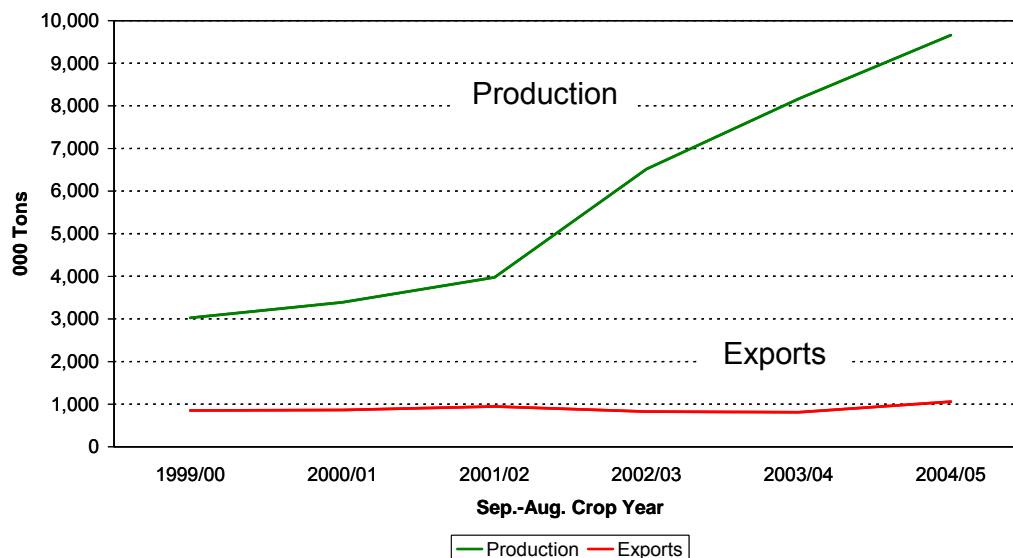
**Map 5: Broiler Production by State: Number Raised (000's), 2003**



Source: USDA, National Agricultural Statistics Service, April 2004.

Despite the rapid increase in DDGS production over the last decade, DDGS exports have stayed within 600,000 to 1.06 million tons (Figure 19). Over half of the exports have historically gone to the European Union, with Canada and Mexico also significant markets. Over the last couple of years, the Asian market for DDGS has begun to develop, although current volumes are modest.

**Figure 19: U.S. Distillers' Grains Production and Exports**



Source: Informa Economics et al., Biobased Multi-Client Study, March 2006.

#### 4. Ethanol Producer Net Margins

The ethanol industry has enjoyed significant returns in recent years as the price of oil reached record highs and corn prices have remained low. What if the price of oil were to retreat to \$25 a barrel and corn were to rise to \$4 a bushel? How would the ethanol industry be affected? Table 7 illustrates how changes in critical financial variables affect the bottom line. What follows is an elaboration of the method used to construct the matrix and observations regarding some of the findings.

Net ethanol producer operating margin (excluding depreciation and taxes) is calculated as follows:

- Ethanol Rack Price
- Transportation and Handling Costs
- Cash Corn Cost
- + DDGS Cost
- Natural Gas Costs
- Interest Expense (for a 100-million gallon facility)
- Operating and Other Costs (e.g., chemicals)
- = Net Ethanol Producer Operating Margin (excluding depreciation and taxes)

- The two most important factors in determining ethanol producer margins are corn and ethanol prices.
- With ethanol rack prices at \$1.80 a gallon; producer operating margins are still estimated to be slightly positive with corn prices as high as \$5.00 a bushel. It should be noted that in a high corn price environment, such as \$5.00 a bushel, DDGS prices would also be commensurately higher, trading in a range well above \$200 a ton. The higher DDGS prices would help offset a small portion of the higher feedstock prices. Note: after accounting for depreciation and other non-operating costs, net income could be negative on average. Given the same ethanol rack price of \$1.80 a gallon, margins would be approximately \$0.71 a gallon with corn prices of \$2.00 a bushel.
- If oil prices fall to their long run average of \$25 a barrel (corresponding to an ethanol price of \$1.20 a gallon based on historical relationships), corn prices would have to remain below \$3.00 a bushel for ethanol producers to achieve a positive operating margin. This demonstrates the key role of energy prices in determining the profitability of an ethanol producer.

**Table 7: Cash Ethanol Producer Net Margins Matrix (Excluding Depreciation)**

		Energy Prices										
		Ethanol f.o.b. Plant Price (\$/gallon)	1.00	1.20	1.40	1.60	1.80	2.00	2.20	2.40	2.60	
		Natural Gas (\$/mmBtu)	2.23	3.40	4.58	5.76	6.93	8.11	9.29	10.47	11.64	
Cash Corn and DDGS Prices	Corn (\$/bushel)	DDGS (\$/ton)										
	1.50	66	0.18	0.34	0.50	0.66	0.82	0.98	1.14	1.30	1.46	
	1.75	77	0.13	0.29	0.45	0.60	0.76	0.92	1.08	1.24	1.40	
	2.00	88	0.07	0.23	0.39	0.55	0.71	0.86	1.02	1.18	1.34	
	2.25	99	0.01	0.17	0.33	0.49	0.65	0.81	0.97	1.13	1.28	
	2.50	110	(0.04)	0.11	0.27	0.43	0.59	0.75	0.91	1.07	1.23	
	2.75	121	(0.10)	0.06	0.22	0.38	0.53	0.69	0.85	1.01	1.17	
	3.00	132	(0.16)	(0.00)	0.16	0.32	0.48	0.64	0.79	0.95	1.11	
	3.25	143	(0.22)	(0.06)	0.10	0.26	0.42	0.58	0.74	0.90	1.05	
	3.50	154	(0.27)	(0.11)	0.04	0.20	0.36	0.52	0.68	0.84	1.00	
	3.75	165	(0.33)	(0.17)	(0.01)	0.15	0.30	0.46	0.62	0.78	0.94	
	4.00	176	(0.39)	(0.23)	(0.07)	0.09	0.25	0.41	0.57	0.72	0.88	
	4.25	187	(0.45)	(0.29)	(0.13)	0.03	0.19	0.35	0.51	0.67	0.83	
4.50	198	(0.50)	(0.34)	(0.19)	(0.03)	0.13	0.29	0.45	0.61	0.77		
5.00	220	(0.62)	(0.46)	(0.30)	(0.14)	0.02	0.18	0.34	0.49	0.65		

Assumptions:

- 34,000 Btu of natural gas used per gallon of ethanol produced.
- Ethanol conversion: 2.68 gallons/bushel of corn (average across U.S. plants; new facilities achieve a yield of 2.8 gallons//bushel or higher).
- DDGS yield: 17.5 lbs/bushel of corn.
- Interest expense: \$3.4 million.
- "Other" costs: 27¢/gallon.

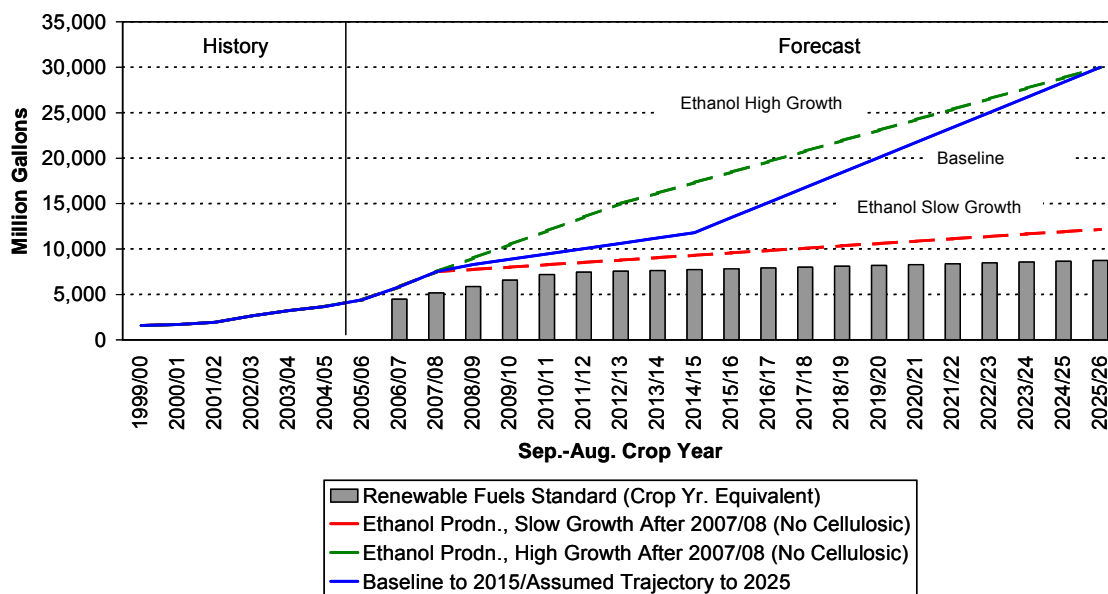
Source: Informa Economics et al., Biobased Multi-Client Study, March 2006.

## 5. Ethanol Outlook to 2025

This analysis assumes that cellulosic ethanol is not expected to be commercially viable on a large scale until at least 2015. Furthermore, ethanol is expected to have a higher value as an octane enhancer than as a primary fuel such as E85, since ethanol gets fewer miles per gallon due to its lower energy content. Since not all areas of the country will have the infrastructure to receive and handle ethanol and since there is a myriad of fuel composition requirements in different areas of the country affecting the functionality and applicability of ethanol, some resistance to further volume gains is likely as an average of 10 percent ethanol blend nationwide is approached. Further growth would suppress ethanol prices, and processing margins, based on the current outlook for corn prices, with an important determinant of corn prices being the expectation of increased corn yields. Thus, the baseline forecast is for ethanol production to reach 12 billion gallons in calendar 2015.

To determine the ability of the corn sector to absorb a larger increase, it was assumed that ethanol production would reach 30 billion gallons in calendar year 2025 with feed grains remaining the predominant feedstock (Figure 20). This would imply a compound annual growth rate of 10 percent, which is slightly less than the growth rate between 2005 and 2015, although this growth rate is forecast to slow significantly after 2008. The effect on corn production and prices is discussed later in chapter VIII, "Growth of the Biobased Economy: Projections and Impacts". While a corn based industry of 30 billion gallons is analyzed, it is also recognized that the potential for cellulosic ethanol to become commercially viable will improve, although grain would likely remain an important feedstock.

**Figure 20: Ethanol Production and the Renewable Fuels Standard Through 2025**



Source: Informa Economics et al., Biobased Multi-Client Study, March 2006.



## B. Biodiesel

### 1. The U.S. Biodiesel Market

Compared to the ethanol sector, the U.S. biodiesel market is still in its infancy. Average biodiesel capacity<sup>4</sup> for 2006 is estimated at 364 million gallons a year (mgy) including dedicated biodiesel capacity and existing oleochemical capacity that is being used for biodiesel production. Other estimates include 354 mgy (the National Biodiesel Board)<sup>5</sup> and 300 mgy (Archer Daniels Midland [ADM]) in the February 2006 issue of *Renewable Fuel News*. This capacity represents considerable growth: actual production and use of biodiesel was estimated at 91 mgy in 2005.

Development of the U.S. industry is highly dependent on Federal and state incentives that enable the production and distribution of biodiesel to compete with petroleum based diesel.

### 2. Federal Policy Environment

Biodiesel was a minuscule component of the U.S. motor fuel supply as recently as 1999, when production was only 500,000 gallons. The USDA Bioenergy Program initiated in 2000 created a boost in biodiesel production by compensating producers for feedstocks used for increased production (in comparison to the previous year). The compensation ratio was 1 feedstock unit for every 2.5 units used in the case of facilities with less than 65 million gallons of annual production capacity, and a ratio of 1 to 3.5 for larger facilities. Payments were made on 6.4 million gallons of biodiesel in FY 2001 and 8.9 million gallons in FY 2002<sup>6</sup>. The Farm Security and Rural Investment Act of 2002 continued the program through 2006 and broadened the list of eligible feedstocks to include animal byproducts and fat, oils, and greases (including recycled fats, oils, and greases).

While the bioenergy program provided some incentive to produce biodiesel, the surge in interest since 2004 has been a result of the American Jobs Creation Act of 2004, the EPACT of 2005, and high petroleum and diesel prices. The American Jobs Creation Act of 2004 established the first national incentive for biodiesel consumption by granting biodiesel blenders a tax credit of \$1.00 per gallon of biodiesel made from oil crops and animal fats and a \$0.50 per gallon tax credit for biodiesel made from recycled fats and oils. The incentive took effect on January 1, 2005, and was originally set to expire 2 years later. However, the 2005 EPACT extended this program until December 31, 2008.

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<sup>4</sup> Production capacity adjusted for the months during a calendar year that plant under construction does not operate. For example, a 12-mgy plant that starts operation on July 1 will only have production capacity for 6 months.

<sup>5</sup> Estimate of existing capacity as of February 2006.

<sup>6</sup> Fiscal year October to September.

The EPACT also created a new credit for agri-biodiesel <sup>7</sup> producers equal to 10 cents a gallon on the first 15 million gallons for facilities with annual capacity not exceeding 60 million gallons. Historically, small ethanol producers were allowed a similar credit. The credit can be offset against the alternative minimum tax, and sunsets December 31, 2008.

The EPACT established that starting in 2013 the share that 7.5 billion gallons of renewable fuels represents of the total volume of gasoline sold or introduced into commerce in 2012 will have to be maintained in future years, with a minimum of 250 million gallons derived from cellulosic biomass. The current volume of ethanol production capacity far exceeds that of biodiesel capacity, and, as a consequence, ethanol will likely account for most of the RFS volume. However, biodiesel's share of the RFS and its tax incentive is spurring increases in biodiesel production capacity.

Additional Federal incentives to stimulate investment in biodiesel include:

- Credit for Installation of Alternative Fuel Refueling Infrastructure. The installation of infrastructure that dispenses biodiesel-blended fuel (20 percent minimum blend) qualifies for this credit.
- Biodiesel Engine Testing Program. Authorizes funding of \$5 million a year (FY2006 - 2010) to initiate a collaborative research project testing biodiesel in advanced diesel engine and fuel system technology.

### **3. State Programs and Incentives**

Recent initiatives by several states to encourage biodiesel use - often via mandates that biodiesel be blended with petroleum diesel sold in particular markets or throughout the whole state - are expected to increase consumption. In 2003, Minnesota was the first state to pass legislation requiring nearly all petroleum diesel to be blended with 2 percent biodiesel (B2). The B2 Law requires Minnesota to have a production capacity of at least 8 million gallons of biodiesel fuel per year, with approximately 16 million gallons of biodiesel fuel needed to meet the state B2 requirement. The law takes effect whenever Minnesota plants come on line, triggering a 30 day public notification.

Other states are pursuing policies to enhance the use of biofuels. State incentives are critical to the biodiesel industry:

- In 2004, 130 biodiesel related bills were introduced; 27 passed (30 percent increase over 2003).
- In 2005, 142 biodiesel related bills were introduced in 33 states (Map 6).

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<sup>7</sup> Agri-biodiesel mean biodiesel derived solely from virgin feedstock oils and animal fats (versus, for example, spent feedstock oils from restaurants), including esters from virgin vegetable oils.



## b) U.S. Biodiesel Production and Capacity: Structure and Outlook

U.S. biodiesel production was roughly 91 million gallons in 2005. However, given the passage of the JOBS Act in late 2004, the 2 percent state requirement in Minnesota and the passage of EPACT, a number of firms have started construction or announced plans to build biodiesel production facilities. Information collected from the National Biodiesel Board, *Biodiesel Magazine*, and biodiesel companies indicates an estimated annual capacity (i.e., assigned to the year or portion of the year in which the biodiesel developer claimed to start operations) and production for different volumes of feedstock used, as of February 2006:

- At least 149 mgy of biodiesel capacity was available in 2005, growing to over 350 mgy in 2006. Capacity growth is due to both construction of new dedicated biodiesel capacity and the conversion of additional oleochemical capacity.
- As of March 2006 there were 59 active biodiesel plants, with capacity ranging from 60,000 gallons a year to 30 mgy.
- An additional 14 plants were under construction, with a combined capacity of 205 mgy; about one-third of this capacity would be available for production in calendar year 2006<sup>8</sup>.
- Ten proposed expansion projects could add another 62 mgy in capacity.
- Forty-five new plants were proposed with combined capacity of 692 mgy.

Based on this capacity, biodiesel production is estimated to grow to 298 million gallons in 2006. Approximately 83 percent of the biodiesel produced uses soybean oil as a feedstock. Yellow grease accounts for about 9 percent, animal fats for 6 percent, and other vegetable oils for 2 percent.

Some of the production capacity is from oleochemical companies that have converted to produce biodiesel. In 2005, the National Biodiesel Board estimated that the oleochemical industry had 110 mgy of capacity that could be used to produce biodiesel.

The biodiesel industry is largely concentrated in the Midwest where most soybean oil is produced, but there are many plants in the Northeast, South Central, and West Coast states (Map 7). In these regions, biodiesel production tends to use more yellow grease or animal fats than in the Midwest. This geographical distribution is in

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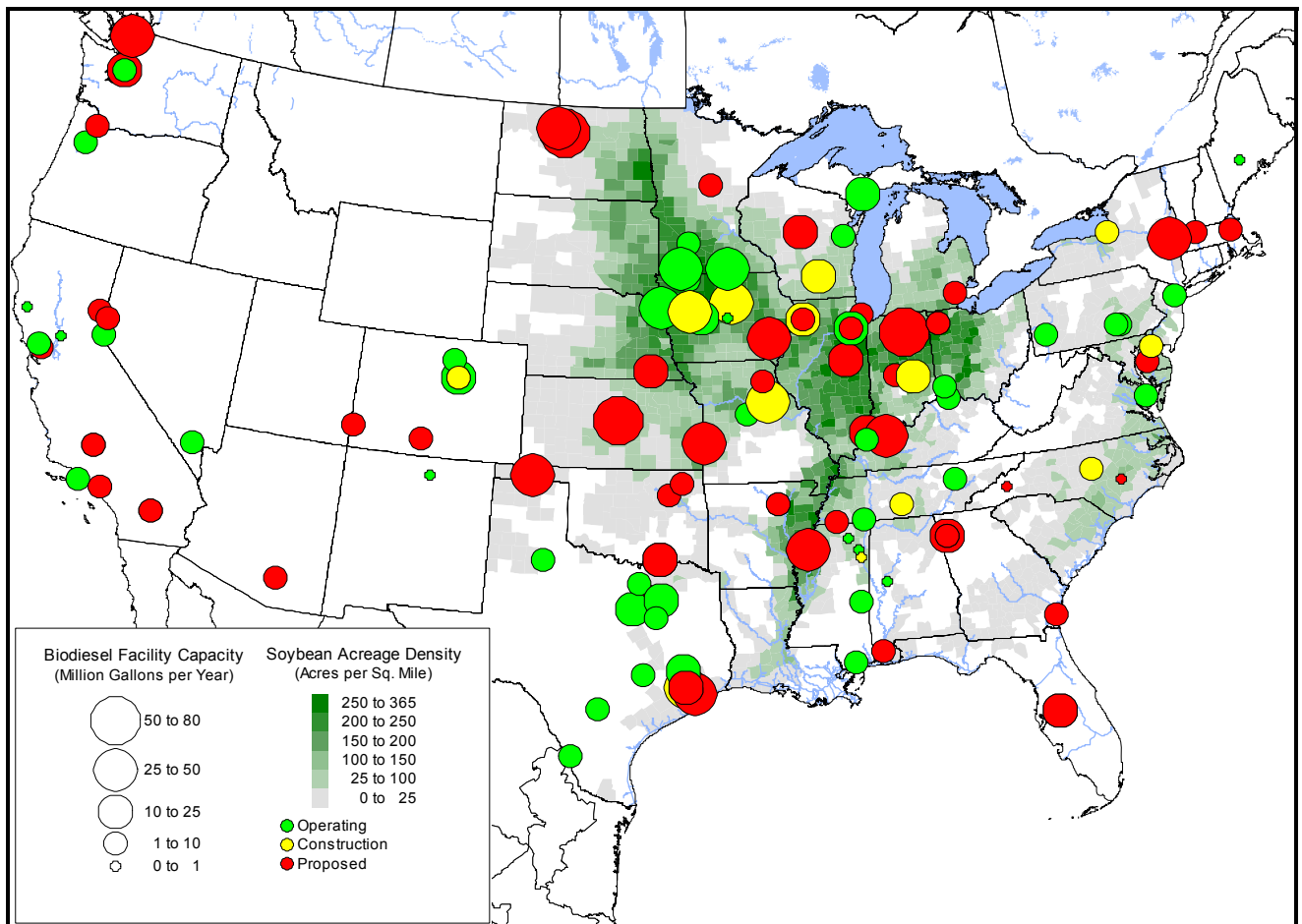
<sup>8</sup> The National Biodiesel Board has indicated that up to 35 companies have reported that their plants are currently under construction and are scheduled to be completed by July 2007. Their combined capacity, if realized, would result in another 278 mgy of biodiesel production.

contrast to ethanol production, which is almost exclusively in the Midwest where corn is grown.

The ethanol industry has been characterized by the clustering of plants around its feedstock source - corn. But as profit margins have expanded, plants are beginning to migrate to “destination markets” with corn now shipped greater distances. The biodiesel industry is emerging as more of a hybrid between destination and localized processing. Map 8 highlights the geographic dispersion of biodiesel production relative to the type of feedstocks being used and soybean production density.

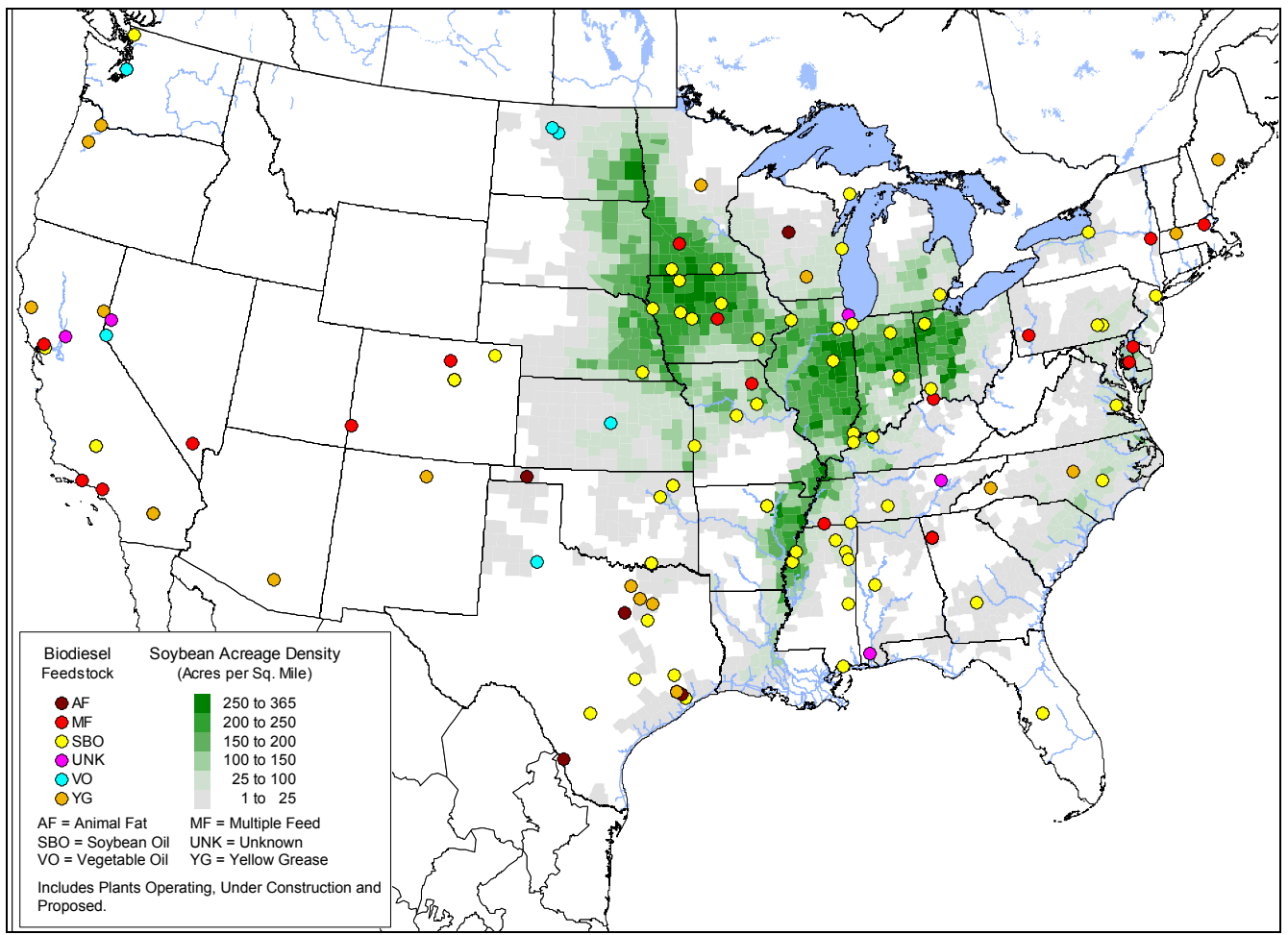
Biodiesel’s diverse feedstocks equate to potentially broad geographic support in Washington. Policies that enable biodiesel development have found widespread support outside of traditional farm states.

**Map 7: Major Biodiesel Facilities Currently Operating, Under Construction or Proposed Relative to U.S. Soybean Production, 2006**



Sources: U.S. Department of Agriculture, National Agricultural Statistics Service (soybean production), and Informa Economics (Survey of the Biodiesel Industry).

**Map 8: Biodiesel Facilities by Type of Feedstock Versus Soybean Acreage Production Density, 2006**



Sources: U.S. Department of Agriculture, National Agricultural Statistics Service (soybean production), and Informa Economics (Survey of the Biodiesel Industry).

**(1) Demand Implications**

Diesel demand over the next decade is expected to increase at the historical long-term trend growth of 2 percent a year (EIA)<sup>9</sup>. Demand will reach 65.7 billion gallons by 2015, an increase of 11.4 billion gallons over 2005 (Table 8).

**Table 8: U.S. Diesel Demand Outlook**

Million Gallons	2003	2004	2005	2006	2007	2008	2009	2010	2015
<b>Commercial</b>	1,285	1,425	1,498	1,527	1,566	1,610	1,651	1,681	1,816
<b>Industrial</b>	1,587	1,937	1,918	1,955	2,005	2,062	2,113	2,152	2,325
<b>Oil Company</b>	396	471	562	572	587	604	619	630	681
<b>Farm</b>	2,618	3,439	3,260	3,322	3,407	3,504	3,591	3,657	3,950
<b>Electric Power</b>	1,087	625	800	815	836	860	881	897	969
<b>Railroad</b>	2,618	2,814	2,864	2,919	2,993	3,079	3,155	3,213	3,471
<b>Vessel Bunkering</b>	1,580	1,971	1,889	1,924	1,973	2,030	2,080	2,118	2,288
<b>On-Highway Diesel</b>	37,104	37,125	38,613	39,347	40,348	41,502	42,534	43,311	46,787
<b>Military</b>	232	324	306	312	320	329	337	343	371
<b>Off-Highway Diesel</b>	2,160	2,861	2,572	2,621	2,687	2,764	2,833	2,885	3,116
<b>Total Diesel</b>	50,666	52,992	54,282	55,314	56,722	58,344	59,794	60,887	65,774
<b>Total Distillate</b>	60,202	62,384	64,207	65,428	67,092	69,011	70,727	72,020	73,290

Excludes heating oil demand

Source: U.S. Department of Energy (history) and Informa Economic (analysis and forecast).

While full biodiesel (B100) can be used in unmodified diesel engines and heating oil systems, technical barriers may restrict this practice to environmentally motivated consumers. Potential problems with B100 include material compatibility with seals, gaskets, and other fuel system components; cold weather freezing; storage stability; and NO<sub>x</sub><sup>10</sup> emissions. B100's technical problems (other than NO<sub>x</sub> emissions) can be minimized by retrofitting fuel system components, adding fuel system heaters, and using storage stability additives and biocides if necessary. B100 fuels are used in National Parks, sensitive waterways, and other locations where environmental or human health concerns are especially important.

The most popular biodiesel blends in the marketplace today are:

- B20, approved by Congress in 1998 as an EPACT fuel for Federal, state, and publicly owned fleets required to meet alternative vehicle use targets.
- B2, promoted at the state level.

B100 will likely be limited to small niche markets in the foreseeable future because of its price disadvantage and because most current equipment would need minor modifications to use it (NREL). B20 can be used wherever diesel fuel is used - on-road transportation, farm equipment, etc. - without equipment modifications. B20 mitigates problems associated with cold weather, stability, material compatibility,

<sup>9</sup> Heating oil is not included under the estimated diesel demand. Heating oil is particularly a factor in the residential and commercial market segments, but not in the transportation segment.

<sup>10</sup> Nitrogen oxide, or NO<sub>x</sub>, is the generic term for a group of highly reactive gases, all of which contain nitrogen and oxygen in varying amounts.

NOx increases, storage tank cleanliness, and cost. By and large, the problems are minimized to where they are either manageable or undetectable.

Some biodiesel feedstocks include: tallow, lard, and some yellow grease - contain high levels of saturated fatty acids. Biodiesel produced from them has a high risk of losing its viscosity in tanks and forming crystals that plug fuel filters. Blending these feedstocks into a B20 blend reduces but does not eliminate these risks. The cold flow of saturated fatty acid feedstocks (these feedstocks solidify in cooler temperatures) would imply that vegetable oil based diesel has an advantage in northern states. Although a B20 or lower blend reduces the potential for flow problems, the transport of and the blending process of B100 from fatty acid saturated feedstocks may be problematic.

As of April 2006, biodiesel blends such as B2 are still being sold commercially as a premium diesel fuel; however, this apparent premium will be eliminated over time, as biodiesel becomes a more developed market (a more detailed analysis of prices is included later in this report). B5 and lower blend levels meet the ASTM International standard for diesel fuel and all engine manufacturer warranties. A B2 advantage is that it adds lubricity, particularly for ultra-low-sulfur diesel (ULSD), which will be made available nationwide by June 2006.<sup>11</sup>

The production process for making ULSD severely reduces the lubricity of diesel; however, petroleum refiners generally plan to use a variety of low-cost additives to solve the problem.<sup>12</sup> Petroleum based lubricity additives would add 0.5 to 0.75 cent per blended gallon. Refiners also have the option of adding biodiesel if the price is competitive. B2 can be blended into bulk storage tanks of diesel fuel upon entry into a tank farm, potentially reducing the terminal storage and distribution costs associated with conventional fuel additives.

If blends are B5 or lower, all feedstocks could be used, including saturated animal fats and greases. The difference in cold-flow performance between biodiesel made from various feedstocks becomes minor at the B2 level (NREL).

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<sup>11</sup> Refineries are required to produce ULSD for U.S. motor vehicles beginning June 1, 2006. Retail locations and wholesaler purchasers/consumers are required to sell ULSD for motor vehicle use beginning September 1, 2006. The EPA has announced plans to modify the transition period, allowing a slight delay in the ULSD compliance date for retail and wholesaler purchasers/consumers, but the plan does not delay the June 1 refinery requirement to produce ULSD.

<sup>12</sup> To date there are concerns that have come to light during the early introduction of ULSD, which include: over-additization causing fuel filter plugging, under-additization that could lead to fuel pump failures, and unanticipated reactions between two or more different additive packages that could occur in bulk storage or while traveling cross country.



## **(2) Demand Implications for the Development of the Biodiesel Market**

The potential demand for biodiesel should not be measured by the total demand for diesel, but rather by a fraction of it that represents a realistic blend. Currently, there are limitations to widespread use of a B100 blend in motor vehicles and other uses. A 20 percent biodiesel blend should be considered the maximum average for the aggregate market, and a 2 percent to 5 percent biodiesel substitution rate is more realistic. Consider that ethanol, a more developed market, accounts for less than 3 percent of on-highway gasoline demand.

Even at diesel displacement rates of 2 percent to 5 percent, the potential demand for biodiesel far exceeds current production and 10-year projections. Biodiesel demand will largely depend on its price relative to conventional diesel rather than market constraints. At the right price (i.e., equal to or below conventional diesel), demand for on-highway biodiesel could be as high as 9.3 billion gallons by 2015 (Table 9).

**Table 9: Implied Biodiesel Demand from Alternative Diesel Displacement Rates Scenarios**

<i>Million Gallons</i>	2005	2006	2007	2008	2009	2010	2015
<b>Total Diesel Demand</b>	54,282	55,314	56,722	58,344	59,794	60,887	65,774
<u>Potential Scenarios</u>							
20% Substitution	10,856	11,063	11,344	11,669	11,959	12,177	13,155
5% Substitution	2,714	2,766	2,836	2,917	2,990	3,044	3,289
2% Substitution	1,086	1,106	1,134	1,167	1,196	1,218	1,315
<b>On-Highway Diesel Use</b>	38,613	39,347	40,348	41,502	42,534	43,311	46,787
<u>Potential Scenarios</u>							
20% Substitution	7,723	7,869	8,070	8,300	8,507	8,662	9,357
5% Substitution	1,931	1,967	2,017	2,075	2,127	2,166	2,339
2% Substitution	772	787	807	830	851	866	936
<b>Farm Diesel Use</b>	3,260	3,322	3,407	3,504	3,591	3,657	3,950
<u>Potential Scenarios</u>							
20% Substitution	652	664	681	701	718	731	790
5% Substitution	163	166	170	175	180	183	198
2% Substitution	65	66	68	70	72	73	79

Sources: U.S. Department of Energy, Energy Information Administration, and Informa Economics (analysis and forecast).

### **c) Economics of Producing Biodiesel from Various Feedstocks**

Feedstocks make up the largest share of production costs for methyl esters. Animal fats and vegetable oils generally account for 80 - 85 percent of the cost of producing

a gallon of biodiesel. The other components, usually an alcohol source and a base catalyst, comprise an additional 4 to 6 percent of production costs (Informa Economics et al., Biobased Multi-Client Study, March 2006).

Fats and oils used in biodiesel production come from a variety of plant and animal sources. Even though these feedstocks are generally interchangeable in the production process once they have been pre-processed or refined, their physical and molecular structures can affect the handling and quality characteristics of the methyl esters (Informa Economics et al., Biobased Multi-Client Study, March 2006).

### ***(1) Vegetable Oils***

The oil used to produce biodiesel is the most important cost factor in its manufacture. The higher the cost of the feedstock, in general, the higher the production cost of fuel. The vegetable oil most used in the United States is soybean oil, while rapeseed is favored in Europe. These oils also have good flow characteristics at low temperatures.

Oil expelled from the oilseed using high-pressure extruders is significantly different than oil extracted from the oilseed by solvents (the more common process). The difference in quality (chemical properties of the oil) across feedstocks is important.

- FFA is the amount of free fatty acids contained in the product. Fats and oils are triglycerides, compounds containing three fatty acids, each chemically connected to an oxygen on a glycerin molecule. Free fatty acids are those structures that are no longer connected to the glycerin. A high-quality fat has a low FFA level.
- MIU stands for moisture, insolubles, and unsaponifiables. It is a measure of the remaining compounds in the oil that are not fatty acids or triglycerides. It is also a measure of quality, as is color. In general, the lower the MIU level, the higher the quality of the oil and the easier it is to process into biodiesel.
- TITER is the solidification point of the fat or oil in degrees Centigrade, and is a rough measure of the saturation level of the oil or fat. The higher the titer, the more saturated the fat or oil. Highly saturated oils and fats make biodiesel that will gel more quickly in a fuel tank than low-saturated oils like vegetable oils. This can be extremely important for smooth engine function.

### ***(2) Animal Fats***

Biodiesel has been made from fish oils, poultry fat, beef tallow and pork lard. These oils usually have higher titers (or lower iodine values) than most vegetable oils. Biodiesel made from these oils will often have slightly higher cloud points (the temperature at which the biodiesel starts to form solid crystals), and so are less desirable in colder climates.

### (3) Recycled or Waste Oils and Greases

Oils coming from a food cooking/processing operation will have high levels of impurities such as moisture and free fatty acids. Waste oils and greases from commercial and retail cooking and frying can be collected regularly and processed into biodiesel. Recycled cooking oils are called yellow grease. They may contain some waste vegetable oils (usually hydrogenated or partially hydrogenated so they act more like animal fats) as well as animal fats from cooking operations. Therefore, most of the waste oils and greases are a blend of animal fats and vegetable oils. The color of the biodiesel is normally darker, but the biodiesel can meet ASTM quality standards with the proper technology.

FFA, MIU and suspended solids (SS) vary considerably among feedstock fats and oils (Table 10). The quality of the feedstock is important in selecting the technology used to make biodiesel. In most cases, the oils are caustic refined to remove the free fatty acids and then flash dried to remove excess moisture. Biodiesel yield/gallon of oil processed will be lower when free fatty acids are present.

**Table 10: Composition Analysis of Select Types of Fats and Oils**

<b>Animal Fats</b>	<b>% FFA</b>	<b>% MIU</b>	<b>% SS</b>	<b>TITER</b>	
Edible Tallow	0.8	0.05	0.00	41.0	
Edible Lard	0.5	0.05	0.00	38.0	
Extra-Fancy Tallow	2.0	1.00	0.00	41.0	
Choice White Grease	4.0	0.50	0.01	36.0	
Yellow Grease	10.0	0.50	0.05	36.0	
<b>Vegetable Oils</b>	<b>% FFA</b>	<b>% MIU</b>	<b>Chlorophyll</b>	<b>Phosphorus</b>	<b>Tocopherols</b>
<i>Crude, Degummed</i>			<i>ppm</i>	<i>ppm</i>	<i>ppm</i>
Canola	1.0	0.30	>5	>10	25
Corn	4.5	3.00	>3	>3	10
Cottonseed	3.5	0.70	>3	>3	10
Soy	2.5	0.25	>4	>5	11

Explanation: Free Fatty Acids (FFA), moisture in percent (MIU), suspended solids (percent SS).  
Source: Bailey's Industrial Oil and Fat Products.

#### d) U.S. Supply of Oils and Fats: Biodiesel Potential

Soybean oil is the predominant oil (72 percent of the 27 million pounds of vegetable oil) produced in the United States and will likely be the primary feedstock for biodiesel. Other oils are minor relative to soybean oil, and more costly.

Some animal fats such as beef tallow could also be shifted to biodiesel (e.g., 1.9 million pounds of fats were exported in 2004/05). However, production of animal fats will not increase with biodiesel demand. Biodiesel produced from saturated fats such as tallow has a high risk of solidifying in tanks and forming crystals that plug

fuel filters in cold weather. Blending these feedstocks into a B20 blend only reduces these risks. Still, animal fats are a less expensive feedstock.

Imports are a potential feedstock source. The United States is a net importer of vegetable oils (418,000 lbs in 2004/2005), and imports of palm oil, for example, could be used to produce biodiesel domestically.

The U.S. supply of yellow grease (i.e., recycled restaurant oil) is limited to 198 million gallons a year (i.e., assuming all yellow grease is turned into biodiesel). Growth in the biodiesel and continued high petroleum prices would provide incentives for greater collection of recycled cooking oil and increase the available supply of yellow grease.

Table 11 shows the U.S. supply of oils and fats and their respective potential supplies of biodiesel that can be processed. For example, if all the soybean oil net exports of 2004/05 had been processed into biodiesel, then the United States would have produced 182 million gallons of soybean based biodiesel. If the entire U.S. soybean oil production had been used, then the biodiesel would have produced 2.5 billion gallons of biodiesel (note that this is an unrealistic case but useful to illustrate the upper limits of potential biodiesel production, at least in the short and medium term). Table 11 also shows the availability of various feedstock options; clearly soybean oil has the greatest potential from a domestic feedstock supply perspective.

The feedstock implications and potential for biodiesel need to be examined in the near and long term. In the near term, biodiesel feedstocks will be shifted primarily away from export markets and potentially from inventories/stock and into biodiesel production. The primary feedstock for biodiesel production will likely come from virgin vegetable oil, primarily soybean oil, which has the largest exportable supply and lowest cost. (Corn oil exports are also large, but corn oil averages 4.5 cents a lb more than soybean oil).

The supply of yellow grease will be important, but insufficient to sustain a large biodiesel industry. Also, inconsistent supplies of yellow grease make this feedstock more difficult to handle (higher processing costs). Non the less, yellow grease, where available, is by far the cheapest source of biodiesel. Yellow grease is popular among smaller or midsize (1 to 15 mgy) biodiesel producers located near large urban centers (the supply of yellow grease tracks U.S. population density, where food service is concentrated). Large biodiesel producers would need to source 15 percent of the total supply of *rendered* yellow grease (1.4 million pounds in 2004/05) in order to run a facility capable of 30 mgy.

Some of the exportable supplies of animal fats could be used for biodiesel, especially because of their cost advantage over vegetable oils. Animal fat products such as tallow or poultry fat are marketed at a premium over corn in terms of their caloric content; for example, the price of inedible tallow is 1.6 times higher in terms

of caloric content than corn.<sup>13</sup> In the long run, animal fat supplies can be shifted from other uses such as feed, where animal fats are priced at a premium over corn.

**Table 11: U.S. Supply of Oils and Fats - Biodiesel Potential, 2004/2005**

	<b>Feedstock Supply</b>					<b>Biodiesel Potential</b>	
	<b>Production</b>	<b>Imports</b>	<b>Exports</b>	<b>Demand</b>	<b>Stocks</b>	<b>Supply Source</b>	
	<i>Thousand Pounds</i>					<i>Million Gallons</i>	
						<b>Net Exports*</b>	<b>Production**</b>
<b>Vegetable Oils (Crude)</b>	<b>26,858</b>	<b>3,638</b>	<b>3,220</b>	<b>26,615</b>	<b>2,533</b>	<b>295</b>	<b>3,137</b>
Coconut	0	900	12	774	245		0
Corn	2,425	55	825	1,693	115	101	318
Canola	776	1,150	275	1,652	90		102
Cottonseed	923	2	60	894	80	8	121
Palm	0	850	20	821	150		0
Peanut	159	30	10	175	15		21
Safflower	56	55	40	85	10		7
Soybean	19,313	15	1,400	17,300	1,703	182	2,532
Sunflower	283	75	115	253	30	5	37
<b>Animal Fats</b>	<b>8,884</b>	<b>74</b>	<b>1,875</b>	<b>7,088</b>	<b>335</b>	<b>236</b>	<b>1,165</b>
Edible Tallow	1,787	1	300	1,484	25	39	234
Inedible Tallow	3,609	65	1,400	2,280	240	175	473
Lard	1,135	6	160	983	10	20	149
White Grease	1,175	2	15	1,163	45	2	154
Poultry Fat	1,178	0	0	1,179	15	0	154
<b>Yellow Grease</b>	<b>1,425</b>	<b>0</b>	<b>325</b>	<b>1,106</b>	<b>55</b>	<b>43</b>	<b>187</b>
<b>Fats and Oils</b>	<b>37,167</b>	<b>3,712</b>	<b>5,420</b>	<b>34,809</b>	<b>2,923</b>	<b>574</b>	<b>4,489</b>

\* Maximum gallons of biodiesel produced from net exports supply.

\*\* Maximum gallons of biodiesel produced from production supply.

\*\*\* The yield from crude to refined oil is 0.97percent and the yield from oil/fats to biodiesel is 1 to 1.

Source: USDA, Informa Economics et al., Biobased Multi-Client Study (March 2006)

In the long term, imports, particularly palm oil, can provide additional biodiesel feedstocks. Palm oil in the world market is priced competitively with soybean oil and has ample exportable supplies and growth prospects, especially in Southeast Asia. Prospects for a palm oil based biodiesel plant are better in oilseed-deficit regions or near entry points for imports such as Texas or California. The United States imported 850 million pounds of palm oil in 2004/05, and this is likely to increase.

Growth in the biodiesel sector can increase the demand for U.S. soybean oil and soybeans. Additional soybean production could result from improved yields, increased planted soybean acreage (or acreage shifts from wheat or other small grains); increased crushing volume and capacity; and supply shifts from other uses (e.g., feed) to biodiesel. The 1.1 billion bushels of soybeans exported in 2004/05 is equivalent to 11.8 billion pounds of oil if crushed domestically.

If biodiesel is to make a significant entry or market penetration, it must be priced comparably to diesel fuel and without much economic hardship to fuel marketers and consumers. Stable supply and competitive costs are not as significant in niche markets where consumers buy biodiesel for environmental or other reasons.

<sup>13</sup> Concentrated forms of energy such as animal fats have some benefits over corn. The price per caloric content is not the only variable examined by livestock operations when selecting a particular feed ingredient.

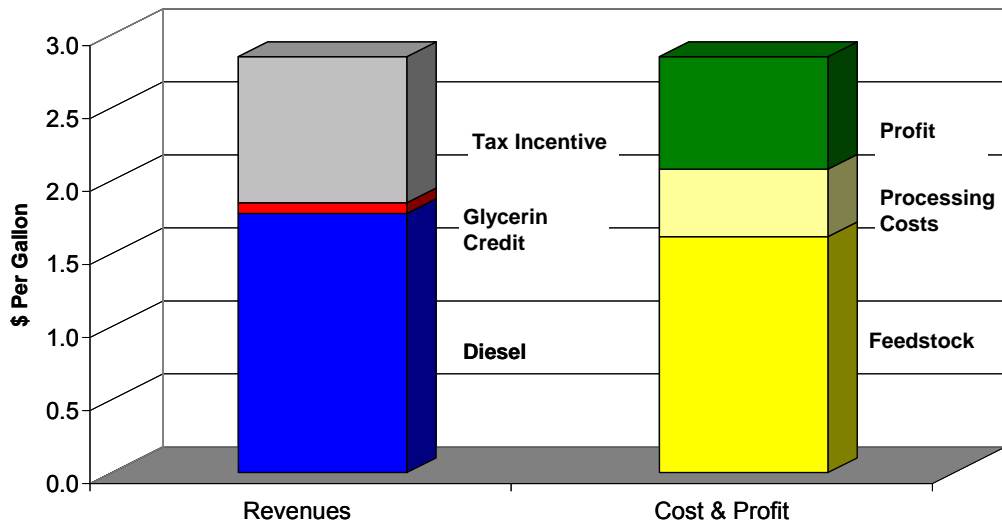
Vegetable oil and, more notably, soybean oil will be the primary feedstock in the production of biodiesel for the foreseeable future. Consider the following that supports the assertion:

- Soybean oil is the most abundant biodiesel feedstock in the United States.
- The soybean industry, both producers and processors, has been one of the major factors in the growth and commercialization of biodiesel.
- Federal incentives favor vegetable oil over yellow grease.
- Soybean oil is the least expensive vegetable oil.
- Biodiesel produced from animal fats will solidify at higher temperatures.

#### **4. Biodiesel Producer Gross Margins**

Biodiesel is expensive to produce because it requires a high-value feedstock - vegetable oil or animal fats. It takes about 7.43 pounds of refined soybean oil to make a gallon of biodiesel. For example, with CBOT soybean oil at 23.5 cents/lb (as of April 2006), each gallon of biodiesel feedstock would cost \$1.75/gallon plus additional costs of refining, transportation, storage, etc. - considerably more than ethanol with feedstock costs of perhaps \$0.81/gallon at corn prices of \$2.20/bushel. However, biodiesel contains more energy than ethanol. Each gallon of ethanol contains 76,330 Btu, while biodiesel contains 128,000 Btu/gallon. Biodiesel and ethanol feedstock costs, by Btu, are a closer match: \$0.81/gallon of ethanol versus \$0.96 for biodiesel. Still, even considering the higher energy content of biodiesel, ethanol currently has a cost advantage.

The economic feasibility of biodiesel is a function of (1) feedstock costs, (2) price of diesel, (3) tax incentives/credits, (4) glycerin credit, and (5) processing costs (i.e., energy, chemicals, labor, capital, etc.). Figure 21 shows the current economic structure for soybean based biodiesel, based on the April 2006 average wholesale diesel prices from the Department of Energy of \$1.81/gallon (i.e., petroleum prices of \$62/barrel) and soybean oil prices of 23.5 cents/lb.

**Figure 21: Economics of Biodiesel – Example with Soybean Oil for 2005**

Source: Informa Economics et al., Biobased Multi-Client Study, March 2006 and DOE.

The following feedstock cost analysis is based on average prices over the 2000 - 2005 market years. Soybean oil and imported palm oil are the most competitive vegetable oil sources (Table 12). However, the price used for palm oil is a CIF (commodity, insurance, and freight) at a U.S. Gulf port (e.g., Galveston, Texas). If palm oil is transported to Iowa, for example, the price will increase to reflect transportation costs of about 14 cents/gallon<sup>14</sup> and erode most of the price advantage over soybean oil. From 2001 to 2005, the price for crude soybean oil (Decatur) averaged 21.11 cents a lb. Animal fats and grease are less costly than vegetable oils, but when all costs and credits are considered, the price advantage over soybean oil is minimal. Quality (freezing in cold temperatures) and supply concerns of animal fat and grease based biodiesel further erode the competitiveness of these feedstocks.

<sup>14</sup> Estimate based on BNSF rail rates from Galveston, TX to Iowa as of March 2006.

Table 12: Economics of Biodiesel Production by Feedstock

	Biodiesel Feedstock Costs			Processing Costs						Margins	
	<i>*2000-2004 Average Feedstock Prices</i>			Pretreatment and Processing	Glycerin Credit	Feedstock+ Processing	Fuel Freight, Handling, Marketing Exp.	Margin over Diesel	Tax Incentive	Margin over Diesel	Margin over SBO
	Feedstock Costs /2	Feedstock Costs/4	Margin over Diesel								
<b>Vegetable Oils</b>	Cts/lb	Cts/Gal	\$/Gal	\$/Gal	\$/Gal	\$/Gal	\$/Gal	\$/Gal	\$/Gal	\$/Gal	\$/Gal
Coconut	22.48	1.71	<b>0.06</b>	0.46	0.05	2.12	0.08	<b>-0.43</b>	1.00	<b>0.57</b>	<b>-0.10</b>
Corn	23.62	1.80	<b>-0.03</b>	0.46	0.05	2.21	0.08	<b>-0.52</b>	1.00	<b>0.48</b>	<b>-0.19</b>
Canola	24.75	1.89	<b>-0.11</b>	0.46	0.05	2.30	0.08	<b>-0.60</b>	1.00	<b>0.40</b>	<b>-0.28</b>
Cottonseed	27.27	2.08	<b>-0.31</b>	0.46	0.05	2.49	0.08	<b>-0.80</b>	1.00	<b>0.20</b>	<b>-0.47</b>
Palm /3	19.77	1.46	<b>0.31</b>	0.38	0.05	1.79	0.08	<b>-0.10</b>	1.00	<b>0.90</b>	<b>0.23</b>
Peanut	47.14	3.60	<b>-1.82</b>	0.46	0.05	4.01	0.08	<b>-2.31</b>	1.00	<b>-1.31</b>	<b>-1.99</b>
Soybean	21.11	1.61	<b>0.16</b>	0.46	0.05	2.02	0.08	<b>-0.33</b>	1.00	<b>0.67</b>	
Sunflower	30.04	2.29	<b>-0.52</b>	0.46	0.05	2.70	0.08	<b>-1.01</b>	1.00	<b>-0.01</b>	<b>-0.68</b>
<b>Animal Fats</b>											
Edible Tallow	17.18	1.31	<b>0.46</b>	0.61	0.04	1.89	0.08	<b>-0.19</b>	1.00	<b>0.81</b>	<b>0.13</b>
Inedible Tallow	15.44	1.18	<b>0.60</b>	0.61	0.04	1.75	0.08	<b>-0.06</b>	1.00	<b>0.94</b>	<b>0.27</b>
Lard	18.12	1.38	<b>0.39</b>	0.61	0.04	1.96	0.08	<b>-0.26</b>	1.00	<b>0.74</b>	<b>0.06</b>
White Grease	15.35	1.17	<b>0.60</b>	0.61	0.04	1.75	0.08	<b>-0.05</b>	1.00	<b>0.95</b>	<b>0.27</b>
Poultry Fat	13.08	1.00	<b>0.78</b>	0.61	0.04	1.57	0.08	<b>0.12</b>	1.00	<b>1.12</b>	<b>0.45</b>
<b>Yellow Grease</b>	12.09	0.92	<b>0.85</b>	0.61	0.04	1.50	0.08	<b>0.20</b>	0.50	<b>0.70</b>	<b>0.02</b>

**Diesel Reference Price (\$/gal); 2005 Average**

Average Spot Price (NY, Gulf, Los Angeles) for No 2 Diesel Low Sulfur FOB (\$/gal) - 1.774

Oil WTI Spot Price FOB (Dollars per Barrel) - 62

**Price Notes**

Soybean Oil, Crude FOB Decatur (Cents/Pound)

Corn Oil, Crude FOB Decatur (Cents/Pound)

Cottonseed Oil, PBSY Mississippi Valley (Cents/Pound)

Sunflower Oil, Dakotas (Cents/Pound)

Coconut Oil, Crude CIF Pacific (Cents/Pound)

Canola Oil, Crude Toronto (Cents/Pound)

Poultry Fat (Arkansas)

Palm Oil, RBD CIF US Gulf (Cents/Pound)

Peanut Oil, Southeast (Cents/Pound)

Edible Tallow, FOB Chicago (Cents/Pound)

Loose Lard, FOB Chicago (Cents/Pound)

Yellow Grease - 10 Acid, Delivered New York City (Cents/Pound)

Choice White Grease, Delivered New York City (Cents/Pound)

Tallow - Packer (FOB Chicago)

1/ Includes pretreatment and processing costs for crude oil. Pretreatment costs when applicable are assumed to be 8.0 cts/gallon (Lurgi PSI)

2/ These prices are for crude vegetable oil. The analysis assumes that a pretreatment (or refining unit) would be in place. These costs are added to the processing costs.

3/ Palm oil prices are for refined oil; hence pretreatment costs are not included.

4/ The yield of crude oil to biodiesel is on average 97%. The yield from refined oil to biodiesel is one.

Marketing years 2000/2001 to 2004/2005.

Source: Informa Economics et al., Biobased Multi-Client Study, March 2006.



### Processing and Pretreatment Costs

The processing and pretreatment costs estimated by Informa were based on estimates obtained from Lurgi PSI and “The Biodiesel Plant Development Handbook”. Processing costs represent 10 - 15 percent of biodiesel operating costs. These costs include energy, chemicals (e.g., methanol), process labor, capital investment depreciation and maintenance, sales, and quality control. Processing costs are approximately 15 cents a gallon higher for animal fats and greases than for vegetable oil.

Pretreatment costs for refined crude oil are an estimated 8 cents a gallon (1.07 cents/lb). If a plant uses refined oil instead, the price of crude oil would need to be adjusted to reflect oil-refining margins, which can range from 3 to 4 cents/lb.

Biodiesel plants that use yellow grease are typically smaller than those that use vegetable oil. Processing costs of smaller plants are anywhere from 4 cents a gallon to 30 cents a gallon higher than for a 30 mgy plant.

### Biodiesel Margins

Yellow grease based biodiesel is the only feedstock that shows a positive margin (over diesel) of 6 cents a gallon when no tax incentive is provided. Other feedstocks would seemingly yield negative margins in the absence of government incentives (or higher diesel prices). After the \$1.00 a gallon incentive for virgin oil/animal fats and the \$0.50 incentive for recycled greases, all feedstocks except peanut and sunflower oils become cost competitive and show positive operating margins ranging from 20 cents a gallon to \$1.12 a gallon. (Note that these estimates are based on 2000/01 - 2004/05 average feedstock prices and 2005 average diesel spot prices). Only palm oil and animal fats show a better potential operating margin than soybean oil (67 cents a gallon) (Table 12).

The economics of biodiesel are driven by diesel and feedstock prices. Table 13 shows the biodiesel gross margin (including capital costs and handling/marketing charges) based on alternative price scenarios.

With soybean oil prices of 23.5 cents/lb (April 2006) and diesel prices of \$1.81 a gallon (April 2006), the gross margin per gallon is about \$0.52 a gallon. Hence, a 30 mgy facility in 2005 could have a gross profit of \$15.6 million, or 45 - 55 percent of the capital equipment costs required to build a new biodiesel plant.

Based on the average April 2006 CBOT price for soybean oil of 23.5 cents/lb, the break-even<sup>15</sup> net wholesale biodiesel price for soybean based diesel price is \$44.50 a barrel (or 128 cents a gallon). This means that if petroleum prices drop below \$44.50 a barrel, the operating costs would be greater than the operating revenues. (This break-even cost is for a “generic” plant, and could be higher for a specific location).

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<sup>15</sup> The price at which revenues (biodiesel price) equal costs (feedstock + glycerine credit + tax incentive + processing costs).

**Table 13: Biodiesel Gross Margin Scenarios, Cents per Gallon**

	\$/Barrel	Cts/Gal	CBOT Soybean Oil (Average Nearby Future)							Cts/lb
			Cts/Gal							
			Low	- 2stv	Avg.	+ 2stv	High			
		#2 Diesel	14.0	16.7	19.4	22.1	24.8	26.0	30.2	Cts/Gal
		Cts/Gal	104	124	144	164	184	193	224	Cts/Gal
Average of Cushing, OK WTI Spot Price FOB	20	55	(2)	(23)	(44)	(64)	(85)	(94)	(126)	
	30	85	28	7	(14)	(34)	(55)	(64)	(96)	
	40	115	57	37	16	(5)	(25)	(35)	(67)	
	50	145	87	67	46	25	5	(5)	(37)	
	55	160	102	82	61	40	20	10	(22)	
	60	175	117	97	76	55	35	25	(7)	
	65	190	132	111	91	70	49	40	8	
	70	205	147	126	106	85	64	55	23	
	80	234	177	156	136	115	94	85	53	

\* Based on processing costs of a 30MGY facility.

#### Definitions:

Cts – cents, CBOT – Chicago Board of Trade, Gal – gallon, Lb – pound, SBO – soybean oil, Stv – standard deviation

Source: Informa Economics et al., Biobased Multi-Client Study, March 2006.

#### Implications of Government Biodiesel Incentives

Without the \$1.00 a gallon tax incentive, biodiesel production will not be profitable unless crude oil prices are above \$78 a barrel, assuming soybean oil prices of April 2006 at 23.5 cents/lb.

As of April 2006, the biodiesel gross operating margin<sup>16</sup> ranged from \$0.40 to \$0.50 a gallon, so the industry could not be profitable without the \$1.00 a gallon tax incentive. The Federal biodiesel credit will likely be extended because it has broad and bipartisan legislative support. However, if the growing budget deficit changes the political and economic landscape before 2008, the credit may be reduced or defeated.

## 5. Biodiesel Outlook

The ethanol industry, which is more mature, can serve as a potential analog for the biodiesel sector. The ethanol industry overestimated its projected capacity despite the fact that the industry had been established for 2 decades and was the recipient of a long-established excise tax exemption (now converted into a tax credit). The biodiesel industry has emerged in roughly the last 5 years and its main tax incentive is currently scheduled to end at the end of 2008. Therefore, all the biodiesel capacity planned in 2006 may not actually be built and come online.

Unlike ethanol, which has a track record of consumption in certain clean-air programs and regions, the consumption of biodiesel is relatively recent. The Renewable Fuels Standard (contained in the Energy Policy Act of 2005) and the tax incentive that has

<sup>16</sup> Biodiesel Gross Margin = (biodiesel + glycerin credit) - (feedstock + processing costs).

been available since the beginning of 2005, is likely to propel biodiesel consumption far beyond historical levels.

For near-term forecasts 2006 to 2010, volumes were based on estimates of production capacity coming online. Based on the ethanol industry's record, it was assumed that not all of the announced construction and proposed facilities would come to fruition. In determining what proportion of the biodiesel volume would be produced from soybean oil versus other feedstocks, the announced feedstock orientation of existing and planned plants was used in the near term. For the medium term, 2010 to 2015, a review of the literature and industry contacts regarding the competitiveness of various feedstocks was taken into account. For the end-point of the forecast in 2015, biodiesel adoption rates in other countries (mainly Germany) and ethanol adoption rates in the United States were considered.

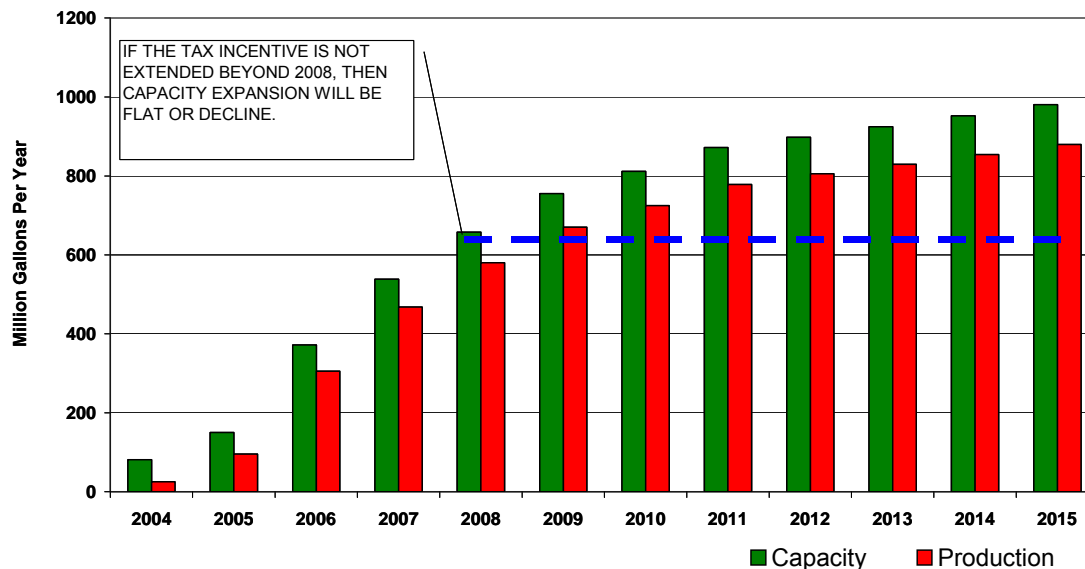
If the tax incentive is not extended beyond 2008, capacity expansion will be limited. Without the \$1.00 a gallon tax incentive, biodiesel production will not be profitable unless crude oil prices are above \$70 - \$75 a barrel - assuming average crude soybean oil is 22 - 24 cents a gallon. Based on these factors, biodiesel capacity is forecast to be 688 million gallons in 2008 and rise steadily to 880 million gallons by 2015 (Figure 22). Feedstock use accounted for by soybean oil is forecast to reach 70 percent by 2015. Animal fats, other vegetable oils and, to a lesser extent, greases are expected to account for the remaining 30 percent.

#### Availability of Crushing Capacity

Official industry statistics do not exist regarding soybean oil refining capacity or refining capacity for vegetable oils and fats in general. Therefore, it is not possible to determine current levels of capacity use or the levels implied by expected growth in the biodiesel industry. However, statistics on crude soybean oil production and use and refined soybean oil production enable some inferences about refining capacity.

For 2000 - 2005 (Oct. - Sept. crop marketing years), production of crude soybean oil averaged 18.5 billion pounds a year, of which 16.9 billion pounds were used domestically (Table 14). Refined soybean oil production has averaged 15.4 billion pounds; adjusted for the loss of material that results from the refining process, 94 percent of the crude oil that has been consumed domestically has been refined. On average, 87 percent of all crude soybean oil produced in the United States (including oil exported in crude form) has been refined.

**Figure 22: U.S. Biodiesel Production**



Sources: National Biodiesel Board (historical: January 2006), Informa Economics (forecast).

**Table 14: Refined Soybean Oil Production and Conversion Rates Compared to the Production and Domestic Use of Crude Oil**

Crop Year	(Million Pounds)			Refined as % of Crude Production, Adj. For Refining Loss	Refined as % of Crude Domestic Use, Adj. For Refining Loss
	Crude Oil Production	Crude Oil Domestic Use	Refined Oil Production		
1992/93	13,778	13,012	12,184	92%	97%
1993/94	13,951	12,939	12,308	92%	99%
1994/95	15,613	12,913	12,435	83%	100%
1995/96	15,240	13,465	12,299	84%	95%
1996/97	15,752	14,267	12,351	81%	90%
1997/98	18,143	15,261	13,389	77%	91%
1998/99	18,078	15,653	13,002	75%	86%
1999/00	17,825	16,058	14,782	86%	95%
2000/01	18,420	16,318	14,779	83%	94%
2001/02	18,898	16,833	15,559	85%	96%
2002/03	18,430	17,083	15,695	88%	95%
2003/04	17,080	16,894	15,197	92%	93%
2004/05E	19,313	17,300	15,521	83%	93%
<b>Maximum Monthly Production</b>					
Oct. 2002	1,693	1,660	1,452	89%	91%
Annualized	20,311	19,924	17,420		
% of last 5 Yrs Avg.	110%	118%	113%		

Source: Informa Economics et al., Biobased Multi-Client Study, March 2006.

The biodiesel outlook implies a use of 4.0 billion pounds of soybean oil by 2010, or 18 percent of estimated U.S. supply (Table 15). This significant increase in “new demand” will reduce soybean oil exports.

By 2010, biodiesel will account for 1.7 percent of the projected demand for on-highway diesel fuel. For comparison, ethanol's current share of the on-highway gasoline market is close to 2.5 percent. Also by 2010, biodiesel will represent a small (8.2 percent) but growing share of the renewable fuels market.

**Table 15: Implications of the Biodiesel Production, Medium-Term Outlook**

<b>CY</b>	<b>Unit</b>	<b>2004</b>	<b>2005</b>	<b>2006</b>	<b>2007</b>	<b>2008</b>	<b>2009</b>	<b>2010</b>	<b>2015</b>
Biodiesel Production	Mil. Gal	25	96	305	468	580	670	725	880
Biodiesel from Soybean Oil	Mil Gal.	18	70	250	383	448	499	530	617
Soybean Oil - Crude	Mil. Lbs	140	537	1,909	2,924	3,415	3,804	4,040	4,708
Soybeans	Mil Bu.	13	48	172	263	308	343	364	424
<b>Indicators</b>									
% of SBO Supply	%	0.7	2.6	8.9	13.3	15.4	17.1	18.1	20.4
% of SB Supply	%	0.5	1.5	5.0	7.0	8.2	9.6	10.7	12.6
% of Renewable Fuels/ 1	%	0.7	2.4	6.0	6.8	6.8	7.9	8.2	
% of Total Diesel	%	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1
% of On-highway Diesel	%	0.1	0.2	0.8	1.2	1.4	1.6	1.7	1.9

1/ Ethanol and Biodiesel

Sources: U.S. Department of Energy, U.S. Department of Agriculture, Informa Economics (forecast).

Some challenges and threats to the biodiesel industry could limit its development. These include the uncertainty of government incentives, diesel prices, imports of palm oil and/or biodiesel, and the availability of vegetable oil crushing and refining capacity.

The highest monthly production during 2000/2001 - 2004/2005 was 1.45 billion pounds in October 2002. If this level of refined soybean oil production were maintained across an entire year, annual volume would be 17.4 billion pounds. This is 1.7 billion pounds (11 percent) higher than the peak annual production, and 2.1 billion pounds (13 percent) above the average annual level.

Assuming that the Federal tax credit for biodiesel use is maintained, consumption of all oils and fats for biodiesel production is forecast at 668 million gallons in marketing year 2010/11, of which 551 million gallons, or 4.2 billion pounds, would be soybean oil based. On average, roughly 500 million pounds of refined oil are exported annually from the United States, while 1.2 billion pounds of crude soybean oil are exported, although crude oil volumes vary significantly from year to year (Table 16). Thus, redirected exports of refined oil could meet approximately 12 percent of the 2010/11 needs for soybean oil in biodiesel production (Informa). Unless additional refining capacity is built or capacity use increased, any diverted volumes would need to be used by facilities with pre-processing equipment that allows them to utilize crude soybean oil (Informa).

**Table 16: Composition of U.S. Soybean Oil Exports**

		(Million Pounds)					Oct.-July Comparison	
Commodity	Tariff Code	October-September Crop Year					2003/04	2004/05
		1999/00	2000/01	2001/02	2002/03	2003/04		
Crude Soybean Oil	1507100000	873	989	1,983	1,563	511	430	785
Percent of Total		64%	72%	79%	70%	58%	58%	75%
Fully Refined Soybean Oil	1507904050	330	284	365	503	293	245	202
Percent of Total		24%	21%	15%	22%	33%	33%	19%
Once-Refined Soybean Oil	1507904020	154	104	160	173	79	63	65
Percent of Total		11%	8%	6%	8%	9%	9%	6%
Total		1,357	1,377	2,508	2,240	882	738	1,052

Source: U.S. Department of Agriculture, Foreign Agricultural Service.

Since official statistics are insufficient to gauge the refining industry and its likely response to biodiesel growth, interviews were conducted with representatives of large-scale soybean oil producers and users. The general consensus of the firms interviewed was that integrated crushing/refining companies would want to perform the refining rather than selling crude soybean oil to biodiesel facilities with pre-processing equipment, and that refining capacity either is currently sufficient to meet short-term demand or could be expanded at acceptable cost (and without long lag times). However, given that oil has represented only 36 percent of the combined meal and oil product value to crushers and that the tax incentive currently is slated to expire at the end of 2008, it is unlikely that additional crushing capacity would be built specifically to meet biodiesel demand, especially by major crushers.

## 6. Biodiesel Outlook to 2025

According to Informa, absent a mandate to include a minimum blend of biodiesel, the biodiesel industry will only flourish if returns are attractive. As of April 2006, a new plant in the Midwest can realize a gross operating margin of \$0.40 - \$0.50 a gallon. With this level of returns, the industry can grow rapidly and increase faster than the ethanol industry expanded in its developing stage.

The greater risk exposure of biodiesel is the revenue side (diesel and government incentives), which is independent of expenses (i.e., feedstock cost). Hence, the long-term outlook will be primarily driven by energy prices, assuming the government maintains a credit for biodiesel. Again, without the \$1.00 a gallon tax incentive, biodiesel production will not be profitable unless crude oil prices are above \$70 - \$75 a barrel and feedstock prices are 22 - 24 cents a gallon.

Because the trajectory of world oil prices is uncertain, Informa constructed two biodiesel outlook scenarios: (1) a baseline scenario based on reference or average crude oil prices; and (2) a high-end scenario based on higher crude oil prices (Figure 23). Both scenarios assume the \$1.00 a gallon tax credit remains in effect. Biodiesel production would decline under other scenarios: if the tax credit is phased out; if crude oil prices drop below \$40 a barrel; or if feedstock prices such as soybean oil soar past 33 cents a gallon. The assumptions and implications of these two scenarios are discussed next.

### Baseline Scenario: Average Crude Oil Prices (Informa)

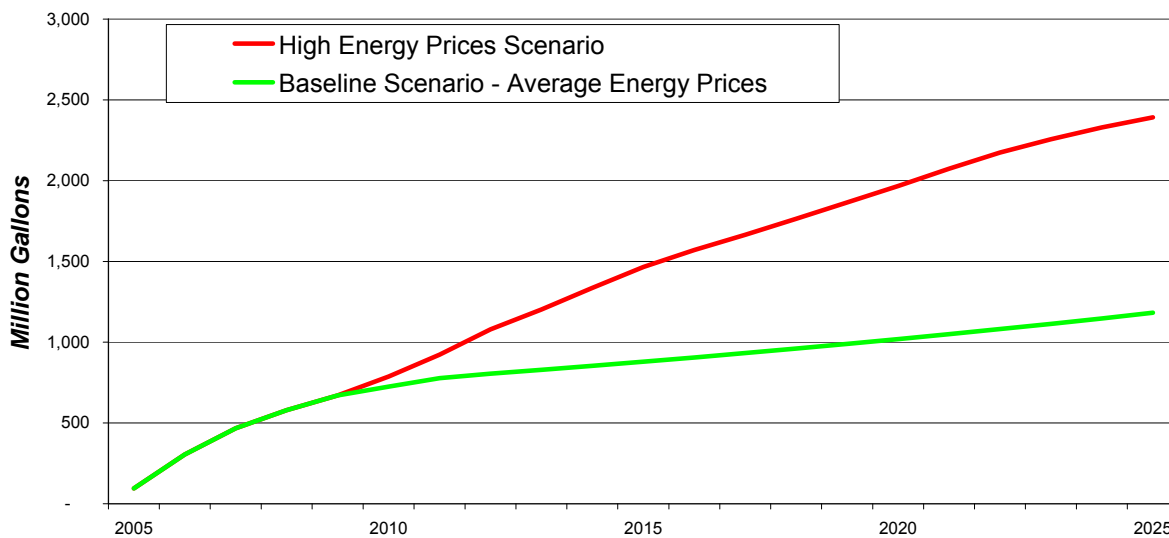
#### Assumptions

- Crude oil remains at \$60 - \$65 a barrel until 2010, declines progressively to \$50 a barrel by 2015, and remains there, on average.
- The Federal tax credit is not phased out.
- Feedstock prices (e.g., CBOT soybean oil prices) are not above 25 cents/lb for an extended period of time.
- Biodiesel made from imported vegetable oils is not excluded from the Federal biodiesel tax credit.

#### Implications

- Biodiesel production will reach 1.2 billion gallons by 2025.
- Biodiesel will represent 0.2 percent of diesel use, or 2.2 percent of on-highway diesel demand.
- Although the 1.2 billion gallons forecast for 2025 could be sustained by domestic feedstock, imported oil, primarily palm oil, will likely supplement U.S. feedstock.
- Animal fats and vegetable oils other than soybean oil will be more widely used as feedstock.
- Prices for biodiesel will be equal or even a few cents/gallon below standard petroleum diesel.

**Figure 23: Biodiesel Outlook to 2025**



Source: Informa Economics (forecasts).

*High Crude Oil Prices Scenario (Informa)*

Assumptions

- Crude oil at \$60 - \$65 a barrel until 2010 and progressively increase to \$75 a barrel, on average, after 2015.
- The Federal tax credit is not phased out.
- Feedstock prices (e.g., CBOT soybean oil prices) are not above 25 cents/lb for an extended period of time.
- Biodiesel made from imported vegetable oils is not excluded from the Federal tax credit.

Implications

- Biodiesel production will reach 2.4 billion gallons by 2025.
- Biodiesel will represent 0.3 percent of U.S. diesel use, or 4.5 percent of on-highway diesel demand.
- Palm oil will need to play a larger role in the U.S. vegetable oil market, either as feedstock for biodiesel or as a substitute for soybean oil in food uses.
- Biodiesel volume could increase even more if some states mandate a 2 percent minimum biodiesel blend.



## IV. Biobased Products

### A. Introduction

The production of industrial and consumer products from biomass is not a new idea. Prior to 1920, a large proportion of chemicals were alcohols derived from wood and grain. Most polymers were derived from cotton, and most U.S. energy was derived from wood. The introduction of inexpensive and abundant fossil energy displaced this carbohydrate based economy during the remainder of the 20th century. With the increasing cost and diminishing supplies of fossil fuels, the economy is poised to potentially swing back toward a carbohydrate base.

The emerging biobased economy will drive the production of nontraditional products from biomass, such as fuels, chemicals, and materials currently produced from petroleum feedstocks. Over \$400 billion in products are currently produced from biomass in conventional manufacturing (Energetics, Inc., 2003). These products include inorganic and organic chemicals, pharmaceuticals, soaps and detergents, pulp and paper, fuels, lubricants and greases, adhesives, and paints.

There are three main categories of biobased products: biobased chemicals; biobased plastics, including polymers, films, packaging; and cellulose fiber products. These general categories which include industrial feedstocks, intermediate materials and products, as well as final (end use) products are described in Sections B, C, and D respectively. Sections B, C, and D provide a general overview of these categories and focus on present and emerging technology issues for the various product and material groups.

The industry of biobased products is obviously very broad and many segments are intermingled. Additionally, many biobased product markets are not fully mature. The stage of development in the various biobased products ranges from research to early development and from the path towards commercialization to adoption by the marketplace or to market maturity. In order to provide an overview of the biobased markets without detailing every segment and intermediate production step, market analysis is performed solely on biobased end products. The market overview of 18 biobased end use products with the largest market potential and commercial viability in the U.S. economy is provided in section E. Section F presents the case of pharmaceuticals and nutraceuticals separately (because of the size and importance of these two markets for the biobased sector).

Future projections for biobased chemicals and materials are provided in section G. In addition to market forecasts, this section also includes the market potential that is envisioned in the development of platform chemicals.

## B. Overview of Biobased Chemicals

The production of common chemical substances has a long history. The solvents acetone, butanol, ethanol, plus citric, lactic, itaconic, gluconic and related organic acids were produced primarily by fermentation until the middle of the 20<sup>th</sup> century, and only lost the biological connection to fuels and chemicals in the past half-century. Even 25 years ago, the concept of replacing fossil carbon feedstocks with “biomass” was well considered (Lipinsky).

The chemical industry has the following market segments: commodity, specialty, fine chemicals and polymers. Commodity chemicals are manufactured in very large volumes, typically more than 3 million tons per year, worldwide. Specialty chemicals are for special uses or intermediates, and are also produced in large volumes. Fine chemicals are manufactured in smaller batches and intended mainly for pharmaceutical intermediates, enzymes, flavors and fragrances, and polymers.

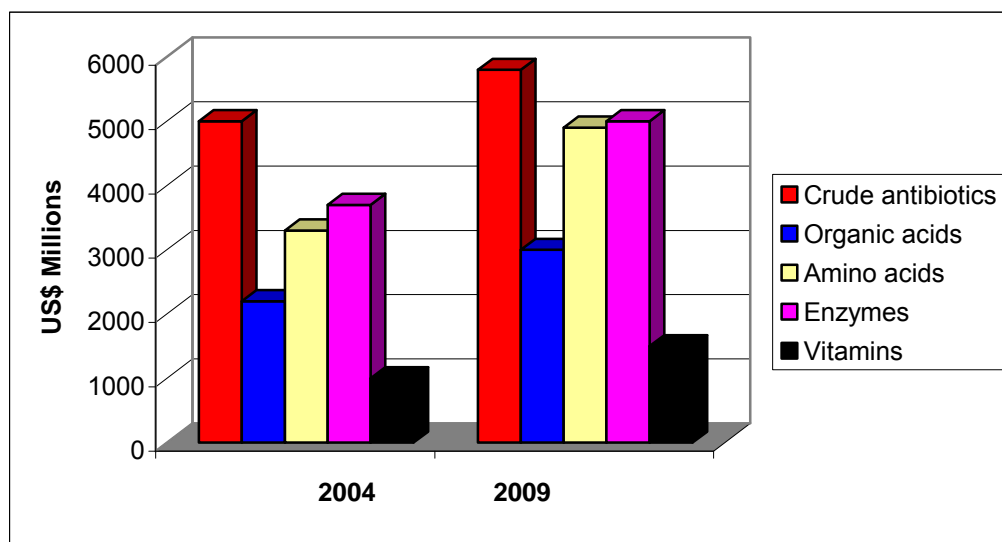
The potential of biotechnology and metabolic engineering is not questioned for the production of many compounds; from simple commodities such as organic acids to complex structures such as beta-lactam antibiotics and vitamins that sell in large volumes. In this report, biobased chemicals describe chemicals that could be produced by processes that are dependent on carbon from existing biological sources. Such sources as lignocellulosic materials, vegetable oils, chitin, and agricultural wastes are promising, but largely unexplored as chemical feedstocks. Some products currently made by biological methods - such as antibiotics, vitamins, enzymes, and high-fructose corn syrup - have never faced competitive commercial processes based on petrochemical feedstocks, but demonstrate the utility of biological production methods (Figure 24).

Both the chemical and a biobased chemicals industries share a dependence on fuel products. The chemical industry overall accounts for about 10 percent of the petrochemical feedstock use (Danner and Braun). The ability to cover production costs of nonfuel chemical products from a high-volume, fuel-product stream is of enormous importance. The technical requirement is that nonfuel chemical production processes be fully integrated with fuel production processes. In 2004, ethanol was estimated to be about 2.6 percent of the U.S. gasoline pool, with biodiesel at about 0.5 percent. To compete with nonfuel chemical products, biobased chemicals will need to be integrated with biofuel production. Integration with biofuel production will allow operational and financial efficiency as bioproduct output from existing biofuel infrastructure leads to a multiproduct operation.

Beyond the nearly universal consideration of process integration, biobased chemicals face two economic pressures also faced by fossil based chemicals: the cost of capital and the cost of energy. Existing chemical plants have the advantage with respect to capital costs, but even these plants must be improved, expanded, and repaired. In a 2003 report, *McKinsey Quarterly* concluded that returns on invested capital matter far more than revenue growth, and the generally poor performance of the chemical industry

was largely the result of decades-long neglect of capital improvements and plant capacity (Augat et al.). To the extent that biobased chemical production is performed in existing petrochemical infrastructure, additional capital costs are restricted to improvements, expansions, and repairs. Integration of biobased products to biorefineries would entail further capital costs.

**Figure 24: Global Market for Fermentation Products by Category, 2004 - 2009**



Source: Business Communication Consultants.

In addition to energy costs, feedstock costs posed another possible barrier to entry (or re-entry) of biobased chemicals into the general market. For commodity chemicals (i.e., those with current market prices below \$1/kg), the product price is affected mainly by raw material costs. Such costs are recognized as being far more than “immediate production costs.” The costs of energy consumed during the production and collection of biobased feedstocks, and the amount of land required to produce them, are considerable. For specialty chemicals (i.e., \$2 - \$5/kg), process and recovery costs, including energy, are even larger factors in final prices.

The potential impact of biobased chemicals can be viewed in terms of their impact on the existing chemical industry. Paths to value creation for biobased products are in the production of raw materials (such as changing from petroleum to corn or corn stover), reduction of process costs (reduced process steps, increased yield), reduction of risk (reliable and stabilized supply), value-added processes (shorter time to market, “natural” label), and new business lines (routes to compounds not accessible through classical chemistry). An estimated 55 percent of value-creation potential in biotechnology will be driven by revenue increases. The segment-specific impact on cost and revenues is shown in Table 17. By 2010, an estimated 20 percent of the chemical market will be biobased, amounting to value creation of \$160 billion (Bachmann, 2003).

**Table 17: Estimated Biotechnology Impact on Cost and Revenues**

Chemical segment	Cost reduction (process improvements)	Revenue or new value creation
Fine chemicals	35 percent	65 percent
Polymers	40 percent	60 percent
Bulk chemicals	75 percent	25 percent

Source: Bachmann, 2003.

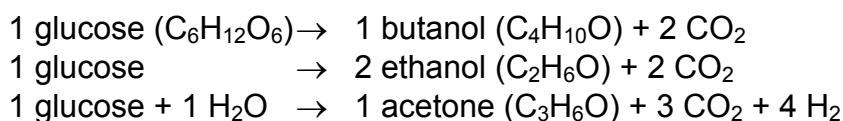
## 1. Commodity Chemicals

### a) Solvents

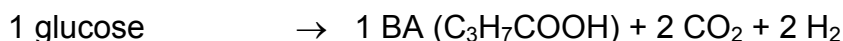
#### Existing Technology

Acetone, butanol, and ethanol (ABE) were commercially produced by fermentation processes up to 1950 with *Clostridium acetobutylicum*, the organism of choice for conducting this fermentation. This organism was originally isolated by Charles Weizmann and his process was of enormous importance to the British war effort during the First World War. The process was patented in the U.S. in 1919 (Weizmann). Between 1945 and 1950, 66 percent of n-butanol (over 45 million pounds) and 10 percent of the acetone was produced by fermentation of molasses and starch. Increased prices of the sugar feedstock and decreased prices of petrochemical feedstock ended the formative production of these solvents. With the low-cost petrochemical feedstocks beginning in the 1950s, fermentation based processes became economically unattractive and most commercial installations were closed by 1952. With petrochemical feedstocks growing more costly, the production of these important solvents by fermentation is increasingly attractive. Current production of butanol involves the hydrogenation of *n*-butyraldehyde. The cost of production is approximately \$0.66/kg.

In biological production, fermentation yields the three solvents (acetone, butanol, and ethanol) in an approximate ratio of 3:6:1. The formal stoichiometry of the chemical reaction from glucose for the various products is:



Butyric acid (BA) can also be recovered. The stoichiometry for this product is:



This is an anaerobic fermentation that produces carbon dioxide and hydrogen as off-gases. Presumably, the acetone can be reduced to isopropanol as there are sufficient reducing equivalents available, but this would require capturing the hydrogen as cellular

reducing equivalents (NADH or NADPH), and this is not considered part of the ABE fermentation. It is, however, an obvious extension of the fermentation and should be possible with conventional molecular biology. Traditional petrochemical solvents such as acetone, ketone, xylene, toluene, and methylene chloride are being replaced by biobased solvents with great success.

### Emerging Technology

Considerable recent work has been performed applying the modern tools of molecular biology to production of ABE. Studies on the genome of the original organism (Nolling et al.), a new hyper producing strain of *Clostridium beijerinckii* with yields of total solvents up to 165 g/L (Qureshi and Blaschek), process issues (Ezeji et al.), and full-scale production economics (Qureshi and Blaschek) have all been published. Lactose (whey) is an alternative feedstock to glucose (starch) and yields up to 100 g/L total solvents with an overall molar yield of 0.44. As lactose inhibits ABE fermentation, a process was designed to circumvent this (Qureshi and Maddox, 2005). Fermentation conditions can be adjusted to give different ratios of the three solvent products. Using glucose, fermentation conditions were arranged to give 77g/L acetone and 152 g/L butanol, with almost no ethanol (3 g/L) and very low total acids (8 g/L). Under these conditions, the molar conversion was 47 percent. Process patents continue to be sought despite the history of this endeavor.

Concerns over volatile organic compounds and associated health concerns are driving the introduction of environmentally benign solvents. These include methyl soyate and lactate esters. These solvents are gaining an increasing share of the market and are valid replacements for petrochemicals in a number of applications, including removal of metal working fluids, ink and paint removal, adhesive removal, household cleaners, and in the production of semiconductors. These environmental solvents are competitive in performance and in price (Table 18). Over 75 soy-derived solvents are now produced for the industrial and consumer markets. Producers of biobased solvents include Vertec Biosolvents, Purac, AG Environmental Products, Bio Chem Systems, Florida Chemical Company, and CPC Aeroscience, Inc.

**Table 18: Selling Price of Common Solvents**

<b>Solvent</b>	<b>Price (\$/kg)</b>
Methyl soyate	0.66 – 1.00
D-limonene	Up to 0.88
Methylene chloride	0.66
Methyl ethyl ketone	1.00
Trichloroethylene	1.43
Perchloroethylene	0.77

Source: United Soybean Board, Soy Based Lubricants, 2002.

## b) Lactic Acid

### Existing Technology

Lactic acid has been known as a discrete chemical since the late 19<sup>th</sup> century. It is the principal ingredient in sour milk, hence the German name Milchsäure. It is produced by the fermentation of lactose by *Bacillus* species or related organisms such as *Lactobacillus delbrueckii*, *L. bulgaricus*, etc., and is performed on a large scale using whey (lactose), cornstarch (glucose), potatoes, molasses, and other mixed sugar streams from various agricultural processes. The fermentation is carried out above 40°C and at pH below 4.5. Lactic acid is a product of the glycolysis pathway of central carbon metabolism, resulting from the reduction of pyruvate. As a commodity chemical itself, lactic acid is used as an acidulant and a preservative in foods, with annual U.S. consumption of 72 million pounds (Energetics, Inc. 2003).

### Emerging Technology

Cargill's most recent U.S. patent application covering the fermentation of lactic acid from glucose discloses examples in which the culture (referenced only as a "homolactic acid-tolerant bacteria") was capable of growing at pH 3.8 in the presence of 100g/L of glucose, and producing nearly 100g/L of lactic acid (Carlson and Peters). At this low pH, over half of the lactic acid is protonated, considerably enhancing the recovery of the lactic acid for the subsequent process steps to poly lactic acid (PLA).

While Cargill's patent literature suggests that all the lactic acid fermentation is run from glucose (from corn starch), it is very possible to produce lactic acid by other organisms growing on both hexoses (such as glucose from either starch or cellulose) as well as pentoses, which are the carbohydrates making up hemicellulose. Further, the properties of PLA are significantly affected by the chirality of the lactic acid produced. The Cargill patent application reveals that the lactic acid produced is essentially the pure L-isomer. Obviously, PLA made from the pure D-isomer would be expected to have identical bulk properties, but varying the ratio of the L- and D-isomers used to make the PLA would affect the properties of the bulk material.

A metabolically engineered *E. coli* strain has been constructed to produce the D-isomer of lactic acid growing on only minimal salts and glucose under either aerobic or anaerobic conditions, with excellent conversion of glucose to D-lactic acid (Zhou et al.). While the publication does not contain an experimental example of the use of pentoses, it does state that *E. coli* is capable of fermenting pentoses, and presumably this particular engineered *E. coli* can produce lactic acid from pentoses.

## c) Glutamic Acid

### Existing Technology

Glutamic acid is a nonessential amino acid for humans and is the most abundant amino acid in foods. It is produced primarily by fermentation using the microorganism *Corynebacterium* (there are patents for processes using *Brevibacterium* also). The vast majority of glutamic acid is used to produce monosodium glutamate (MSG), a food

flavoring agent. Glutamic acid is also used in pharmaceutical applications such as ophthalmic preparations and nasal solutions, as well as industrial applications, such as surfactants and fabric coatings. The annual demand for monosodium glutamate (MSG) worldwide is 1.1 million tons. Primary producers are Ajinomoto, Kyowa Hakko, and CJ Corp, although Chinese manufacturers are now entering the market as well.

#### Emerging Technology

Glutamic acid has the potential to be a building block for the production of five carbon polymers that could improve and provide new functionality to polyamides and polyesters. The current production of MSG is a single fermentation that produces the sodium salt of glutamic acid. To fully exploit the potential of glutamic acid as a building block, low-cost fermentations must be developed that produce the free acid. This approach would significantly lower the cost by eliminating neutralization and simplifying downstream purification. Improvements could also be made in the productivity and yields of existing production strains. Catalysts for the efficient production of desired derivatives - particularly glutaminol, 5-amino-1-butanol, 1,5-pentanediol, and norviline - also need to be developed.

### **d) Lysine**

#### Existing Technology

Lysine is an essential amino acid but is not produced in grains in sufficient amount to supply the nutritional needs of animals. Lysine can be chemically synthesized, although at 1.5 times the cost of production by fermentation of carbohydrate feedstocks. Annual world market value for feed-grade lysine exceeds \$1 billion (Source: Monsanto Company). Ajinomoto and Archer Daniels Midland (ADM) hold 25 percent and 22 percent of the market, respectively. Other producers include Degussa and CJ Corp. The lysine market has been extremely volatile since 2002, with prices ranging from \$1.20 to near \$3/kg. Current prices are depressed due to the recent increased production in Asia. However, growing demand in Asia for swine and poultry feed is expected to generate an increase in demand of 8 percent, according to ADM.

Lysine is a limiting amino acid in feeds for poultry and swine, as are threonine, methionine, and tryptophan. Production of lysine, threonine, and tryptophan are accomplished by fermentation, but methionine is currently manufactured by chemical synthesis from acrolein. While the market for amino acids as feed additives is substantial, the largest growth for amino acids in the next 5 years is expected to be for use in synthesis applications in the pharmaceuticals and biotechnology markets. The market for amino acids for synthesis applications is expected to grow at 7 percent/year through 2009, increasing from \$713 million to \$1 billion (Business Communications Company 2005).

#### Emerging Technology

An alternative approach to providing lysine in animal feeds is a genetically engineered feed corn, high in lysine, developed by Renessen, LLC, a joint venture of Cargill, Inc., and Monsanto Co. The product contains about one-fourth the amount of lysine needed

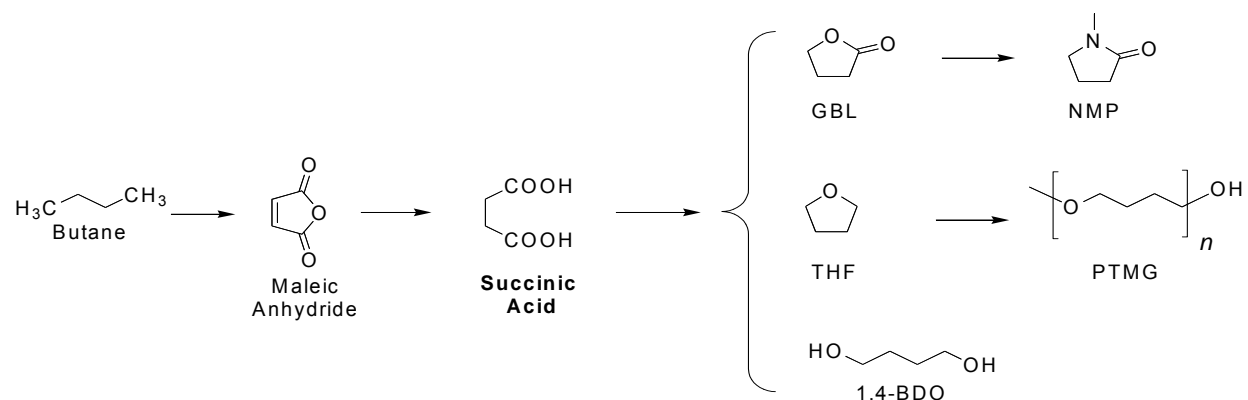
in a poultry broiler's diet (~1,000 ppm lysine). A second-generation product is expected to provide the full lysine requirement, eliminating the need for supplemental lysine in animal feed products. To date, methionine has been produced by fermentation only at laboratory scale and is not economical for commercial production. Development of organisms with pathways for efficient production of methionine could offer a fermentative alternative to its synthetic production, which produces hazardous waste streams.

Lysine could also soon be used for the production of caprolactam. Caprolactam is a monomer used in the production of polyamide-6 (Nylon 6) for use in the artificial fiber industry, as well as a structural material in the automotive and electronics industries. BASF and DSM produce over a billion pounds a year using cyclohexane as the feedstock (Chemical Market Reporter). New technologies are being developed that produce caprolactam from L-lysine (John Frost, Michigan State University, personal communication).

### e) Succinic Acid

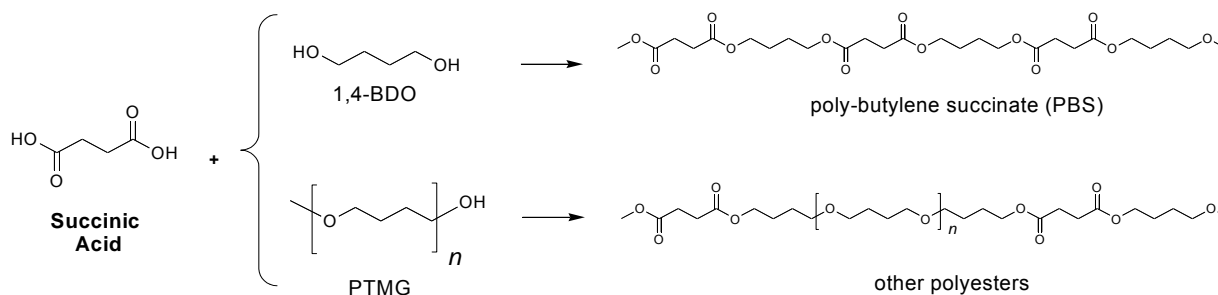
#### Existing Technology

The production of noncaptive succinic acid as a final product is small, and is purchased mostly by the food and pharmaceutical industries where it is used as an acidulant and a salt-forming compound agent for specific formulations. However, succinic acid is an intermediate occurring in the great majority of current industrial processes that use maleic anhydride as starting material. Maleic anhydride, in turn, is made by a number of processes from butane, isolated from natural gas, and from petroleum cracking. Approximately 4 billion pounds of maleic anhydride are consumed globally each year. Maleic anhydride is first converted to succinic acid (or in some processes, the dimethyl ester of succinic acid). A number of well-established, high-volume processes produce the solvent tetrahydrofuran (THF); the diol 1,4-butanediol (BDO); and another intermediate,  $\gamma$ -butyrolactone (GBL). The chemical processes used require hydrogen and operate at high temperatures and pressures, but the conditions can be adjusted to yield any of the three products out of the same process. THF can be opened and partially polymerized to give low-molecular-weight polymers of polytetramethylene glycol (PTMG), while GBL can be taken on to another solvent, N-methyl pyrrolidone (NMP).





Further, BDO can be used with PTMG and (captive) succinic acid to make polyesters, which in turn are used in polyurethane materials. The company Invista (a subsidiary of DuPont) markets PTMG as TERATHANE® glycol, the key intermediate for both LYCRA® elastane and high-value polyurethanes.



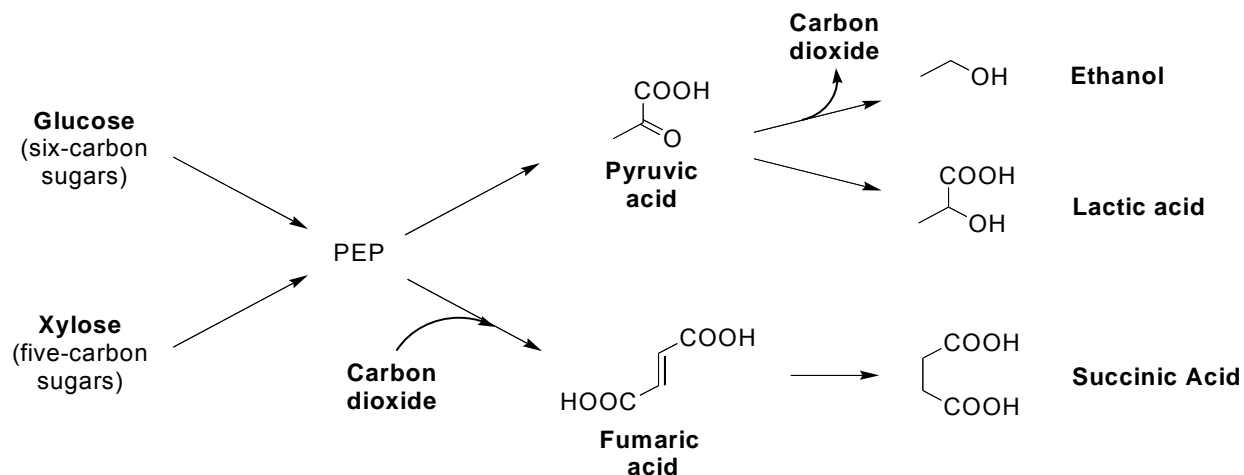
### Emerging Technology

Succinic acid has attracted much attention for several reasons:

- The biochemistry from monomeric sugars (both pentoses and hexoses) is known.
- All of the enzymes involved have been cloned and are available for manipulation by standard biotechnology.
- The processes are very well studied from the perspective of fermentation engineering and process scale-up.
- The product has a small but established market in the food industry as an acidulant.
- The product can be used to replace maleic anhydride by simple, well-established industrial chemistry, with annual production of 4 billion pounds.

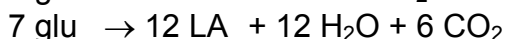
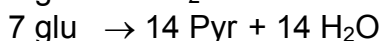
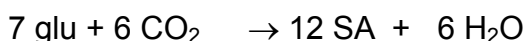
Figure 25 shows a very simplified scheme of the metabolic pathways to succinic acid, plus other products of biobased production (ethanol, lactic acid, and potentially pyruvic acid and fumaric acid). While significant portions of the metabolic pathways have been omitted, the flow of carbon is complete. The consumption of both the five-carbon sugars (the pentoses, xylose, and arabinose from hemicellulose) and six-carbon sugars (hexoses, of which glucose from starch and fructose from cane sugar are the chief examples) goes through a common intermediate, phosphoenol pyruvate (PEP). Clearly, the production of ethanol requires the production of carbon dioxide for redox balance. Not shown are the other pathways from PEP, which also require the production of carbon dioxide to maintain the redox balance for the production of lactic acid.

**Figure 25: Biochemical Pathways to Ethanol, Lactic Acid and Succinic Acid via Phosphoenolpyruvate (PEP)**



The production of succinic acid can be capnophilic in some organisms. That is, the redox balance is maintained by the consumption of carbon dioxide. This is chemically possible because succinic acid is slightly more oxidized (has a higher redox potential) than hexoses or pentoses. The correct stoichiometry for the production of ethanol (EtOH), lactic acid (LA), pyruvic acid (Pyr), and succinic acid (SA) from glucose is given by the equations below.

Redox-balanced stoichiometry:

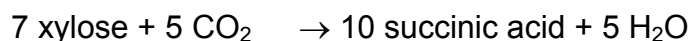


For comparison, the balanced equation for the complete oxidation of glucose to carbon dioxide is below. This equation is chemically correct for both the cellular metabolism of glucose (respiration) and the actual burning of glucose in air; in both cases, the same amount of energy is released.



However, productivity is critical to production of commodities and requires more than the right metabolic pathways. Very few microorganisms are known to produce succinic acid in sufficiently high concentrations to permit economical production. A review of the patent literature reveals three well-studied organisms for which claims of useful succinic acid production have been allowed; *E. coli* (ATCC 202021; Donnelly et al.); *Anaerobiospirillum succiniciproducens*, for which two strains are patented (ATCC 29305 and ATCC 53488; Datta, 1992; Guettler and Jain); and *Actinobacillus succinogenes* (ATCC 55618; Guettler et al.).

Of this list of organisms, *A. succinogenes* is unique in its ability to use both hexoses (glucose) and pentoses (xylose and arabinose) simultaneously, and is thus well suited for the biobased production of succinic acid from lignocellulosic feedstock. The stoichiometry for the production of succinic acid from pentoses is:



#### f) Propanediol

##### Existing Technology

Propanediols (PDOs) can exist as different isomers. Two of these, 1,2-propanediol and 1,3-propanediol, have significant utility. 1,2-propanediol (propylene glycol) is currently produced from petrochemical feedstocks mainly by the hydration of propylene (which is the monomer for the production of polypropylene). Like lactic acid, 1,2-PDO has a chiral center and exists in two enantiomers. However, the current methods for production of 1,2-PDO from petrochemical feedstocks produce equal amounts of the two enantiomers, and chiral 1,2-PDO is considered an expensive, low-volume specialty chemical. The primary uses of 1,2-PDO is in unsaturated polyester resins, liquid laundry detergents, pharmaceuticals, cosmetics, antifreeze and de-icing formulations. In 2004, the annual global market for propylene glycol was an estimated 3.1 billion pounds. Dow Chemical is the largest producer, with a capacity of 1.2 billion pounds/year. Prices have been increasing steadily due to cost increases for the petrochemical feedstocks.

##### Emerging Technology

It is possible to engineer metabolic pathways to both enantiomers of 1,2-PDO, and this has been published and patented (Altaras and Cameron; Cameron et al.). The 1,3-isomer of propanediol (1,3-PDO) cannot be easily produced from any current petrochemical propylene chemistry. Although this molecule has been known for many years to have utility as a diol for polyesters, it has only recently become available via biological methods. The biological production of 1,3-PDO from glucose by a metabolically engineered culture of *E. coli* was a joint effort between Genencor and DuPont, and has been extensively presented and patented (Emptage et al.). Formally, only two enzymes are needed to transform glycerol to 1,3-PDO: glycerol dehydratase and 1,3-propanediol dehydrogenase. Practically however, the metabolic engineering is more complicated and improvements have been published by others (Zhu et al.). A re-activation factor is required to make the dehydratase useful, and since *E. coli* does not produce glycerol metabolically from glucose, two additional genes have to be inserted and three potential pathway branch points blocked.

The current *E. coli* construct used by DuPont is reported to be capable of producing 120 g/L 1,3-PDO in 36 - 40 hours, using only glucose as the carbon source. 1,3-PDO is one of two components for the polyester Sorona™, and DuPont has announced the construction of a fermentation facility in Loudon, Tennessee, that will produce 100

million pounds of 1,3-PDO/yr, and is estimated to have 4 - 5 million liters of production capacity.

### **g) Hydroxypropionic Acid**

#### Existing Technology

There is no viable petrochemical production route to 3-hydroxypropionic acid, although several of the derivative chemicals are produced from petroleum feedstocks.

#### Emerging Technology

3-hydroxypropionic acid is a platform chemical from which several commercially valuable chemicals - including 1,3-propanediol, malonic acid, acrylic acid, and acrylamide - could be derived. These are high-volume chemicals used to manufacture polymers, resins, plastic packaging, fibers, and adhesives. Cargill teamed with the Pacific Northwest National Laboratory and Codexis, Inc., to develop a process for production of 3-hydroxypropionic acid from glucose. The annual market for acrylic acid derivatives is estimated at \$950 million, and the market for acrylamide derivatives is estimated at \$370 million.

Worldwide production of acrylic acid reached 2.9 billion pounds in 2002. Rohm and Haas/StoHaas, BASF, American Acryl, Celanese, and Dow are the major producers. Most acrylic acid is consumed in the form of a polymer. Growth in demand for super absorbents (diaper and hygienic products) increased consumption at an annual rate of 6.5 percent until 2000. Current growth has slowed due to oversupply and a slow demand growth economy. While prices for acrylic acid increased 5 percent in 2002, feedstock propylene prices increased 15 percent, depressing margins. Growth is expected to continue at around 5 percent, and the utilization of biobased feedstocks could offer a competitive advantage as petrochemical feedstock prices increase.

## **2. Fine Chemicals**

### **a) Pharmaceuticals**

#### Existing Technology

Current pharmaceutical technology is too broad in nature for discussion with regard to this study; however certain market trends can be addressed. The global market for pharmaceuticals was an estimated \$466 billion in 2003 (Norwegian Association of Pharmaceutical Manufacturers). Biopharmaceutical products accounted for approximately 12 percent of global sales. Visiongain estimates the 2005 biopharmaceutical market at \$70.8 billion. By 2010, biopharmaceutical products are expected to represent 17 percent of total pharmaceutical sales (Visiongain, 2005). The global market for antibiotics alone is \$25 - \$30 billion (Visiongain, 2004; Gavrilescu and Christi). Cephalosporins dominate, with 26.3 percent of the market. However, quinolones and fluoroquinolones are expected to gain market share in the near future.

### Emerging Technology

Many pharmaceuticals are semisynthetic molecules in that part of their structure is synthesized by biological means and later modified by chemical processing. The switch from chemical processing to microbial/enzymatic processing is being driven by the development of new enzymes and processing methods. Keneka Corporation has developed a fully enzymatic process for production of amoxicillin using thermostable enzymes, replacing a chemical synthesis method that had problems with product color, low-energy efficiency, and formation of byproducts.

Shikimic acid is a six-member carboxylic ring that is naturally produced in plants and microorganisms. It is an important intermediate in the production of Oseltamivir, marketed by Hoffman-La Roche as Tamiflu®. Presently, the shikimic acid is harvested from the fruit of *Illicium* plants (Chinese star anise), a tedious multistep process that precludes its use in large volumes. The lack of sufficient sources of shikimic acid to support large-scale production has made production of the chemical by fermentation an attractive alternative.

A process for producing shikimic acid from glucose was patented in 2002 (Frost and Knop) and licensed nonexclusively to Roche, which has used the process to produce 8,000 kg for Tamiflu® manufacture (John Frost, personal communication). The market for Tamiflu® is estimated at greater than \$1 billion annually. It is considered a strategic asset in the control of pandemic outbreaks of influenza.

Acid-catalyzed dehydration of shikimic acid yields p-hydroxybenzoic acid, a precursor to parabens and an intermediate in the production of liquid crystal polymers (polymers are discussed in a later section).

Quinic acid can also be produced from glucose in a scheme similar to the Frost shikimic acid route. Quinic acid is used in the production of pharmaceuticals. With the Frost technology, it is possible that hydroquinone (another pharmaceutical) could be produced from quinic acid.

The production and use of biologically active proteins and other biologics is being driven by biotechnology. These products include erythropoietins, interferons, insulins, blood factors, enzymes, growth hormones, monoclonal antibodies, growth factors and therapeutic vaccines (Table 19). In 2003, the market for therapeutic proteins was \$37 billion and could grow to \$90 billion by 2010 with improvements in drug delivery and cost of production (Visiongain, 2005). Companies involved in the production of biologics include Amgen, Johnson & Johnson, Roche, GE Healthcare, Repligen, GlaxoSmithKline, Merck, Cambrex, Baxter, Bayer AG, Degussa AG, Novartis, Novozymes, Genencor International, Schering-Plough, and Wyeth. The expiration of patents on some leading biologics is expected to affect this market during the next few years. The introduction of generic “biosimilars” worldwide is expected to drive prices down and increase the competition for these products. New technologies and new products will be critical for some manufacturers to continue in this field.

**Table 19: Current Biologics and Market Size**

<b>Product</b>	<b>Market size (million US\$)</b>
Erythropoietin	6803
Blood clotting factors	2585
Interleukin	184
Insulin	4017
Inteferon	3919
Monoclonal antibody (cancer)	1751
Monoclonal antibody (various)	1152
Growth hormone	1706
Growth factor	115

Source: Melmer.

An emerging technology is the production of pharmaceutical proteins in plants. Field testing of this technology has been taking place since the early 1990s and has accelerated in the last few years (Table 20). More than 325 sites of field trials were approved between 1991 and 2004 for novel proteins and pharmaceuticals (Elbehri).

**Table 20: Technologies under Development for Plant-Made Pharmaceuticals**

<b>Company</b>	<b>Crop</b>	<b>Pharmaceutical</b>
Ventria Bioscience	Rice	Lactoferrin, lysozyme
Chlorogen, Inc.	Tobacco	Cholera vaccine, human serum albumin, interferon
Medicago	Alfalfa	Hemoglobin
Meristem	Corn, tobacco, alfalfa	Hemoglobin, gastric lipase, albumin, cancer therapeutic antibodies
EpiCyte	Corn	Monoclonal antibodies
SemBio Systems	Safflower	Antiobesit peptid, somatotropin
MPB Cologne	Potato, rapeseed	Antibodies for the detection of food/water borne pathogens
AttaGen	Potato	Hemoglobin, factor VIII, human growth hormone
Large Scale Biology Corp.	Tobacco	Alpha galactosidase A, patient specific cancer vaccines, B-cell non-Hodgkin's Lymphoma

Source: Michigan Biotechnology Institute.

## **b) Enzymes**

Enzymes are biologically produced proteins that catalyze chemical processes without themselves being altered or destroyed. Bioprocessing uses the ability of enzymes to catalyze chemical transformations to produce a variety of chemicals. Enzymes are used industrially to process foods, textiles, leather goods, pulp and paper, grains, and detergents. Enzymes, as a whole, are typically produced biologically by fermentation of a carbohydrate substrate. In fine chemicals, they are used primarily in research and development. These products generally command a higher price than specialty

chemicals; however their low volume limits their overall impact and importance in the emerging bioeconomy.

### **c) Vitamins**

#### Existing Technology

Most vitamins are produced by chemical synthesis. Ascorbic acid (vitamin C) is the most produced vitamin, at 100 million kg/year. Vitamin C has been traditionally manufactured by the Reichstein process, a combination of microbial oxidation and chemical synthesis, although a two-step fermentation method is now being employed. New advances also permit the production of vitamin B<sub>2</sub> by BASF in a single-step fermentation from vegetable oil using the fungus *Ashbya gossypii*. DSM developed another single-step fermentation for production of B<sub>2</sub> from *Bacillus subtilis*. Increases in yield of 300,000 fold reduced production cost by 50 percent over the conventional process. Increasing pressure from Chinese manufacturers has been pushing U.S. manufacturers out of the Vitamin C market.

#### Emerging Technology

New fermentation methods such as the ascorbic acid jointly developed by Genencor International, Argonne National Laboratory, and Eastman Chemicals hold promise for competing against Chinese production. Major producers of vitamins include Archer Daniels Midland Co., BASF/Takeda, Boehringer Ingelheim Consumer Health Care, Cognis Deutschland GmbH & Co. AG, DSM Nutritional Products, Daiichi Pharmaceuticals, Degussa, Jiangsu Jiangshan Pharmaceutical Co., Ltd, Kuraray Company, Lonza Group, North China Pharmaceutical Group Corp, Northeast General Pharmaceutical Factory, Pharmavite, Inc., and Sanofi-Aventis. The global market for vitamins is expected to reach \$1.27 billion by 2009 (Figure 24). Table 21 shows a sampling of industrially produced vitamins and their applications.

**Table 21: Industrial Production of Vitamins**

Compound	Production method			Applications
	Biotechnology	Chemical	Extraction	
Ascorbic Acid (C)	+ <sup>a</sup>			Feed, food, pharmaceutical
Thiamin (B <sub>1</sub> )		+		Food, pharmaceutical
Riboflavin (B <sub>2</sub> )	+			Feed, pharmaceutical
Biotin	+ <sup>b</sup>	+		Feed, food
Pantothenic acid	+ <sup>a</sup>	+		Feed, food, pharmaceutical
Pyridoxine (B <sub>6</sub> )		+		Feed, food, pharmaceutical
Vitamin D <sub>3</sub>		+	+	Feed, food
Vitamin A		+		Feed, food, pharmaceutical
α-Tocopherol (E)	+ <sup>b</sup>	+	+	Feed, food, pharmaceutical, nutraceutical

<sup>a</sup> Combination of microbial and chemical reactions

<sup>b</sup> Pilot scale process

Source: Shimizu.

#### d) Flavors and Fragrances

##### Existing Technology

While Western Europe, the United States, and Japan have historically dominated the flavor and fragrance market; there is significant growth in Asia, Latin America, and Eastern Europe. Food and beverages account for the largest share of the current market, at 47 percent (Global Information, Inc. 2005). Market growth is expected in soft drinks, snacks, convenience foods, confections, cosmetics, and skincare products. The global market for flavor and fragrance products was an estimated \$16.3 billion in 2003 (SRI Consulting, 2004), and is expected to increase at an annual rate of 4.7 percent and reach \$19 billion in 2009 (\$4.4 billion in the United States alone) (Freedonia Group, 2005a).

Demand for more natural ingredients and authentic flavors is expected to be a primary driver in the flavors/fragrances market during the next 5 years, along with increased demand for anti-aging products in cosmetics and skin care.

Microbes have long played an integral role in the complex flavors and aromas of beer, wine, cheese, and soy sauce. Microbial catalysis is currently used for the production of a wide range of flavors and fragrances. Flavoring agents such as citric acid and glutamic acid are produced on a commodity scale and are discussed elsewhere in this study. Many ingredients of flavor/fragrance products are extracted from limited botanical sources. Producing these compounds through the sustainable use of



renewable resources will be important. Other ingredients are chemically synthesized, often from petrochemical resources.

Microbial production of chemicals has the advantage of chiral purity. This can have a significant effect on flavor quality and intensity. Enzymatic transformation can also be used for the optical resolution of racemates, especially with regard to alcohols, esters and carboxylic acids.

#### Emerging Technology

Vanillin has an annual market volume of 12 million kg and is second only to aspartame as a flavor additive. While current manufacture is based on the conversion of ferulic acid to vanillin, technologies are being developed to produce vanillic acid from glucose, using a microbe-catalyzed process, with subsequent reduction to vanillin catalyzed by aryl-aldehyde dehydrogenase isolated from *Neurospora crassa* (Frost, 2002).

Allylix is developing a technology for the production of a range of terpene compounds using high-yield fermentations. Terpenes are typically produced by extraction from plants. Other chemicals that could affect the flavors and fragrances market are succinic acid and sugar polyols. New fermentations are being explored to produce ingredients for fragrances and skincare products.

### **e) Energetic Materials (1,2,4-butanetriol and phloroglucinol)**

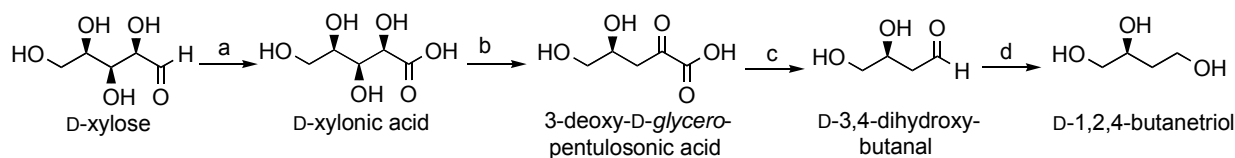
#### Existing Technology

1,2,4-butanetriol (BT) is a polyol intermediate that can be nitrated to produce 1,2,4-butanetriol trinitrate (BTTN), a compound that is thermally more stable, has a lower shock sensitivity, and is less volatile than nitroglycerin. BTTN can be used as a co-plasticizer in castable explosives. BT is currently derived from petrochemical feedstocks. The cost of racemic BT (\$30 - 40/lb) currently limits its use in the production of BTTN (Office of Naval Research).

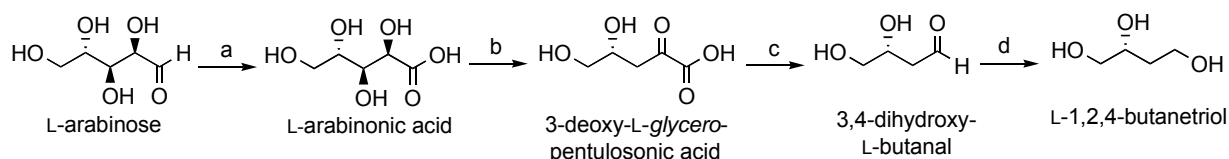
Another intermediate with potential for production of propellants/explosives is phloroglucinol, which could be used in the synthesis of 1,3,5-trinitro-2,4,6-triaminobenzene (TATB), a stable energetic material used by the U.S. military. The current manufacture of phloroglucinol involves oxidation of 2,4,6-trinitrotoluene (TNT), a process that presents an explosion hazard and generates carcinogenic chromates as well as other waste streams. Phloroglucinol can also be used in the synthesis of resorcinol, widely used to produce resins used in adhesive applications for products ranging from tires to plywood.

#### Emerging Technology

Dr. John Frost has developed a synthesis of BT that uses microbial catalysis and renewable carbohydrate feedstocks (Niu et al.). In this process D-BT is produced from D-xylose and L-BT is derived from L-arabinose (Figure 26).

**Figure 26: Production of 1,2,4-Butanetriol from Pentose Sugars**

a. D-xylose dehydrogenase; b. D-xylonate dehydratase;  
c. 2-ketoacid decarboxylase; d. alcohol dehydrogenase.



a. L-arabinose dehydrogenase; b. L-arabinonate dehydratase;  
c. 2-ketoacid decarboxylase; d. alcohol dehydrogenase.

While the market for BTTN explosives and propellants is relatively small, it is anticipated that BTTN could replace nitroglycerin as a vasodilator for the treatment of angina. Advantages of BTTN over nitroglycerin include its resistance to degradation by nitrate reductase and its ability to produce chirally pure D-BTTN and L-BTTN, minimizing the number of metabolites generated from degradation by nitrate reductase.

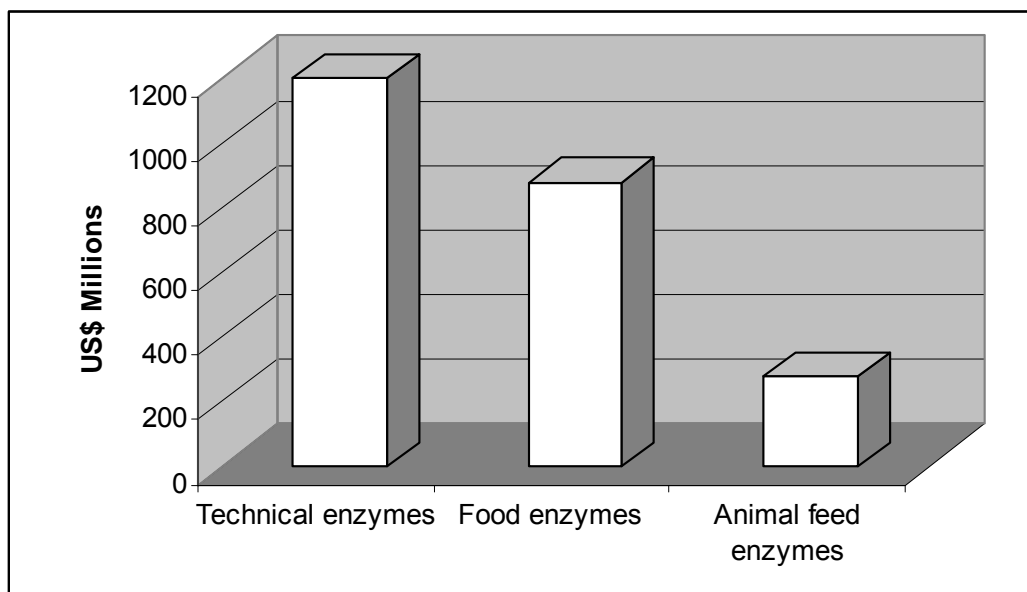
Other possible BT derivatives include chiral intermediates D-3,4-dihydroxybutanoic acid, L-3,4-dihydroxybutanoic acid, D-3,4-dihydroxybutanal, and L-3,4-dihydroxybutanal. Crestor®, a cholesterol-lowering drug manufactured by Astra Zeneca, is derived from D-3,4-dihydroxybutanoic acid. The Frost Group has also developed a process for microbial synthesis of phloroglucinol from glucose and a process for catalytic hydrogenation of phloroglucinol for the production of resorcinol.

### 3. Specialty Chemicals

#### a) Enzymes

##### Existing Technology

The global market for industrial enzymes was \$3.7 billion in 2004 and is expected to grow 6.5 percent a year through 2009 (Freedonia Group, 2005b). Technical enzymes account for 63 percent of the market, food enzymes 31 percent, and feed enzymes 6 percent (Figure 27).

**Figure 27: Projected Global Enzyme Markets Based on Application Sectors 2009**

Source: .Business Communications Company, 2004 and 2005

Distributions of industrial enzymes by substrate are protein hydrolyzing (59 percent), carbohydrate hydrolyzing (28 percent), and lipid hydrolyzing (3 percent). Specialty enzymes for analytical, pharmaceuticals, and diagnostics account for 10 percent of the market. Table 22 shows application areas and types of enzymes used. As the biobased economy emerges, enzymes will play a more significant role.

#### Emerging Technology

Enzymes will replace current catalysts used in chemical synthesis of many products. New enzyme discovery, development of new processes for enzyme production, and development of microbial systems with specific enzymatic steps for production of desired products will drive the commercialization of new biobased products. Cost has long been an impediment to the widespread use enzyme catalysts. Recently, both Genencor and Novozymes embarked on independent programs to reduce the cost of cellulase for the conversion of biomass cellulose to monomeric glucose. This is considered crucial to developing a cost-efficient process for converting biomass to fuels and chemicals. In a 4-year period, both companies reduced the cost over thirty-fold, placing these enzymes nearer the commodity price range than that of specialty chemicals (van Beilen and Li). The development of these enzymes should promote their use in the pulp and paper industry.

**Table 22: Applications for Industrial Enzymes**

<b>Market</b>	<b>Application</b>	<b>Enzyme</b>
Food processing	Baking	Amylase, protease
	Flavor development	Lipase
	Cheese	Protease
	Fruit Juice Clarification	Pectinases
	Cereals	Amylase
	Brewing	Amylase, glucoamylase
	Oxygen removal	Glucose oxidase
	Meat tenderizing	Protease
Grain processing	Corn syrups	Amylase, glucose isomerase
Textiles	“Stone-washed” texture	Cellulases
	Desizing of fabrics	Amylase, protease
Leather	Bating	Protease
Feed	Improve digestibility of animal feed	Phytase, xylanase, cellulase
Detergents	Improved cleaning	proteases
	Cold-soluble laundry starch	Amylase
Pulp & paper	Kraft Bleaching	Xylanases
	Starch modification for paper coating	Amylase
	Recycling/deinking	Cellulase, hemicellulase

Source: Michigan Biotechnology Institute.

## **b) Inks and Dyes**

### Existing Technology

Petroleum-based inks have dominated the market for several decades. However, during the oil crises of the 1970s, inks from soy, linseed, corn, and canola began to infiltrate the market. Today over 90 percent of U.S. newspapers and 25 percent of commercial printers use soy based ink. The market share for vegetable oil based inks increased from 5 percent in 1989 to 25 percent in 2002.

Until 1890, all available dyes (pigments and tannins) were from natural sources. These natural dyes were progressively replaced by synthetic dyes. While the synthetic versions were not as durable they cost much less to produce. Today, the U.S. market for dyes and organic pigments is \$3.1 billion, with a volume of 600 million pounds (Freedonia Group, 2004a). Producers include Ciba Specialty Chemicals, DyStar, Clariant, Sun Chemical, Bayer, BASF, Buffalo Color, and Fabricolor.

### Emerging Technology

Although biobased inks are prevalent in the current market, there is still significant potential for their increased use. New applications for improved biobased inks include

toner for printers and copiers, ink for ballpoint pens, and UV curable lithographic inks. Investigators are pursuing the production of anthraquinone compounds by various fungal species to replace synthetic dyes in the violet, blue, and green hue sectors (Hobson and Wales). In the 1990s, Genencor International developed a biological process for production of indigo with *Ceiba Geigy* (Berry et al.). Others are attempting to genetically engineer crops for production of dyes such as indigo.

### c) Adhesives

#### Existing Technology

Many conventional adhesives contain volatile organic compounds (VOCs) that can combine with atmospheric nitrogen oxide to produce ozone, a major cause of respiratory problems in humans. In the 1930s, urea-formaldehyde and phenol-formaldehyde resins began replacing corn starch and soy based adhesives due to their greater water resistance and lower cost. Today methylene diisocyanate (MDI) adhesives have replaced soy as the primary resins in wood adhesives. Current uses of adhesives are shown in Table 23.

**Table 23: Common Uses of Adhesives**

Industry	Applications
Construction	Manufacture and installation of laminated wood panels, prefabricated beams, wall panels, general building construction; installation of flooring, tile, carpeting, ceiling panels and wall coverings.
Consumer goods	Manufacture of office supplies, hobby and model supplies, and stationery.
Nonrigid bonding	Bonding of woven and non-woven fabrics; manufacture of athletic shoes, rugs, filters, books, and sporting goods.
Packaging	Manufacture of cartons, boxes and corrugated boards; bags, envelopes, disposable products (diapers, paper products); cigarettes; and labels and stamps.
Rigid bonding	Manufacture of appliances, electronics, household products and furniture.
Tapes	Manufacture of all tapes, including those used for surgery, packaging, industrial applications, consumer applications and masking applications.
Transportation	Aircraft and aerospace structural assemblies; automotive, truck, boat, and bus assembly; mobile home manufacturing.

Source: Pacific Northwest Pollution Prevention Resource Center.

#### Emerging Technology

The replacement of petroleum feedstocks with biobased feedstocks is being driven by environmental, health, and safety concerns as new adhesives and sealants are being developed. Packaging is the largest end use of adhesives and sealants, followed by wood and related products. The largest producers of adhesives in the U.S. are Henkel, National Starch, H.B. Fuller, 3M, and Bostik Findley. Producers of starch based adhesives include National Starch, A.E. Staley Manufacturing Company (part of Tate & Lyle), Roquette (France), Croda Chemicals, Cerestar, American Protein Corporation,

and Chitogenics Ltd. Research into new adhesives from corn starch, soy, and sugar based polymer resins is promising new products and applications for biobased adhesives.

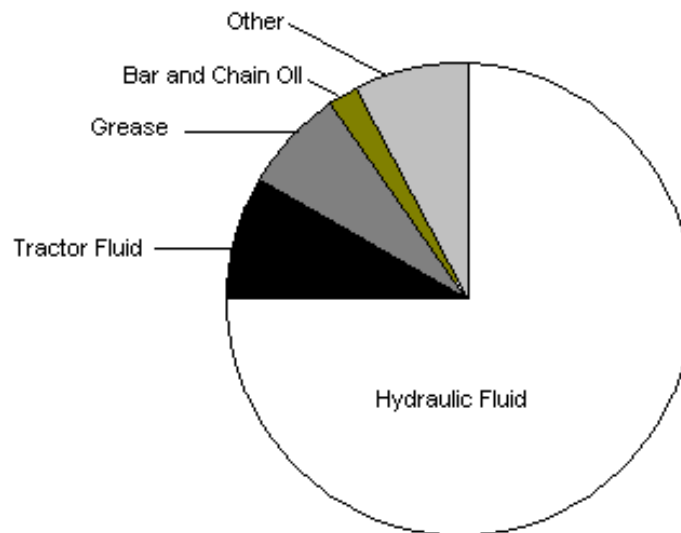
In 2004, Rohm and Haas Company was awarded a \$2 million grant from the U.S. Department of Energy to develop a new generation of adhesives and sealants. Rohm and Haas is working with Virginia Polytechnic Institute and State University, the Eastman Chemical Company, and USDA's Eastern Regional Research Center to develop new adhesives from sugars, soybean oil, castor oil, and other biomass (Rohm and Haas). Other groups pursuing biobased adhesives include Ecosynthetix (Lansing, MI), the Plant Polymer Research group at the National Center for Agricultural Utilization Research, the Thames Research Group at the University of Southern Mississippi, and Omni Tech International, Inc. (along with the New Uses Committee of the U.S. Soybean Board).

#### d) Lubricants and Functional Fluids

##### Existing Technology

Lubricants and functional fluids represent a multibillion-dollar market. Current products are almost exclusively produced from petrochemical feedstocks, although biobased products are starting to enter the market. Hydraulic fluids make up 75 percent of the biobased lubricant market (Figure 28). This represents 2 percent of the total hydraulic fluid market (Miller et al.).

**Figure 28: Use of Biobased Lubricants by Application**



Source: Miller et al.

Vegetable oils are used in such applications as hydraulic fluids, chain bar oils, metal working fluids, industrial gear oils, two-stroke motor oils, wire rope lubricant, and greases. Some advantages of biobased oils are (1) potentially less costly final disposal,

(2) low cost versus high cost synthetic esters, (3) inherent high viscosity, (4) good anti-wear properties, and (5) high flash point (Fields). About 85 percent of vegetable oil based lubricants are derived from canola. Soybean and other oils make up the balance.

Manufacturers of biobased lubricants and hydraulic fluids include large oil companies such as Burmah Castrol, Exxon, Pennzoil, Texaco, Quaker State, and Mobil, as well as Cargill, Lubrizol and a number of smaller companies in North America. By 2010, biobased lubricants are expected to command an estimated 35 percent of the total lubricant market in Europe (PRA/CANUC). It is expected the North America would follow in the same trajectory.

### Emerging Technology

Development of genetically engineered crops such as soybeans with increased levels of oleic acid is expected to yield increased oxidation stability of biobased lubricants. In 2004, Cooper Power partnered with Cargill to launch vegetable oil based transformer oil with several advantages over traditional mineral oils, including better compatibility with paper insulators, greater fire resistance, lower flash point, and fewer environmental concerns over spills (Fields). While the U.S. Government has mandated the increased use of biobased products, biobased lubricants still face several challenges in developing future markets. These include:

- Cost competitiveness.
- Insufficient oxidation stability for more severe applications.
- Lack of environmentally benign additives for both biobased and petrobased lubricants.
- The Environmental Protection Agency's practice thus far not to differentiate between oil types in the event of spills. Consequently even though environmental benefits have been attributed to biobased lubricants, in the event of a spill cost benefits may not accrue to the users of biobased lubricants.

## **e) Gallic Acid and Pyrogallol**

### Existing Technology

Gallic acid and pyrogallol are aromatics that have a high oxygen content. These chemicals are ideal candidates for synthesis of such products as trimethoprim, gallamine triethiodide, and trimetazidine. Propyl gallate is used in food applications as an antioxidant. The market for gallic acid is 170,000 kg annually. The market for pyrogallol is 200,000 kg annually. Gallic acid is currently isolated from insects and pyrogallol comes from the seed pod of a tree native to Peru.

### Emerging Technology

Gallic acid can be produced by fermentation of biomass-derived carbohydrates using a recombinant *E. coli* (Frost, 2002). Gallic acid can be converted to pyrogallol via decarboxylation by another recombinant *E. coli* at a yield of 97 percent.

## f) Sugar-Polyols

### Existing Technology

Sugar polyols are polyhydric alcohols derived from the catalytic hydrogenation of sugars. They occur naturally in plants throughout the world, and most commercial production is based on extraction of the specific sugar from plant material and subsequent processing to the polyol (hydrogenation). The most widely used polyols are sorbitol, mannitol, and malitol, with sorbitol accounting for half of the market. They are used primarily in confectionary, food, and oral care applications. Polyols have the sweetness characteristic of sugars, with fewer calories, and are able to hold moisture. They are versatile ingredients and are used as sweeteners, bulking agents, humectants, freezing-point depressants, plasticizers, chelating agents, color stabilizers, and flavoring agents (Table 24).

In 2004, 690,000 metric tons of sorbitol were produced at a value near \$500 million (SRI Consulting, 2005a). The sorbitol market has increased 1 - 2 percent/year since 1997 and is expected to slow to less than 1 percent through 2009. Producers of sugar polyols include Roquette Freres, Archer Daniels Midland, Danisco, SPI Polyols, Cerestar, BASF, and Bayer AG.

**Table 24: Sugar-Polyol Applications**

<b>Polyol</b>	<b>Applications</b>	<b>Function</b>
Adhesives	Sorbitol	Flexibility and gloss enhancer, plasticizer, shelf-life extender
Paper products	Sorbitol	Anti-static agent, chelating agent, humectant, plasticizer, softener, fluidizing agent
Surfactants	Sorbitol	Raw material
Textiles	Sorbitol	Anti-static agent, chelating agent, humectant
Personal hair care	Sorbitol	Conditioner, softener, shelf-life extender
Food/beverages	Sorbitol, mannitol	Flavoring agent, bulking agent, crystal modifier
Mouthwash/toothpaste	Xylitol, erythritol	Sweetener
	Sorbitol, xylitol	Crystallization inhibitor, flavoring agent/sweetener

Source: SPI Polyols, Inc.

### Emerging Technology

While hydrogenation sounds simple, it is actually a sophisticated process practiced by a few large companies with the appropriate know-how. New research is focused not on new products but rather new applications. Biotechnology is aiming for the complete production of sugar polyols through the use of microbes and microbial enzymes in an effort to eliminate the chemical hydrogenation step (Rainer and Silveira). ZuChem is developing fermentation pathways to the production of mannitol and xylitol, and estimates the global market for mannitol as a reduced-calorie sweetener to be \$100



million/year (In-Pharma Technologist). Other polyols being developed by industry leaders include lactitol and erythritol.

### C. Overview of Biobased Plastics, Polymers, Films and Packaging

Polymers are long chain-link molecules of repeating structural units connected by covalent chemical bonds. The subunits, or building blocks, are called mers, hence the name polymers. Monomers are the small molecules of low to moderate molecular weight used to produce polymers. Cellulose is a homopolymer consisting of glucose (the monomer) molecules connected by  $\beta$ -1,4 ether linkages. If a polymer is constructed from two (or more) different monomers, it is called a copolymer or terpolymer. An example would be the polymerization of ethylene with 1-hexene to form a low-density copolymer of ethylene and hexane.

One way to classify polymers is based on their thermochemical properties. Elastomers have a structure causing them to possess memory or elasticity. Bonds along the carbon backbone of an elastomer undergo reversible bond rotations, allowing the chain to be extended or elongated. Natural and synthetic rubbers are examples of elastomers. Plastics are polymers that can be molded or shaped with heat and generally have a greater stiffness and less elasticity than elastomers. The two main types of plastics are thermoplastics and thermosets. Thermoplastics soften when heated and harden again when cooled. Thermosetting materials, when heated, melt and flow but then further react (cross-link) to form rigid material. Table 25 shows several examples of polymers by type. Thermoplastics account for the majority of commercial usage, and the vast majority of commercial polymers are currently produced from petrochemical feedstocks. Another form of polymers found in nature is the natural fibers formed in plants and animals (cotton, wool, and silk).

**Table 25: Types of Polymers**

<b>Thermoplastics</b>	<b>Thermosets</b>	<b>Elastomers</b>
Polyethylene, polypropylene	Phenolics	Polyisoprene (natural rubber)
Polyvinyl chloride, polyvinylidene chloride	Polyesters (unsaturated)	Polybutadiene (synthetic rubber)
Polystyrene	Epoxies	Polyurethane (foams, spandex)
Acrylonitrile butadiene styrene (ABS)	Polyurethanes	Ethylene-propylene-diene terpolymer (EDPM rubber)
Acrylics		Polysiloxanes
Celluloid		
Cellulose acetate		
Polyacetal		
Polyesters (PET, PBT)		
Polyamides (nylons)		

Source: Michigan Biotechnology Institute.

Polymers may also be classified into groups with regard to chemical structure, such as polysaccharides (polymers composed of sugar monomers), polyesters (contain an ester functional group), polyurethanes (organic units connected by urethane groups), polyamides (monomers joined by amide peptide bonds), polyolefins (hydrocarbon or olefin backbone), and polyacrylates (polymers of vinylic esters or acids).

Cellulose, starch, protein, chitin, and rubber are some of the more abundant naturally occurring polymers. They are produced by plants, animals, and microbes. Commercial use of natural polymers is widespread and has a long history. In this report, biobased polymers are sorted into three different groups. Biopolymers are naturally occurring polymers such as starch, cellulose, protein, cotton fibers, wool, silk, and rayon (formed from cellulose). Biologically derived polymers are derived from biobased feedstock, usually by fermentation. For example, polylactic acid (PLA) is produced from glucose fermentation by an engineered strain of *E. coli*. Copolymers are those polymers produced using a combination of biological and synthetic routes (biological/synthetic). For example, Sorona™ is derived from 1,3-propanediol (produced by fermentation) and terephthalate (produced by petrochemical synthesis).

Biobased polymers (excluding natural rubber) belong to five main types of polymers; polysaccharides, polyesters, polyurethanes, polyamides, and polyacrylates (Table 26). Starch polymer and polylactic acid (PLA) are the most important resins in current biobased production, although this is rapidly changing. The polysaccharides covered here generally represent modified natural polymers.

**Table 26: Overview of Important Groups and Types of Biobased Polymers**

Polymer	Type	Monomer/ feedstock	Source	Commercial <sup>a</sup> stage	Current & potential use <sup>e</sup>
<b>Biopolymers</b>					
Starch	Polysaccharide	Glucose	Plants (corn, potato)	C	Fo, A, T, Pp, Ph, Fm, Pac
Cellulose	Polysaccharide	Glucose	Plants (cotton, trees)	C	Pac, Co, F, Ph, AP, EE
Chitin	Polysaccharide	Glucosamine	Shellfish	C	Cm, Ph, T
Protein	Thermoplastics	Amino acids	Plants (soybean), animals (gelatin), <i>de novo</i> synthesis	C	T, A, MD
Natural rubber	Elastomer	Emulsion <sup>b</sup>	Plants (Para rubber tree)	C	Pa, Co, T, Pac, A MD
Natural fibers	Polysaccharide	Glucose	Plants (cotton) or animals (wool)	C	T
<b>Bio-derived polymers</b>					
Polyhydroxyalkanoates (PHAs)	Polyester	Glucose	Corn, potato	C	Pac, T, Fm
Polybutylene succinate (PBS)	Polyester	Succinic acid	Corn	C	Fm, Pac, T
Poly(lactic acid) (PLA)	Polyester	Lactic Acid	Corn	C	Pac, Fi, T
Ethylene glycol (EG)	Polyurethane	Glucose/glycerol	Corn	C	Polyester substitution
1,2-Propylene glycol (PG)	Polyurethane	Glucose/glycerol	Corn	C	Co, Pa, F, Ph
Polyols	Polyurethane	Triglycerides	Soybean	C	Fms, Fi
Nylon 6	Polyamide	Caprolactam	Corn	R	Fi, Pac, Fu,
Nylon 66	Polyamide	Adipic Acid	Corn	R	Fi, Pac, Fu
<b>Biological/synthetic polymers</b>					
Nylon 69	Polyamide	Oleic Acid		C <sup>c</sup>	Fi, Pac, Fu
Polyethyleneterephthalate (PTT)	Polyester	PDO and terephthalate	Corn	P/C	Fi, T, Pac
Polybutyleneterephthalate (PBT)	Polyester	BDO and terephthalate	Corn	D	AP, EE
Polybutylenesuccinate terephthalate (PBST)	Polyester	Succinic acid and terephthalate	Corn	D	Fm, Pac
Polyacrylamide	Polyacrylate	Acrylonitrile <sup>d</sup>	Petrochemical	C	Pac, Fu, Fi
Starch based polymers	Thermoplastics	Glucose + petrochemical	Corn	C	Fm, Pac

<sup>a</sup> R = Research; D = Development; P = Pilot Scale Production; C = Commercial Production.

<sup>b</sup> Emulsion of proteins, starch, alkaloids, tannins, and gums.

<sup>c</sup> Synthetic pathway from biobased oleic acid.

<sup>d</sup> Enzymatic conversion (nitrile hydratase) of acrylonitrile to acrylic acid.

<sup>e</sup> Uses: Fo = Food T = Textiles Ph = Pharmaceuticals MD = Medical Devices

Pa = Paints Co = Coatings Fi = Fibers A = Adhesives Pp = Paper

Cm = Cosmetics Fm = Films Pac = Packaging

EE = Electrical and Electronics AP = Automotive Parts Fu = Furniture Fms = Foams

Source: Michigan Biotechnology Institute.

In biobased polyesters, the monomer (which may be an alcohol or acid) is generally produced by fermentation from a renewable feedstock. The polyester may be composed of only one type of monomer. Whenever this is not the case, the comonomer is generally a petrochemical (for the products shown in Table 26). Polyhydroxyalkanoates represent a special case since they can be either produced by fermentation or in a genetically modified crop, like potatoes. In polyurethanes, the polyols used are biobased while the isocyanate component is synthesized by petrochemical processes. The three representatives of the fourth group, polyamides, are produced by fermentation or by conventional chemical transformations of a crop-derived feedstock. The monomers in the last group, polyacrylates, can be produced by both fermentation and conventional petrochemical transformations.

Fermentation can also be used to convert biomass into the traditional starting materials and intermediates used to make conventional plastics and polymers. For example, cheaper biobased routes to monomeric raw materials such as ethylene glycol, propylene glycol or even routes that make and dehydrate alcohols to olefins or acrylates could redefine future polymer feedstock production.

Plastic packaging is the single largest market for polymer resins and target of most new biobased products. As oil and natural gas prices continue to rise, biobased packaging will become more price competitive with petrobased plastics. Historically, petrochemical processing costs have exceeded feedstock costs, but greater processing efficiencies have reduced processing costs dramatically. Today, the dominant cost of biomaterials is in processing, but as with the petrochemical industry, processing costs may drop due to both improved fermentation systems and more efficient separation and isolation technology. Many petrochemical processes are more energy intensive than biobased processes, which makes them more sensitive to the availability and cost of natural gas. Oil and energy costs have been rising due to depleted or increasingly inaccessible resources and increased worldwide demand.

Global production of biobased plastics, an estimated 800 million pounds in 2003, should top 1.3 billion pounds by 2008. Prices of two major families of biobased resins, polylactide and aliphatic aromatic polyesters, have dropped nearer those of commodity plastics since 1999, while commodity resin prices have climbed steadily since 2002 (Plastic News).

Table 27 lists current biopolymer producers and products.

One estimate places the maximum substitution potential of biobased polymers for petrochemical based polymers at 33 percent, although variables such as diminishing supplies and high prices for petroleum feedstocks could raise the share (Crank et al.). BASF expects the market for biodegradable plastics to grow by more than 20 percent a year for the next 5 years.

Table 27: Producers of Biobased Polymers

Product and Producer	polymer type and trade name
<b>Starch polymers:</b>	
Novamont, Italy	Mater-Bi™
Rodenburg, Netherlands	Solanyl™
National Starch & Chem Chinese company <sup>1</sup>	Ecofoam™ Thermoplastic starch
BIOP, Germany	BIOpar™
Biotec, Germany	Bioplast TPS™
Japan Corn Starch	Cornpol™
Nihon Shokukin Kato, Japan	Placorn™
Potapakm Avebe Earthshell	Baked starch derivatives
<b>Polylactic acid (PLA)</b>	
Cargill, U.S.	Natureworks™ (Mitsui Lacea in Japan)
Hycail, Netherlands	Hycail™ HM, Hycail™ LM
Toyota, Japan	Toyota Eco-plastic™
Project in China <sup>1</sup>	Conducted by Snamprogetti, Italy
<b>Other potential BB-polyester (currently petrochemical based)</b>	
DuPont, U.S.	Poly(trimethylene terephthalate) PPT Sorona™
Mitsubishi Chemical, Japan	Poly(butylenes succinate)
Showa Highpolymer, Japan	Poly(butylenes succinate) Bionelle™ 1000 and Poly(butylenesuccinate terephthalate) Bionelle™ 3000
	Poly(butylene terephthalate) PBT
DuPont, Japan	Poly(butylenesuccinate terephthalate) Biomax™
Eastman, Japan <sup>2</sup>	Poly(butylenesuccinate terephthalate) Eastar Bio™
BASF, Japan	Poly(butylene adipate terephthalate) Ecoflex™
<b>Polyhydroxyalkanoates (PHA) –</b>	
<b>PHA homopolymers</b>	
Metabolix, U.S.	P(3HB), P(3HO)
Biomer, Germany	P(3HB) Biomer™
Mitsubishi Gas, Japan	P(3HB) Biogreen™
<b>PHA copolymers</b>	
Metabolix, U.S.	P(3HB-co-3HV) Biopol™
P&G, U.S.	P(3HB-co-3HXX) Nodax™
PHB Industrial, Brazil	P(3H-co-3HV)
<b>Biobased Polyurethanes (PUR)</b>	
Metzeler-Scham, Germany	PUR from bio-based polyol
Dow Chemical Company	PUR from bio-based polyol
<b>Biobased Polyamides</b>	
No biobased production	
<b>Cellulosic polymers</b>	
<b>Plant cellulose based</b>	
Lenzing	Regen cellulose Lyocell™
Accordis	Regen cellulose Tencel™
Eastman, U.S.	Cellulose acetate Tenite™
IFA	Cellulose acetate Fasal™
Mazzuccheli	Cellulose acetate Bioeta™
UCB	Cellulose acetate
<b>Bacterial cellulose</b>	
Weyerhaeuser, US	Bacterial cellulose Cellulon™
Ajinomoto, Japan	Bacterial cellulose
<b>Cellulosic esters</b>	
Dow	Methocel™, Ethocel™

<sup>1</sup> Company or plant title not known.

<sup>2</sup> In 2004 Eastman Chemical Co. sold the Eastar Bio™ technology to Novamont SpA

Source: Crank et al.

## 1. Naturally Occurring Biopolymers

### a) Starch

Starch is a major storage carbohydrate (polysaccharide) in higher plants and is available in abundance, surpassed only by cellulose as a naturally occurring organic compound. It is composed of a mixture of two polymers: an essentially linear polysaccharide, amylose, and a highly branched polysaccharide, amylopectin, which are both built of glucose repeat units. Starch derived from plant sources (corn, potatoes, etc.) has many industrial uses in foods, adhesives, textiles, paper, explosives, cosmetics, pharmaceuticals, construction materials, and biodegradable plastics.

Starch polymers may be pure, chemically modified, or fermented. Pure starch polymers undergo no modifications and can be used in extrusion processes or blending with copolymers for production of thermoplastics. Starch may be chemically modified (i.e. crosslinking, replacement of hydroxyl groups with ester or ether groups) to produce polymers with specific characteristics. Starch can be fermented to produce monomers, such as lactic acid, for specialized polymers.

Since starch is relatively low cost, it is an attractive alternative to petrochemical-based polymers. Polymers produced from starch do not typically exhibit high strength characteristics, so they may be mixed with petroleum based plastics such as polyethylene and polyvinyl alcohol to increase strength. Mixtures have been sold as biodegradable plastics, but when composted, only the starch rapidly degrades, while the polyethylene and polyvinyl alcohol do not (Farrin). These polymers dominate the biobased polymer market, which was 30,000 metric tons worldwide in 2002. Approximately 75 percent of starch polymers are used in packaging applications, and leading producers are Novamont, National Starch, Biotec, and Rodenburg. Starch can be used in copolymer (typically petrochemical) form, with as much as 50 percent (wt/wt) composition, although recent blends have been made with biobased resins to give complete degradability.

### b) Cellulose

The class of polymers based on cellulose includes native cellulose from wood and most plant matter; regenerated cellulose fiber (viscose rayon) or film (cellophane); and chemical derivatives including organic esters such as cellulose acetate and ethers and hydroxyalkyl ethers. Cellulose, as a polyhydric alcohol, can undergo the reactions of most alcohols: etherification, nitration, acetylation, etc. Cellulose ethers are made by reaction of base-treated cellulose with methyl chlorides. Cellulose hydroxyalkyl ethers are made by the addition of ethylene oxide or propylene oxide to the free hydroxyl groups on the polymer. Commercial products include Dow Methocel™ and Ethocel™ resins, which serve as water-soluble packaging, suspension agents, coatings, thickeners for food, and binders for ceramics and drug tablets. These have been on the market for decades but are losing market share to petrochemical polymers.

### c) Chitin

Chitin is one of the most abundant polysaccharides found in nature, second only to cellulose. It is a polymer composed of beta 1,4-linked poly-N-acetylglucosamine monomers and is found in the cell walls of fungi, exoskeletons of insects, and shellfish. Shellfish waste represents a major source of this polymer. Chitin is extracted from crustacean shells by treatment with dilute sodium hydroxide at temperatures of 85 - 100°C. Chitosan is the deacylated derivative of chitin and is produced by heating (90 - 120°C) in a strong sodium hydroxide solution (>40 percent). Chitosan has applications in agriculture, water treatment, food, cosmetics, and biomedical uses. The estimated cost to produce chitosan with current technologies is \$8.58/kg, limiting its current use to high value markets (Morrissey). Biotechnological advances in developing an enzymatic deacylation of chitin to chitosan could lower the cost and open up additional markets. HemCon, Inc. has developed a unique wound bandage containing chitosan that accelerates the clotting of blood and has antibacterial properties. The bandages are currently used only in military applications; however, HemCon, Inc. is pursuing FDA approval for other uses.

### d) Protein

Proteins are polymers consisting of amino acid monomers linked by peptide bonds. Proteins have a long history of industrial applications, including adhesives, feed binders, coatings, and drug delivery. Sources of protein include plants, animal tissues, and microbes. Biotechnological advances now allow the expression and production of specific proteins in plants, animals, and microorganisms, as with the production of spider silk protein in mammalian cells (Lazaris et al.). Nexia Biotechnologies has produced spider silk protein in the milk of genetically modified goats; however, commercialization of this technology has not occurred to date (Nexia Biotechnologies).

Protein Polymer Technology (PPTI) is developing synthetic protein polymers for use in medical applications. Their NuCore™ Injectable Disc Nucleus (IDN) was developed for repair of spinal disc damage and has been licensed by Spine Wave, Inc. for commercial manufacture, although its current use is limited to investigational studies outside the United States (Spinewave). DuPont manufactures a soy protein product (Pro-Cote®) used primarily as a paper coating. ADM and Eka Chemicals both produce soy-protein based adhesives for wood products. Proteins are also being developed for use in the production of thermoplastics (Vaz et al.).

### e) Natural Rubber

Natural rubber is found in certain plant species (i.e., the Brazilian rubber tree - *Hevea brasiliensis*) and is a high-molecular-weight polymer of isoprene (2-methyl-1,3-butadiene). Synthetic rubber with similar elastomer properties can be made from polybutadiene (BR), polystyrene-co-butadiene, ethylene-propylene-diene monomers, and polysiloxanes. Approximately 40 - 45 percent of the rubber consumed in the world is made from natural sources. Global consumption of all rubber was 11.8 million metric

tons in 2004 (Tullo), and 8.28 million tons for natural rubber. Natural rubber continues to dominate the market because synthetic rubbers developed to date are weaker and less elastic (Halperin).

Applications of rubber materials are extensive and include paints, coatings, textiles, packaging, adhesives, furniture, medical equipment, carpet backings, and seals. Although there are differences in the performance of various rubber materials, many applications can use either natural or synthetic resin and are driven by price and availability. High oil prices favor use of natural rubber. The largest market for rubber materials is the manufacture of tires and gaskets. Styrene-butadiene copolymers (SBR) are the most commonly used synthetic latex rubber, with 2.4 million tons consumed each year.

Allergic reactions to natural latex rubber have increased to the point where over 20 million Americans exhibit reactions to the proteins found in *Hevea* rubber. USDA developed the use of guayule, a desert shrub, as an alternative source of natural latex and a hedge against the uncertainty of world rubber supplies. Guayule rubber does not contain the proteins responsible for allergic reactions. Yulex™ commercially produces guayule-derived latex products in the United States. Mendel Biotechnology is aiming to increase the rubber content of guayule by using *Arabidopsis thaliana* transcription factors to activate promoter genes in rubber synthesis pathways (Carole et al.). A coproduct of guayule rubber is resins that can be used in adhesives.

#### **f) Plant-Based Polyols**

In addition to the large market opportunity for conversion to glycerin and fatty esters for biodiesel use, seed-oil triglycerides can also be used as intermediates to form polyols. These unsaturated materials can be used to make novel epoxy derivatives or new materials (via metathesis with ethylene) that can be incorporated into a variety of plastics. Polyols (or polyhydric alcohols) are alcohols with several hydroxyl groups. The hydroformylation of seed oils can also generate polyaldehydes that can be converted by (1) reduction to primary alcohols, (2) oxidation to polycarboxylic acids, or (3) reductive amination to polyamines that can be used in polymer applications (Energetics, Inc, 2003).

BioBased Technologies, located in Rogers, Alaska, specializes in the development of polyols derived from soybeans. The products can be used to make flexible and rigid foams and for spray-on foams. The North American market for polyols, for the manufacture of polyurethane, is approximately 3 billion pounds. The United Soybean Board estimates that 800 million pounds could be made with soybean polyol.

Urethane Soy Systems Company (USSC) is another small company that has been issued a patent for a new biobased chemical feedstock based on soybeans called SoyOyl™. A SoyOyl product, the Dow Chemical's BIOBALANCE™ soy based polymer, is a new development for use in carpet manufacture. Dow is initially focusing on developing soy based polyols for flexible slab polyurethane products, the largest market



for polyols. These formulations contain 35 percent soy monomer and can be used in conventional processing equipment without any modifications. Dow is currently sampling customers in the United States and Europe. If pre-commercial trials are successful, full commercial investment will be evaluated.

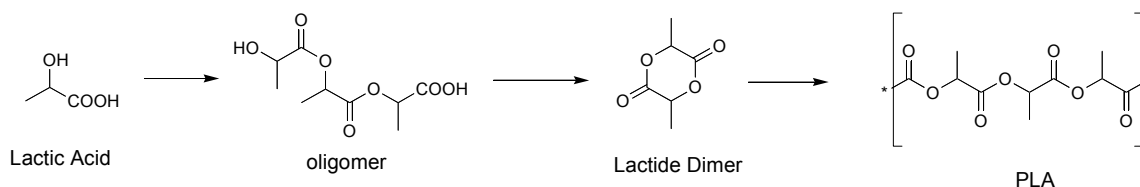
Seed oils can be converted directly to urethane polyols by functionalization (epoxidation, hydroformylation, and hydration) or to generate the unsaturated fatty esters and glycerin by transesterification (biodiesel feedstock). The unsaturated fatty esters can be further converted to alpha olefins, dienes, and 9-decenoic acid by a metathesis reaction under ethylene. The alpha olefins generated (mainly 1-octene) have the potential to be used in linear low-density polyethylenes (comonomer to induce branching) or to make synthetic lubricants. The dienes, although in smaller yields, can be used in rubber, latex, and other polymer applications while the 9-decenoic acid is considered another platform chemical that could be used, for example, to make sebacic acid.

## 2. Bio-derived Polymers

### a) Polylactic Acid

Polylactic acid (PLA) is a thermoplastic resin made from fermenting and processing starch from corn and other crops. The sugar fermentation product is lactic acid, which is converted to a lactide and then purified and polymerized using a ring opening polymerization process (Figure 29). In April 2002, NatureWorks® LCC started up its first large-scale PLA plant in Blair, Nebraska, making resins under the trademark Natureworks™ PLA with a capacity of 140,000 metric tons. The projected market for the product is an estimated 3.6 million metric tons by 2020 (Fahey). With recent upswings in the cost of petroleum based resins, PLA is price competitive (ranging between \$0.75 and \$1.50/pound) with polyethylene terephthalate (PET) and polystyrene (Plastic News).

**Figure 29: Production of PLA from Lactic Acid**



Source: Michigan Biotechnology Institute.

PLA most closely resembles polyethylene in structure and properties. It is a hard, transparent, crystalline plastic. The resin is also stiff, clear, and glossy, with barrier properties similar to PET. It is an excellent water and grease barrier and performs well as both a rigid and flexible material. The resin can be coated on other materials, and copolymerized/blended with other materials to modify its properties. PLA's melting point is high and the resin can be fabricated using conventional polymer processing

equipment by extrusion, injection molding, blow molding, fiber spinning, and thermoforming. The main advantage of this resin is that it is compostable and also recyclable (Farrin).

### **b) Polyhydroxyalkanoates**

Polyhydroxyalkanoates (PHAs) are a family of polymers with a wide spectrum of properties allowing them to compete with much of the plastics market. PHAs can be made by bacterial fermentation. The resins are semicrystalline thermoplastics that can be used in most basic plastic processes and with conventional processing equipment. In the 1990s, poly (3-hydroxybutyrate-co-2-hydroxyvalerate) (PHBV) was commercialized by Zeneca, and later Monsanto, under the trade name Biopol™. However, production costs could not compete with petroleum based plastics using the separation and fermentation technology available at that time. Metabolix, a company spun out of the Massachusetts Institute of Technology in 1992, acquired the biopolymer technology from Monsanto in 2001. They began commercial production of organic polyhydroxyalkanoate (PHA) resin based on fermentation of corn sugar, in partnership with ADM in October 2005. The plant was expected to produce 90 metric tons in 2005 and 907 metric tons in 2006 at a price of \$1.50/pound. The price is expected to drop to around \$1/pound by 2008 (Plastic News). The cost of PHAs could drop if plants (such as corn or switchgrass) can be genetically modified to produce the polymers.

### **c) Polyurethane**

Polyurethane (PUR) resins are formed by mixing a polyol and a polyisocyanate. In polyurethane chemistry, the polyols are polymers or monomers with hydroxyl functional groups available for organic reactions. Examples include polyethers such as polyethylene glycol, polypropylene glycol, or polytetrahydrofuran. Global polyol sales are \$10 billion annually and support the \$20 billion global polyurethane market. Today, 99 percent of polyols are petroleum based, so there is ample market opportunity for biobased polyols. A number of companies are looking to penetrate this large market. The polyol or diol length is adjusted to control the stiffness and other properties of the resins to give either hard or soft segments. Many biobased polyols, typically diols, can be made via fermentation and used as equivalents to petrochemical-derived diols or polyols from ethylene oxide or propylene oxide. Alternative biochemical routes to ethylene glycol and propylene glycol represent a major shift for the chemical industry which relies on olefin epoxidation that generates high-salt byproducts and consumes excessive energy. As other diols, such as 1,3-propanediol and 1,4-butanediol, become less expensive via fermentation, they could also be incorporated in polyurethane formulations. Polyols generated from cheap seed oil sources such as soy oil could also be used. Some typical polyols and diols used in polyurethane manufacture are described below.

#### *Ethylene Glycol and 1,2-Propylene Glycol*

Ethylene glycol (EG) and 1,2-propylene glycol (PG) are commodity intermediates made by the epoxidation of ethylene and propylene respectively, followed by hydrolysis. They are used for making polyols and polyurethanes. They can also be made by

hydrogenation and hydrocracking of sugars or by the reduction of lactic acid or 2-hydroxypropionic acid made by fermentation of sugars. International Polyol Chemicals Inc. has built a 10,000 metric ton/year plant in Changchun, China, and is planning a second 200,000 metric ton/year facility targeted to start in 2006 or 2007. The firm also is considering building a \$130 million plant in eastern Washington or Oregon. ADM recently announced plans to build a polyols facility to produce propylene glycol and ethylene glycol from carbohydrates as an alternative to traditional petroleum based industrial chemicals. Propylene glycol is used primarily in industrial application such as paints, coatings and resins, and is also used in food and pharmaceutical applications. Ethylene glycol is used to produce polyesters and industrial products. Propylene glycol can also be made from lactic acid through the fermentation of glucose. The current market size for ethylene and propylene glycols is 5.95 billion and 1.1 billion pounds a year, respectively, including uses as solvents and other nonpolymer applications.

As described below 1,3-propanediol (PDO) and 1,4-butanediol (BDO) are alcohols that can be made by fermentation of sugars and are targeted mainly in polyester copolymers. These materials can also be used as the diol component in polyurethane formulations with isocyanates to give useful polymers.

#### **d) Polybutylene Succinate and Other Succinate-Derived Materials**

Polybutylene succinate is a copolymer diester that can be made from 1,4-butanediol and succinic acid. Succinic acid, a dicarboxylic acid, is one of the top biobased platforms moving to market. Its production cost has dropped from \$2 a pound in 1992 to \$0.50 in 2003 (USDOE, 2004). Succinic acid is made by fermentation of glucose and has the potential to replace maleic anhydride as one of the primary building blocks of the petrochemical industry. Succinic acid is currently made by the hydrogenation of maleic anhydride. It can also be used to generate 1,4-butanediol (BDO), 1,4-diaminebutane, polyesters, solvents, and polymer intermediates such as tetrahydrofuran (THF), gamma-butyrolactone (GBL), n-methyl pyrrolidone (NMP), and 2-pyrrolidone.

Succinic acid does not polymerize well in a condensation polymerization with amines to form linear high-molecular-weight nylon (polyamides) structures, but can form many useful polyesters. One of these polyesters is polybutylene succinate (PBS), which has properties similar to PET. PBS has applications in packaging, mulch films, and bags. PBS may be blended with the copolymer adipic acid to form polybutylene succinate adipate (PBSA), or with terephthalate (petrochemical) to form polybutylene succinate terephthalate.

Producers of PBS include Showa Highpolymer (Japan), KD Chemicals (Korea), and Mitsubishi (Japan). Current production is based on petrochemical feedstocks. However, Mitsubishi and Ajinomoto plan to produce 30,000 metric tons/year of a biobased succinic acid. Mitsubishi expects this to lower the cost of PBS, which will compete directly with NatureWorks® PLA.

1,4-butanediol can be used to produce polybutylene terephthalate (PBT) or other polymers such as thermoplastic polyurethanes (TPU). These are fully reacted polymers in pellet or granular form that can be processed on standard extrusion and molding equipment and have significant resistance to abrasion. They are used for coated fabrics (e.g. simulated leather), sheathing for wire and cables, and heels for boots and shoes. Copolyester ethers (COPE) can also be derived from BDO. These polymers are flexible, strong, and oil/water resistant even at high temperatures. They are used for automobile hoses, belting, gaskets, grease boots, CV joints, wire and cable insulation, spacers, bushings, and specialized recreational and medicinal products.

BDO may be further processed (via dehydration) to produce tetrahydrofuran and (via dehydrogenation) gamma-butyrolactone (GBL). THF can be partially polymerized to give low-molecular-weight polymers of polytetramethylene glycol (PTMG), which can be used in applications similar to thermoplastic urethanes and copolyester ethers. The company Invista (a subsidiary of DuPont) markets PTMG as Terathane® glycol, an intermediate for both Lycra® elastane and high-value polyurethane. Other producers of PTMG are BASF and QO Chemicals.

Other biobased diacids, such as 2,5-furandicarboxylic acid and itaconic acid, can be made readily by fermentation and have potential uses in polyamides and polyesters. Itaconic acid is made by fermentation of xylose and is used commercially at low levels in Saran polymers to modify properties. Homopolymers of itaconic acid have limited use due to relatively high costs. At lower production costs, itaconic acid could compete with methyl methacrylate (MMA) and other acrylates, as well as in the pressure-sensitive adhesives market. These combined markets account for 1.8 billion pounds a year and are growing.

### **e) Polyamides**

Polyamides (nylons) are commercial resins that are used as high-temperature engineering materials because of high tensile and impact strength, good abrasion resistance, and self-lubricating properties. They are generally synthesized from diamines and dibasic (dicarboxylic) acids, amino acids, or lactams. Properties can be customized by fine tuning the diacids or diamines used. Some common commercial nylons are nylon 4 (polypyrrolidone), nylon 6 (polycaprolactam), nylon 66 (polyhexamethylene adipamide), and nylon 69 (polyhexamethylene azelaamide). The building blocks of caprolactam, adipic acid, and azelaic acid can all be made via fermentation and have been studied extensively. Biobased nylons are fully substitutable, in theory, for their petrochemical equivalents.

### 3. Biobased/Synthetic Polymers

#### a) Polytrimethylene Terephthalate

1,3-propanediol (PDO) is used with terephthalic acid to make the copolymer poly(trimethylene terephthalate) PTT, which has superior stretch-recovery properties and is used in apparel and upholstery markets. PTT was developed and commercialized by DuPont and Shell in the 1990s when a petroleum based process was found for 1,3-propanediol. DuPont, through a partnership with Genencor International, developed a lower cost fermentation route to 1,3-propanediol through biomass sugars. This has led to commercialization of DuPont's Sorona™ polymers, which will transition to biobased 1,3-propanediol made via fermentation in a \$100 million plant being constructed in Loudon, TN. This product is expected to directly compete with nylon and polyesters, which are both currently derived from fossil fuels.

#### b) Polybutylene Terephthalate

The traditional method of 1,4-butanediol (BDO) production is by the Reppe process, in which acetylene is reacted with formaldehyde. Newer processes use maleic anhydride or *n*-butane as starting points. BDO can also be obtained by hydrogenation of succinic acid, which itself can be made from biomass via fermentation. Polybutylene terephthalate (PBT) resin uses 1,4-butanediol as a comonomer and is a thermoplastic material with significant strength and chemical resistance, even at continuous high temperatures. These polyesters are made by Showa Highpolymer, DuPont, Novamont SpA, and BASF. PBT can be machined and used with glass fibers in a wide variety of applications, and has good colorability. BDO can be used in thermoplastic polyurethanes (TPU), which form abrasion-resistant coatings, or in copolyester ethers (COPE) used in automotive hoses, belting, gaskets and cable insulation. BDO can also be dehydrated to produce THF, which can be polymerized to polytetramethylene ether glycol used in TPU and COPE applications.

DuPont markets a low-molecular-weight polyol made by partial polymerization of THF under the trade name Terathane™ polytetramethylene ether glycol, which is used both in polyesters (including Spandex fibers) and as the polyol segment in polyurethane formulations.

#### c) Polyacrylates, Polyamides, and Polyacrylonitriles

Polyacrylates are a major class of commercial bulk polymers that are made by the radical polymerization of acrylic acid and its esters. The acid and ester monomers are made by the air oxidation of propylene, followed by etherification. Similar vinylic polymers can be made by the radical polymerization of acrylamide or acrylonitrile monomers.

### Acrylic Acid

Acrylates (acrylic acid and esters) are a 2-billion pound market and are used to prepare emulsion and solution polymers used in coatings, finishes, textiles, paper, paints, and adhesives. Acrylic acid can also be obtained from fermentation based 3-hydroxypropionic acid (3-HP) via dehydration. This can then be used as a monomer or chemically converted to simple esters, which can be homo- or copolymerized with a variety of vinyl monomers. 3-hydroxypropionic acid can also be used as a precursor to form 1,3-propanediol used in DuPont's Sorona™ polymers. Cargill and Codexis have, over the last 5 years, developed an economical microbial process to this intermediate from corn dextrose (Carr).

### Acrylamide and Poly(acrylamide)

Acrylamide is used to make water-soluble polymers used as flocculants, paper making aids, thickeners, and additives for enhanced oil recovery, with a current market size of 206 million pounds a year (Energetics, Inc., 2003). This monomer was traditionally made by a copper-catalyzed chemical route from propylene, now displaced by an enzymatic process that dehydrates acrylonitrile. Using nitrile hydratase from *Rhodococcus rhodochrous*, Mitsubishi produces over 100,000 tons a year of acrylamide. The biotechnology route developed by Mitsubishi Rayon in Japan - with lower costs, higher selectivity, and lower energy consumption - now dominates this market.

### Acrylonitrile Polymers

Acrylonitrile (AN) can be made by the dehydration of biobased acrylamide and can be copolymerized with many materials, such as synthetic rubbers, where it provides resistance to oil and solvents. This technology is now being developed from 3-hydroxypropionic acid, but must compete with current market prices of \$0.31 - \$0.37/lb. The annual market size for acrylonitrile is about 3.1 billion pounds (Energetics, Inc., 2003). Its main use is in acrylic fibers, closely followed by copolymers with styrene (polyacrylonitrile-co-styrene) and terpolymers with rubber-modified styrene (polyacrylonitrile-co-butadiene-co-styrene) or ABS resins.

## **4. Biodegradability and Recyclability**

While many polymers are marketed as being biodegradable, a better term would be "environmentally degradable." ASTM International, formally the American Society of Testing and Materials (ASTM) defines biodegradation as degradation demonstrated to be caused by biological activity, particularly enzyme activity, leading to significant changes in chemical structure. The resulting degradation products must be chemicals such as water, carbon dioxide, methane, inorganic compounds, or biomass. Materials may also be environmentally degraded by the following processes:

1. Compostable. The material must be demonstrated to biodegrade and disintegrate in a composting system at a rate consistent with known compostable materials (e.g., cellulose).

2. Hydrobiodegradable and photobiodegradable. Material is broken down in a two-step process; an initial hydrolysis or photodegradation stage, followed by further biodegradation. Single-degradation phase “water-soluble” and “photodegradable” polymers also exist.
3. Bio-erodable. This is a misnomer as it involves abiotic (which means it is not the result of biological activity) disintegration, and may include processes such as dissolution in water and oxidative or photolytic disintegration.

Biobased and synthetic polymers both have a wide range of degradation rates in the environment dependant on composition, structure, crystallinity, and crosslinking. In general, biobased materials degrade faster than petrochemical based polymers. However, not all biobased polymers are biodegradable. One group of biobased polymers, starch polymers, is easily biodegradable and incinerable and can be fabricated into finished products such as mulch film and loose fills through existing technology. Biodegradable starch foam and packaging materials are designed to replace polystyrene expanded polyethylene and polypropylene resins. Synthetic biodegradable polyesters are made in modified PET polymerization facilities, often from petrochemical based feedstocks, and are typically used in packaging, which accounts for about half of all disposed plastics. The demand for these materials is growing at about 30 percent a year. There are many variations, including Cargill’s Natureworks™ PLA materials, Eastman Chemical Company’s Eastar Bio™ (now produced by Novamont SpA), and BASF’s Ecoflex™. Both Eastar Bio™ and Ecoflex™ are aromatic-aliphatic copolyesters based on butanediol, adipic acid, and terephthalic acid. These materials have a high moisture and grease resistance, and process much like low-density polyethylene LDPE. Uses include lawn and garden bags, agricultural films, netting, and paper coatings. Japan’s Showa Highpolymer and Korea’s SK Chemicals both have small plants producing aliphatic (polybutylene succinate) and aliphatic-aromatic (polybutylate adipate terephthalate) polyesters. These resins are marketed in the U.S. under the trade name Bionelle™ products.

Synthetic biodegradable polyesters tend to complement one another’s properties, as well as those of PLA, thermoplastic starch, and other organic materials. They are finding markets in blended resins to increase the performance of both materials. Dow Chemical obtained polycaprolactone aliphatic polyesters from its merger with Union Carbide for use in adhesives, compatibilizers, modifiers, and films. These materials are miscible with many other polymers and are inherently biodegradable. Many blends of copolyesters with thermoplastic starch, natural fibers, and polycaprolactones give tailored properties and rates of degradation.

Biobased materials - whether feedstocks, monomers, or polymers - have different rates of degradation in the environment. A biobased material may be quite degradable, but when combined with a copolymer and extensively cross-linked to attain some specific functionality, degradability can change significantly. Biobased polymers are more sustainable than petrochemically derived polymers, because they come from fermenting sugars rather than processing petrochemicals. However, the ultimate method of

recycling and/or disposal of these materials will vary, just as it does today. Some materials will be amenable to recycle, others to biodegradation or incineration.

## **D. Overview of Cellulose Fiber Products**

### **1. Cellulose Fibers**

Research is underway to process cellulose whiskers (very small fibers) to blend with a biobased polymer and form a resin that can be used as a low-cost, biodegradable replacement for glass fibers in polymer composites. This product may be used in the automotive, construction, and other specialty industrial markets. Advantages are reported to include the following:

- Lightweight (*half the bulk density of glass*).
- Biodegradable.
- Safe to handle.
- Less energy intensive.
- Less destruction of process equipment.
- High sound absorption.
- No conversion costs for composite production.
- Lower cost.

Research in this field is being sponsored by USDOE and led by Michigan State University and MBI. The manufacture of these advanced composites would address an estimated global market of over \$3 billion.

These cellulosic products could be manufactured in a biorefinery setting, in conjunction with traditional or enhanced technology, with the related manufacture of fine chemicals (Figure 30). Manufacture of cellulose based biocomposites would not require the degree of cellulose transformation ethanol production does. This technology would likely be available earlier than cellulosic ethanol (Informa Economics et al., Biobased Multi-Client Study, March 2006).

### **2. Lignin**

A byproduct of the industrial conversion of cellulose is lignin. The U.S. pulp and paper industry, one of the earliest forms of biorefineries, produces an estimated 26 million tons of lignin annually. Canadian mills add another 5 million tons to the North American total. Map 9 shows the geographic distribution of paper mills in North America. The map highlights two important factors; (1) the advantage of locating a mill near the primary resource base (i.e., trees) or (2) to be strategically positioned near key transportation networks, such as ports where wood material can be moved by boat in order to produce the value-added products.

At least 95 percent of byproduct lignin is used as boiler fuel in the mill where it is produced, according to industry sources. The lignin not used as fuel, estimated at less

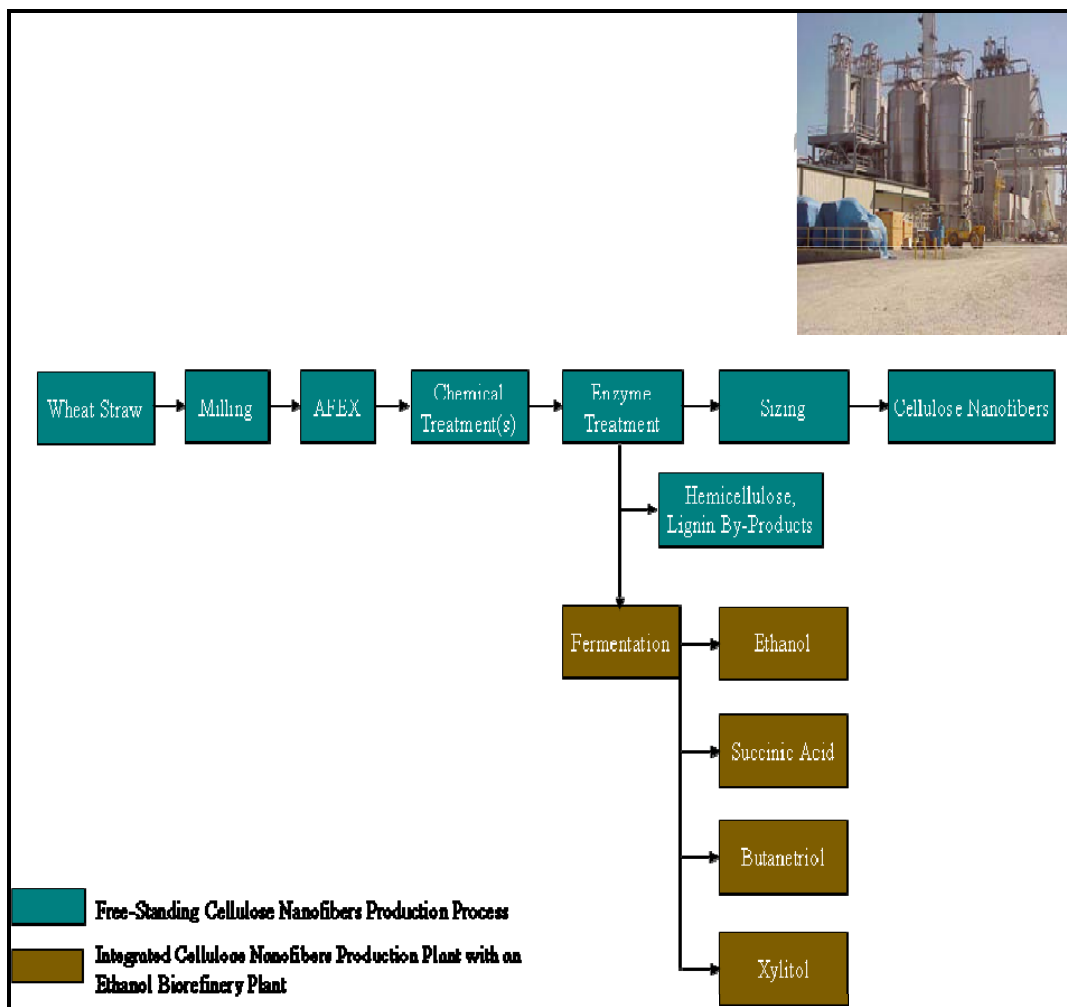


than 2 million tons, enters a variety of markets, like binders and dispersants. Such markets are very low value or small, with little anticipated growth.

The global market for lignin is an estimated \$250 - \$350 million. Leading participants are MeadWestvaco, Granit (Switzerland), and Metsaliiton Teollisuus (Finland). Asian suppliers, especially Chinese, are also important.

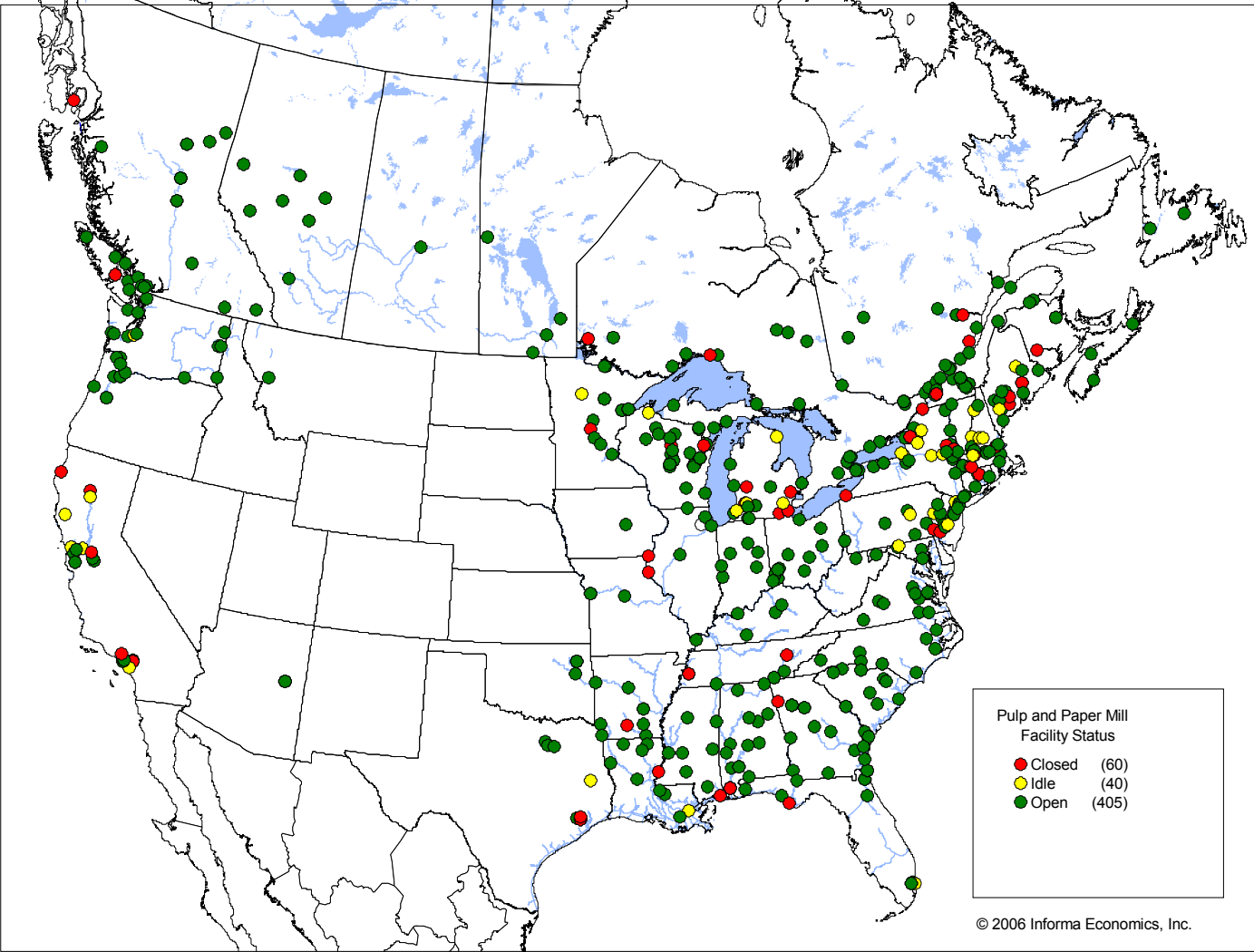
New technology - including lignin precipitation in Kraft mills, Granit's patented process for sulfur-free lignin from nonwoody cellulose and improved pulping methods - may produce much higher quality lignin suitable for new markets like cosmetics and pharmaceuticals. However, recent literature and scientific thinking indicate pessimism toward lignin as a significant financial asset in a cellulose biorefinery. Indeed, most biorefinery plans and feasibility studies treat lignin as a boiler fuel only, citing the difficulty of separating and refining the product. Research sponsored by USDOE examining lignin as a gasoline additive is ongoing, but the commercialization date is uncertain.

**Figure 30: Process Flow Diagram of Cellulose Microfiber Biorefinery**



Source: Informa Economics et al., Biobased Multi-Client Study, March 2006.

Map 9: North American Pulp and Paper Mills, 2005

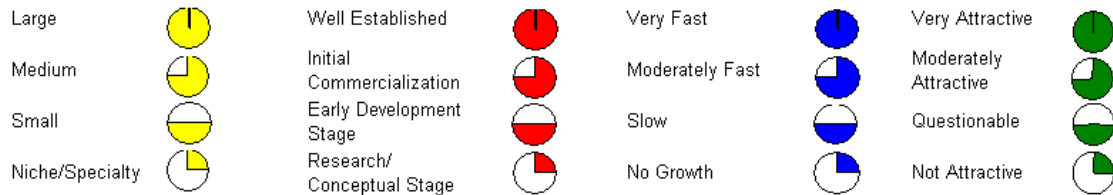


Source: Informa Economics et al., Biobased Multi-Client Study, March 2006.

Our assessment of the outlook for expanded use of lignin hinges on the degree of market awareness regarding nontraditional uses (Table 28). Customers in potential markets (e.g., animal health) tend to change formulations or product characteristics only if significant benefits in performance or cost can be demonstrated. Even with such evidence, the transition is slow, and consideration of lignin appears quite limited.

**Table 28: Summary Assessment of Lignin Market Potential**

Market	Market Size	Stage of Lignin Participation	Market Awareness	Potential Market Growth	Overall Attractiveness
On-site Energy					
Highways					
Binders					
Animal Health					
Resin					
Dispersants					
Cosmetics					
Gasoline Additive					



Source: Informa Economics et al. Biobased Multi-Client Study, March 2006.

The research and development supporting new lignin uses is generally in the conceptual or early development stages. Thus, it appears that biorefinery financial performance is best estimated assuming no new high-value markets for lignin. Private research toward broadening lignin use has seemingly been curtailed or is under funded. Given the potential value of lignin as a chemical feedstock and as a biorefinery asset, related research is potentially a strong candidate for government support.

## E. Biobased End Product Markets

This section analyzes the market potential for a wide array of biobased products categories. These 18 product categories represent the biobased products with the largest market potential and commercial viability apart from ethanol and biodiesel discussed in earlier chapters and the pharmaceuticals categories that are discussed in the next section. The U.S. Department of Agriculture has identified most of these product categories as areas of interest in its BioPreferred™ Program, which requires federal agencies to give procuring preference to biobased products, and is intended to promote the increased development and use of biobased products by increasing federal demand. Because of the diversity of products covered, finding consistent data sources proved challenging<sup>17</sup>. As biobased product sectors mature, improved data will be available. The present examination can serve as a basis for future research and analysis.

Each category discussed includes a short industry overview and an outlook of the potential for biobased products within the industry. The economic potential for biobased products has been extrapolated from the combination of qualitative assessments from numerous interviews with industry leaders, and traditional quantitative economic research and modeling when data were available (Informa Economics et al. Biobased Multi-Client Study, March 2006). Each product was benchmarked relative to the following variables:

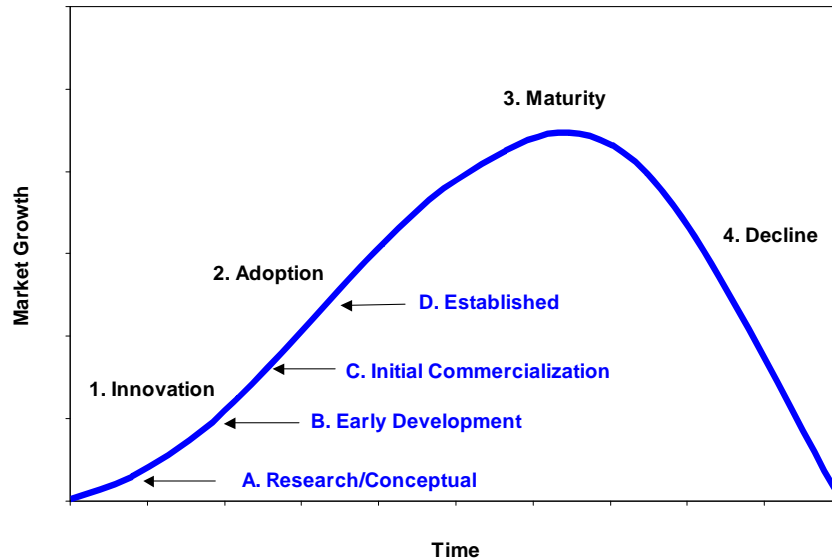
- Estimated size (based on value) of the conventional product industry in which the biobased product resides. For example, the U.S. conventional gasoline industry (biobased product ethanol) is estimated to be over \$230 billion/year.
- Estimated volume/output of the conventional product industry. For example, the conventional gasoline market is 139 billion gallons/year.
- A qualitative assessment/estimate of the biobased product and its stage of product development in the marketplace.
- Estimated annual rate of market growth for the industry or product category. For example, the conventional gasoline industry is forecast to grow more slowly than GDP based on historical patterns of consumption linked to U.S. population growth.
- Estimated market share potential of the biobased product relative to all other biobased products by 2015. For example, the pharmaceutical sector is expected to show significant growth in product development as U.S. baby boomers age and require and desire greater advances in these products.

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<sup>17</sup> Ideally, for example, the data for each market would be in “dollars of sales” or “volume of sales” for the most current full year: 2005.

The traditional product life cycle is usually used to describe the stage of development of a market which is characterized by four distinct phases (1) conception or innovation; (2) adoption by the marketplace, with sales steadily expanding; (3) maturity, where sales continue to increase but more slowly; and (4) decline, where the product begins to lose market share and sales drop. For purposes of this report however, additional stages between innovation and adoption (Figure 31) have been added in order to highlight the emerging nature of the biobased products' industry, the new stages are as follows: (A) research/conceptual; (B) early development; (C) initial commercialization; and (D) well established.

**Figure 31: Modified Biobased Product Life Cycle Curve**



Source: Informa Economics et al. Biobased Multi-Client Study, March 2006.

The results from Informa's analysis of the economic potential for the various markets of biobased products are summarized in Table 29. Ethanol, biodiesel and pharmaceuticals - though analyzed in other sections of the report - are also included in the table to provide a more comprehensive view of all of the biobased products discussed in this report.

**Table 29: Summary Assessment Matrix of Biobased Products, U.S. Markets**

\* Based on the value of the conventional product market

\*\* Represents the growth rate of the product/sector, e.g., conventional gasoline, not the bio-sector growth rate

\*\*\* Represents the % share potential relative to the biobased economy

Rank	Product/Sector	Value \$*	Volume	Bio-Product Stage of Development	Conventional Market Rate of Growth**	Bio-Product Market Share by 2025***
1	Gasoline (Ethanol)	\$230 billion \$6.7 billion	139 billion gal. 3.9 billion gal.			
2	Pharmaceutical	\$113 billion	na			
3	Diesel (Biodiesel)	\$110 billion \$840 million	62 billion gal. 306 million gal.			
4	Clothing (Bioplastic Blends)	\$80 billion	na			
5	Sanitary and Hand Cleaners	\$22.3 billion	na			
6	Coatings	\$19.5 billion	1.6 billion gal.			
7	Plastic Films	\$17.8 billion	na			
8	Carpeting	\$14.4 billion	20.8 billion sq. feet			
9	Fertilizers	\$12.5 billion	na			
10	Containers	\$12.2 billion	13 billion lbs			
11	Adhesives	\$8.4 billion	15.2 billion lbs			
12	Insulation	\$7.7 billion	8.8 billion lbs			
13	Wood Waste Products	\$6.3 billion	317 billion lbs			
14	Motor Oils	\$3.5 billion	1.2 billion gal.			
15	Solvents	\$3.3 billion	11.9 billion lbs			
16	Janitorial Cleaners	\$2.85 billion	na			
17	Wood Substitutes	\$1.95 billion	2.26 billion lbs			
18	Hydraulic Fluids	\$1 billion	222 million gal.			
19	Sorbents	\$400-500 million	na			
20	Transformer Fluid	\$200 million	40 million gal.			
21	Composite Panels	\$100 million	na			

Well Established		Very Fast = > GDP Growth +2%		Large	
Initial Commercialization		Moderately Fast = GDP Growth +2%		Medium	
Early Development Stage		Slow = Avg GDP Growth		Small	
Research/Conceptual Stage		Flat = < GDP		Niche/Specialty	

na: not available

Note: bio-product is short for biobased product

Source: Informa Economics et al., Biobased Multi-Client Study, March 2006

Table 29 shows that clothing, pharmaceuticals, plastic films, carpeting, containers, composite panels, sorbents, solvents, adhesives and insulation are at well established stages of development. Of these products, pharmaceuticals, coatings, plastic films, containers, adhesives, insulation, wood waste products and composite panels are expected to hold a substantial share in the biobased industry. The importance of the biopharmaceutical industry is recognized by the magnitude of its value and volume relative to other biobased industries; its growth also depends on the potential of biotechnology and the increased consumption of nutraceuticals.

An overview of each market follows. This summary highlights how many biobased products are commonly used in daily life. Biobased products can range from motor oils and fuel in our cars; to the clothes we wear, to the cleaning products we use to wash our hands and homes. The companies that produce biobased products are also diverse in terms of size, age and location. Appendix 3 presents preliminary findings on the characteristics of these firms.

Given advances in new technologies that are helping to derive lower cost biobased products, the potential for increased importance in the U.S. economy over the next 20 years is significant.

## **1. Motor Oils**

Motor oils have been used since the development of steam engines as a buffer between moving and static engine components. They prevent metal-to-metal contact and transfer friction based heat away from the contact point. Automotive engine oil and transmission fluids accounted for 54% of the total U.S. lubricant market in 1997 (2.5 billion gallons).

In general, auto manufacturers are recommending longer intervals between oil changes, which is limiting the growth in motor oil sales. The average drain interval is now 5,200 miles. The continued popularity of light trucks and sport utility vehicles, though, is helping motor oil sales. These vehicles house V-8 engines that may need up to 6 quarts to fill their crankcases.

Table 30 shows the potential U.S. market for biobased motor oils. Automotive engine oil presents a huge market opportunity, but performance requirements and the low price of petroleum alternatives make entrance to this market difficult. Nonetheless, two companies are selling plant based automotive engine oils. Agro Management Group derives its product (called AMG2000) from canola, soy, and other vegetable oils, while Renewable Lubricants, Inc. uses canola, sunflower, soy, and corn oils.

**Table 30: U.S. Potential Markets for Biobased Motor Oils**

<b>Oil Use</b>	<b>U.S. Market (1000 tons)</b>	<b>Probable percent Market acceptance of Biobased</b>
Crankcase	3900	24
Marine	189.3	75

Source: Johnson and Allen.

Motor oil consumption is expected to grow 2.2 percent a year through 2010. Motor oil sales will depend greatly on quick lube outfits and car dealers. Independent quick lube operators - with 14,000 freestanding units and about 7,000 dealers in 2005 - capture as much as 80 percent of the automobile and light truck motor oil market.

## 2. Hydraulic Oils

Hydraulic oils are a large group of liquids made of many components. These oils are used in cars (automatic transmissions, brakes, power steering); fork lifts; tractors; bulldozers; industrial machinery; and airplanes. Industrial hydraulic oils alone represent a 222 million gallon market.

In 2004, the United Soybean Board estimated that the probability of soybean oil's acceptance for use in hydraulic oils is 40 percent, with a possible market share of 5 percent. This market share would require 8 million bushels of soybeans a year. The soy based hydraulic oil market will be limited to niches where environmental safety concerns are high (United Soybean Board 2004).

The outlook for soy based hydraulic oils is positive if they can meet performance specifications and any emerging regulatory requirements, while remaining low in cost.

Biobased hydraulic oils currently make up 2 percent of the total hydraulic oils market, but market potential is considerable (Informa). USDA has designated biobased hydraulic fluids for mobile equipment for preferred procurement by federal agencies.

Exxon Mobil, Chevron, Texaco, and E.F. Houghton, a supplier of industrial hydraulic oils, offer rapeseed based products, while Pennzoil offers a hydraulic fluid made with sunflower oil.

## 3. Plastic Films

One of the fastest-growing market areas for soy is the manufacture of soy based plastics. The market for petroleum based polyols is 3 billion pounds a year in the United States and 9 billion pounds worldwide. The U.S. plastic film market is \$17.8 billion a year, with about 200 firms in the industry.

The major end uses of plastic are packaging (25 percent) and construction (22 percent) (Agri Food Canada, 2005). Food packaging will provide growth opportunities in areas



such as snack foods, confections, and produce. Slower growth in other segments such as textile, apparel, and paper product packaging will reflect market maturity.

Plastic packaging will account for three-fourths of film uses in 2008 due to cost and source advantages over rigid packaging, as well as potential in areas such as breathable films and standup pouches. Opportunities for growth are anticipated in secondary packaging products such as retail bags and stretch wrap due to growing consumer spending and industrial activity (Global Information Inc., Plastic Films, 2004).

U.S. biodegradable plastic demand will grow 13.7 percent annually through 2008 as prices and quality become more competitive with conventional polymers. Biodegradable/compostable types, especially polylactic acid (PLA), will lead gains. Film and ring carriers will dominate packaging uses, while degradable foodservice items grow fastest (Freedonia, Plastic Films).

#### 4. Containers

It is currently not possible to identify the market value of the biobased container sector. However, market information regarding the traditional container industry provides a proxy for understanding the market potential for biobased containers. Plastic containers accounted for about 18 percent of the market in 2004 as shown in Table 31 (Freedonia, Containers 2004). The plastic container market is valued at \$12.2 billion (Freedonia, 2004). Demand for resins to make plastic containers was about 13 billion pounds in 2004, and is projected to grow 5.3 percent annually through 2008 (Salomon Smith Barney Research). As the container industry grows, consumers are expressing greater concern regarding the use of plastics in packaging and the link to negative environmental impacts, which increases opportunities for biodegradable plastics. The level of plastic bottle recycling has grown significantly from 1990 to 2004, (Figure 32).

The U.S. beverage sector plays a significant role in container market. Production of containers with beer, soft drinks, milk, water, fruit juices, and other drinks account for billions of units sold each year. Table 32 through Table 34 highlight trends of beverage unit sales from 1992 to 2000 (Informa Economics, et al., 2006). The demand for plastics for containers is forecast to exceed 165 billion units in 2008, which will require over 14 billion pounds of resin. Plastic bottles are expected to grow the most, accounting for 75 percent of all plastic containers (by weight) by year 2008 (Salomon Smith Barney Research).

**Table 31: Type of U.S. Containers by Type of Inputs, 2000**

Container Types	Percent Share
Glass	20.2 percent
Plastic	17.6 percent
Metal	62.2 percent

Source: Salomon Smith Barney Research.

**Table 32: Container Inputs, U.S. Packaging Shipments by Material: Beer**  
(billion units)

Containers	1992	1994	1996	1998	1999	2000
<b>Glass</b>	12.8	15.1	16.7	17.7	18.2	18.4
<b>Metal</b>	38.2	36.8	34.6	33.4	33.4	32.9
<b>Plastic</b>					0.05	0.15
<b>Total</b>	51.0	51.9	51.3	51.1	51.6	51.4

Source: Informa Economics et al. Biobased Multi-Client Study, March 2006.

**Table 33: Container Inputs, U.S. Packaging Shipments by Material: Assorted Liquid Food, Fruit, Fruit Juice Packaging**

(billion units)

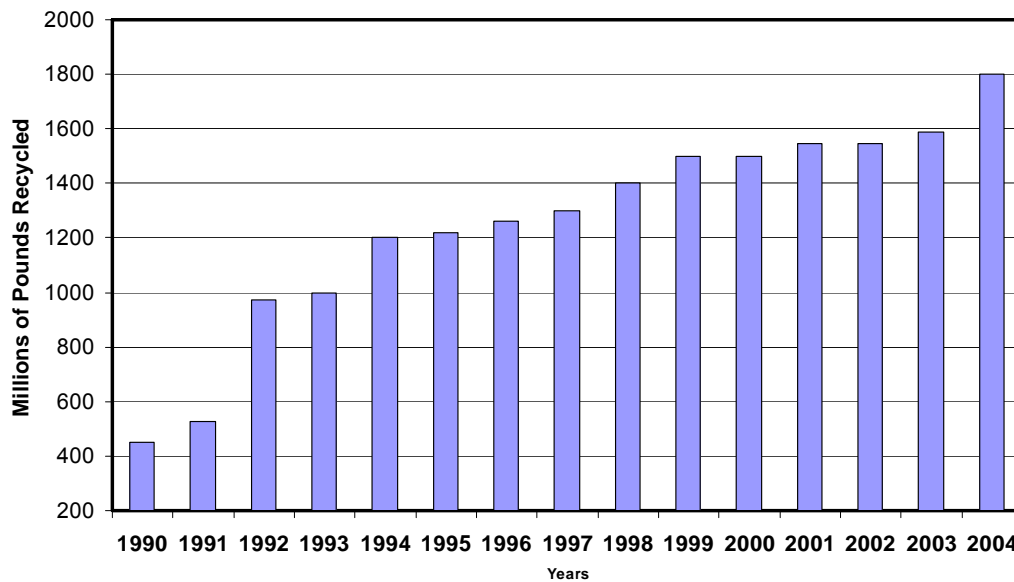
Containers	1992	1994	1996	1998	1999	2000
<b>Glass</b>	14.2	16.1	13.2	9.0	9.2	8.6
<b>Metal</b>	12.5	12.2	11.6	11.7	12.1	11.6
<b>Plastic</b>	11.4	13.4	16.1	18.8	20.3	22.3
<b>Total</b>	38.1	41.7	40.9	39.5	41.6	42.5

Source: Informa Economics et al. Biobased Multi-Client Study, March 2006.

**Table 34: Container Inputs, U.S. Packaging Shipments by Material: Soft Drinks**  
(billion units)

Containers	1992	1994	1996	1998	1999	2000
<b>Glass</b>	7.8	4.5	1.6	1.4	1.4	1.4
<b>Metal</b>	57.4	66.3	64.5	69.4	68.9	67.4
<b>Plastic</b>	9.8	13.3	16.8	20.6	21.4	22.0
<b>Total</b>	75.0	84.1	82.9	91.4	91.8	90.7

Source: Informa Economics et al. Biobased Multi-Client Study, March 2006.

**Figure 32: Growth in Consumer Plastic Bottle Recycling**

Source: American Plastics Council.

## 5. Insulation

Insulation is a conservation measure that can save significant amounts of energy. Standards requiring better insulation in new buildings would reduce the consumption of natural gas and fuel oil and make the use of solar power and electrical heating less costly.

The U.S. insulation market has grown rapidly; it was estimated to be \$7.7 billion in 2005, and is forecasted to reach \$8.9 billion by 2008 (Informa Economics, et al. Biobased Multi-Client Study, March 2006). Fiberglass accounts for approximately 62 percent of the insulation market; foamed plastic accounts for a 20 percent share, biobased insulation accounts for 7 percent; mineral wool accounts for 5 percent of the insulation market; and other products account for 5 percent. Biobased insulation had only four U.S. distributors in 2003.

Gains in the insulation market will be based on accelerating durable goods shipments, increasing nonresidential building construction, installing more insulation per structure, and conducting upgrades of insulation for existing buildings.

The new energy bill which passed in 2005 offers U.S. builders incentives (a \$1,000 tax credit) to build more energy-efficient homes. Biobased Insulation - an energy-efficient, soy based foam - can help them meet government requirements.

## 6. Textiles with Blends of Bioplastics

The U.S. textile industry includes about 10,000 companies with combined annual sales of \$80 billion. The industry has become more concentrated in recent years, with the 50

largest companies controlling more than 60 percent of the market. About 100 companies have annual sales over \$100 million. Although the industry currently employs an estimated 660,000 people, approximately 441,000 jobs have been lost since 2000 due to closings of 279 textile plants, according to the National Council of Textile Organizations (RSM McGladrey).

Textile firms sell to apparel manufacturers, automotive firms, furniture manufacturers, other textile companies and various retailers. The end uses of U.S. textiles (in pounds) are apparel (35 percent), floor coverings (25 percent), industrial/other (23 percent), and home furnishings (16 percent). Annual U.S. textile exports total about \$9 billion, a large portion of which goes to Central and South American countries that manufacture apparel for re-export to the U.S. Textile imports by the U.S. are \$7 billion, with the largest amounts from China, Canada, Korea, and Italy.

On January 1, 2005, the last remaining quotas protecting the U.S. industry (under the Multifiber Agreement) were phased out, in accordance with the General Agreement on Tariffs and Trade (GATT). According to the World Bank, upwards of \$200 billion in textile manufacturing could shift to China over the next few years. Negotiations between the United States and China continue in an effort to work out a new agreement that will balance each country's interests. China is pressing for 15 percent growth in textile exports to the United States. The U.S. textile industry wants growth contained at 7.5 percent through 2008.

U.S. apparel sales increased 4 percent in 2005, to \$181 billion (NPD Group, 2006). At \$27 billion, 2005 sales of children's clothing grew 2 percent. Sales of men's apparel grew 5.5 percent to \$53 billion, and women's apparel sales rose 4.3 percent to \$101 billion.

The U.S. textile industry saw revenue fall 8.9 percent (compound annual growth) from 2000 through 2004 due to a general slowdown in the economy and broad industry restructuring. Economists expect the industry to grow 8.8 percent from 2005 through 2008.

DuPont and Tate & Lyle PLC have formed a joint venture to produce 1,3-propanediol (PDO), the key building block for the DuPont™ Sorona® polymer, using a proprietary fermentation and purification process based on corn sugar. This biobased method uses less energy, reduces emissions, and employs renewable resources. Currently, Sorona® polymer is manufactured from petroleum based PDO and is available commercially from DuPont and its licensees. In 2006, commercial-scale quantities of biobased PDO from corn sugar will be available from DuPont Staley Bio Products' manufacturing facility in Loudon, Tennessee. This will contribute to DuPont's goal of deriving 25 percent of its revenue from nondepletable resources by 2010.<sup>18</sup> DuPont derived 14 percent of its 2002 revenues from nondepletable resources (DuPont Press Release, 2004).

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<sup>18</sup> Note: DuPont uses the term "nondepletable" resources in place of "renewable" resources.

Cargill's PLA plant at Blair, NE, turns 14 million bushels of corn into 300 million pounds of PLA. Cargill is the original inventor of polylactic acid (PLA), a polymer derived from natural plant sugars (corn dextrose) and marketed as NatureWorks PLA and Ingeo fibers, which can be used in a wide range of textile applications.

Some resistance in the market arises from lack of guarantee that the corn used for PLA is free from genetic modifications. Patagonia and other companies campaign against GMOs. Further resistance to biobased textiles is due to past industry experience with products such as Ramie Cotton. This biobased cotton blend rapidly lost its properties and became dry. Customers noted a brittle feel and loss of shape in apparel made from this product.

## 7. Fertilizers

There is limited market information concerning the value or volume of sales related to biobased fertilizers. This is an extremely diverse category of products. Farmers have been using animal waste (manure) for thousands of years in order to amend soil and fortify plants with nutrients like nitrogen (N), phosphorus (P), and potassium (K) in order to stimulate growth and development. Experts estimate that without commercial fertilizers, the world would be without one-third of its food supply.

Perhaps the most comprehensive base of information regarding the U.S. fertilizer industry comes from The Fertilizer Institute (TFI), in Washington, D.C. TFI conducts annual surveys of the industry to determine such information as value of sales, sales volumes and cost of goods sold. Table 35 highlights key findings of the TFI's 2004 survey. In 2004, nine firms participated in the survey, compared to 13 firms in 2000. The total sales value for survey participants has ranged from \$8.0 billion in 2002 to \$10.8 billion in 2004. Informa Economics estimated that total annual sales for 2005 for the industry were \$12.5 billion.

**Table 35: Survey of U.S. Fertilizer Companies**

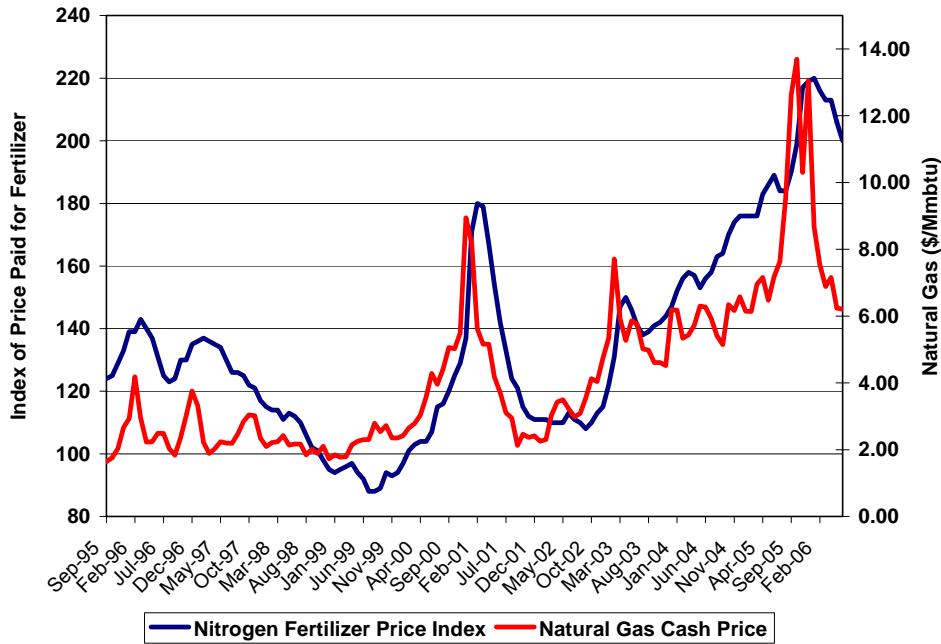
	2000	2001	2002	2003	2004
Number of Reporting Companies	13	13	12	11	9
Value of Sales (\$'000)	\$9,324,444	\$8,786,227	\$8,048,077	\$9,150,805	\$10,799,119
Volume of Sales (short tons)	76,485,000	67,030,000	68,144,000	53,941,000	65,813,000

Source: The Fertilizer Institute, TFI 2004 Annual Fertilizer Financial Facts, March 2006.

The U.S. fertilizer industry has increased its use efficiency. Nitrogen use on corn fell by 1.3 percent from 1976 to 2003, while corn output grew over 60 percent. Phosphate use

on corn fell by 28.1 percent over the same period. The high cost of energy inputs, however, especially natural gas, which is an input in the production of nitrogen based fertilizers, can significantly impact nitrogen producers' profitability (Figure 33). As the cost of natural gas based fertilizers rise, farmers are expected to rely on biobased fertilizers become more important as a substitute.

**Figure 33: Natural Gas Cash Price (Henry Hub) Versus Nitrogen Fertilizer Index of Prices Paid by Farmers**



Source: U.S. Department of Agriculture, National Agricultural Statistics Service, and Informa Economics.

### 8. Coatings

The coatings industry, after having moved away from its earlier dependence on biobased oils (e.g. linseed oil), has begun to move back towards biobased coatings, now including soybased products as well.

The U.S. coatings industry is forecast to grow 2.2 percent a year through 2008 (Informa). The U.S. market for coatings (which includes paints and surfactants) tops 1.2 billion gallons. Half of the market is architectural coatings for both home and commercial applications. U.S. consumption of paint additives alone was \$710 million in 2002.

### 9. Adhesives

The U.S. adhesives market was \$8.4 billion in 2004, with demand an estimated 15.2 billion pounds. Packaging adhesives make up the majority of the market. Assembly and electrical adhesives are beginning to grow in demand. In 2003, global sales of

adhesives totaled \$29.5 billion, with a volume of over 32 million dry pounds (Chemical Market Reporter, March 7, 2005). The world market is growing 2 - 3 percent/year on average; however, new applications such as electronics and medical adhesives are growing 4 - 5 percent.

Wood adhesives made from soybeans have existed for more than 70 years. However, with the introduction of effective petroleum based adhesives in the 1930s, soy adhesives were replaced. Acrylic acid used in adhesives and polymer is an attractive target for new biobased products, at about 2 billion pounds of production annually. Water based, hot-melt, and reactive formulation adhesives are gradually replacing solvent based adhesives in response to environmental concerns.

## 10. Sanitary and Hand Cleaners

Ethanol based products are used as sanitizers; citrus based products are used largely as general cleaners. A variety of soy based hand cleaners are available, with co-ingredients ranging from corn to aloe vera. Vegetable oils have long been a source of fatty acids for detergents and soaps, and they compete effectively with petroleum based surfactants.

In 1988, the United States produced 7.3 billion pounds of surfactants, of which 12 percent were biobased. More recent production of surfactants is an estimated 43 billion pounds (USDA, USDOE, 2003). Based on these numbers and assuming 15 percent growth in the use of biobased surfactants since 1988, biobased surfactants would be 9.7 billion pounds, or 22.5 percent of the market. The compound annual growth of the U.S. soap and cleaning compound manufacturing was 3.6 percent from 2002 to 2004. Soap and other detergent manufacturing, a subset of the above product, category had a compound annual growth of 5.4 percent between 1999 and 2002 (Table 36).

**Table 36: U.S. Sanitary and Hand Cleaner Value of Shipments, 1999 - 2004**

NAICS Code	Industry Group	Year	Value of Shipments (million US \$)
32561	Soap and cleaning compound manufacturing	2004	33,057
		2003	30,217
		2002	30,801
325611	Soap and other detergent manufacturing	2002	17,328
		2001	15,557
		2000	15,115
		1999	14,801

Source: U.S. Department of Commerce, Annual Survey of Manufactures, 2004.

## 11. Biobased Carpet

U.S. industry shipments in 2004 totaled 2.3 billion square yards, or \$14.4 billion at the mill level. In 1950, industry shipments were 97 million square yards. Mills located within a 65 mile radius of Dalton, GA, supply 80 percent of the U.S. carpet market. The United States supplies approximately 45 percent of the world's carpet (Informa).

In 2001, 53 percent of carpet sales were for residential applications and 47 percent for commercial applications. Commercial installation is broken down into six categories: corporate (30 percent), retail (18 percent), educational (15 percent), health care (15 percent), hospitality (13 percent), and "government and other" (9 percent) [Informa].

Urethane Soy Systems Company has received patents for the use of a new "biobased" polyol, made from soybean oil (brand name Soyol™), which can replace many petroleum based polyols in the manufacture of polyurethane products. Carpet backing and padding is one of the uses of polyurethane than can be made from soy oil.

Tate & Lyle's joint venture with DuPont to create the new synthetic fabric Sorona will have repercussions in the carpet industry. The product uses 50 percent less petroleum than its competitors, relying instead on a corn based starch. The corn based polymer is shipped to customers in U.S. and Asian carpet and textile plants, where it is spun into fiber then woven or knitted into materials for carpeting and apparel.

Mohawk Industries Inc., and DuPont have partnered to provide a new line of residential carpet to the flooring industry: SmartStrand™ with the DuPont™, Sorona® polymer.

Cargill has agreed to buy out Dow Chemical's 50 percent interest in their Cargill Dow polylactic acid (PLA) joint venture. PLA is made by polymerizing lactic acid that has been fermented from corn-derived glucose. Interface Flooring manufactures carpet with PLA. Cargill Dow projects a market for PLA of 8 billion pounds by 2020.

## 12. Solvents

The U.S. solvents market is an estimated 11.9 billion pounds (\$3.3 billion) per year. The market is forecast to reach \$4.4 billion in 2010, with biobased solvents growing 6 percent annually to account for nearly 25 percent of the market. Conventional solvents will post modest gains (Freedonia Group, 2006), largely by replacing hydrocarbons and other problematic solvents.

Tetrahydrofuran is a potential biobased solvent and a key ingredient of adhesives, printing inks, and magnetic tape. The annual U.S. market for these uses is estimated at 255 million pounds (Informa).

The global demand for solvents is forecast to increase 2.3 percent a year through 2007 to 19.7 million metric tons (Informa).



### 13. Wood Substitutes<sup>19</sup>

The United States is the world's second largest forest products exporter, totaling \$20 billion in 2004 exports (including paper products). However, the value of imports actually exceeds exports, and, in fact, the United States is the world's largest forestry importer, at \$33.3 billion in 2004. In 2004, U.S. softwood lumber imports hit a record high of 57.3 million cubic meters. Canada is the main source, supplying 50.3 million cubic meters, or 88 percent, of U.S. softwood lumber imports.

There are three main alternatives for lumber substitutes: recycled plastic only, wood-plastic composites, and fiberglass-plastic composites. Wood-plastic composites are the largest segment of the market. Recycled-plastic lumber first became available in the 1980s. Unlike most new products, its development was driven not so much by end-use needs as by the runaway growth of plastic deposited in landfills: 19 million tons a year, equivalent to more than 120 pounds per person.

Wood-plastic composites products usually contain 50 percent high-density polyethylene (HDPE) and 50 percent wood waste. The wood reduces the weight of the lumber, improves its strength and stiffness, and reduces thermal expansion and contraction. Mobil Chemical developed the first wood-plastic composite, now called Trex. AERT, Inc., produces decking and handrails (ChoiceDek™) with deep corrugations that reduce weight without significant loss of rigidity. ChoiceDek is made using a mix of high-density polyethylene (HDPE) and low-density polyethylene (LDPE). For the wood fiber, the company uses oak or red cedar chips left over after extracting the aromatic oils. Nexwood, from Composite Technology Resources Ltd., uses rice hulls, the very strong fiber left over after threshing rice.

Although not as common as pressure-treated or cedar lumber, more and more recycled-plastic lumber is being used around homes. Decking is the most common use. Plastic lumber replaces pressure-treated wood and premium rot-resistant woods such as cedar, redwood, and teak.

In landscaping, recycled-plastic lumber, including commingled plastic products, can be used in retaining walls to stabilize steep slopes. The landscape timbers are bolted together or pinned into the ground. In gardens, plastic lumber is an alternative to preservative-treated lumber for providing stakes, garden edging, and support for raised beds. Recycled-plastic lumber adds longevity to outdoor furniture.

Some wood-substitute products are more expensive, but longer life and less maintenance offset this. Others, such as Oriented Strand Board (OSB) are less expensive. Wood-substitute products are also perceived as more environmentally beneficial than traditional lumber products. Compared with wood, plastic and composite lumbars are heavier (up to 2 - 3 times) and more subject to thermal expansion and contraction.

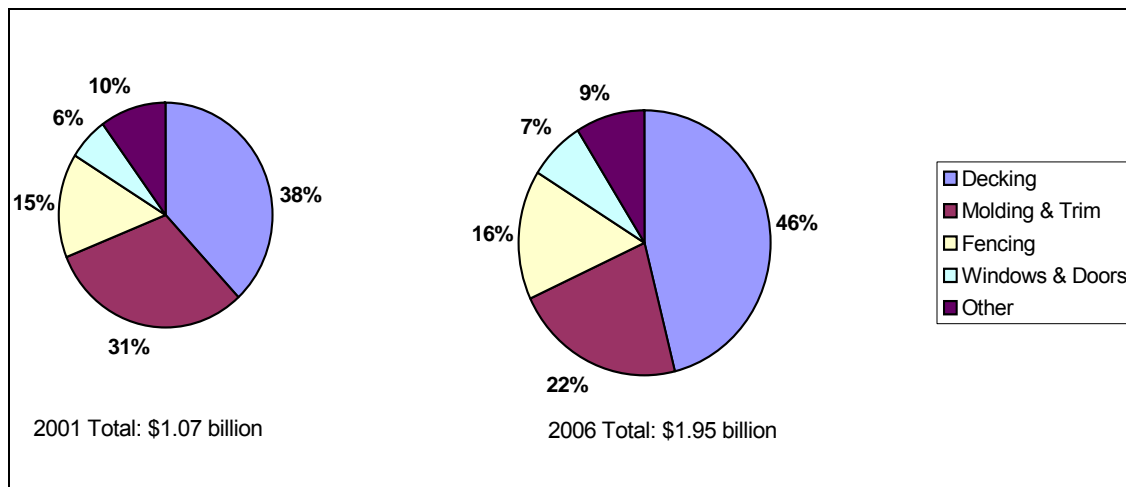
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<sup>19</sup> Dimension lumber

Softwood lumber continues to be displaced by substitute materials in segments of the residential construction industry that it traditionally dominated: wall, floor, and roof framing. Residential builders cite the rising prices of softwood lumber and a perceived drop in lumber quality.

Wood-substitute products are growing by as much as 20 percent a year, and this trend is expected to continue for many years. The largest growth has been in decking (Figure 34).

**Figure 34: Plastic and Wood-Plastic Lumber Demand**



Source: Informa Economics et al. Biobased Multi-Client Study, March 2006.

The most commonly used products in residential construction are softwood lumber, OSB, steel framing, finger jointed lumber, wood trusses, laminated veneer lumber (LVL), and wood I-joists.

In 1980, North American OSB panel production was 751 million square feet (3/8" basis). By 2001, this figure had grown to 22.0 billion square feet. Plywood has lost market share to OSB, and the gap is expected to grow. In 2000, for the first time, OSB exceeded plywood production for the first time, and by 2004 it had grown to nearly 60 percent of the North American panel market share.

Softwood lumber dominated wall framing in 1998 (83 percent market share), but it has lost ground to non-wood products such as steel, engineered wood products and, plastic-fiber lumber, particularly among large firms. Softwood lumber's share of the floor framing market declined from 59 percent in 1995 to 42 percent in 1998 (University of Washington).

## 14. Composite Panels

Composite panels are composed of nonstructural composite material such as highly engineered blends of recycled paper products or agricultural wastes, biobased resins, and coloring. Molding and trim was the largest end use for composite and plastic lumber in 2003, at about 47 percent of the total. Through 2008, demand for composite and plastic lumber in molding and trim applications is projected to expand 7.1 percent a year, with almost all this growth being in plastic lumber (Informa Economics et al. Biobased Multi-Client Study, March 2006).

Biobased building composites for both commercial and residential markets in the United States have grown rapidly from an estimated \$12 million in 2000 to over \$100 million in 2005 (Drzal, Mohanty, Burgueno, Misra, 2003).

Residential building use will remain the largest market for composite and plastic lumber over the 2008 forecast. Although new home construction is expected to slow through 2008, biobased materials will continue to achieve growth through increasing market penetration at the expense of other materials.

## 15. Products from Wood Waste

Wood waste is defined as end-of-life products, failed products, off-cuts, shavings, and sawdust of all timber products. This definition of wood waste excludes forest residues, often referred to as primary wood waste, and green or garden waste materials such as branches, bushes, and tree stumps.

There are three different categories of wood waste:

- Untreated timber includes hardwoods and softwoods.
- Engineered timber products (ETP) include particleboard, medium-density fiberboard, plywood, (ETP) hardboard, low density fiber board, oriented strand board, finger-jointed timber, and glulam beams.
- Treated timbers include timbers treated with copper chrome arsenate (CCA), light organic solvent preservative (LOSP), and creosote preservative.

Depending on the level of contamination, wood waste can be a valuable resource for recycling and processing into secondary products. The separation of wood waste by category is an important aspect of the recycling process. Suitable wood waste is used in products such as feedstock to industrial processes, amended soil and compost products, landscape mulch, animal bedding, firewood, and impact absorbing playground material.

The timber industry has been using wood residues from primary wood processing mills for decades for fuel, pulpwood, and as feedstock for products such as particleboard. The recovery and reuse of wood from two other major waste streams - municipal solid waste (MSW) and construction and demolition waste - is only now being seriously

considered. MSW is waste from residential, commercial, institutional, and industrial sources. Paper and paperboard is its largest component, constituting 75 million metric tons or 36 percent of all MSW. Just over 12.0 million metric tons of solid wood waste was generated in the wood component of MSW in 2002 (Informa).

An estimated 34.5 million metric tons of wood products was used for new residential construction in 2002. Wood waste was about 11 percent of all wood used to build residential structures. In 2002, an estimated 5.6 million metric tons of wood waste was generated from all residential repairs and remodeling activities; about 3.8 million metric tons was recoverable (Informa).

The following products can be made from wood waste:

- Boiler fuel
- Chunkrete
- Compost amendment
- Erosion control
- Ethanol
- Fireplace log
- Hardboard/fiberboard
- Landfill cover
- Landscape mulch
- Methanol/syngasOriented strandboard/waferboard
- Packaging filler
- Particleboard
- Pet litter
- Playground/Handicapped access groundcover
- Potting soil
- Pulp and paper
- Road stabilization
- Soil amendment
- Topsoil
- Wood pellets
- Wood-plastic composite

Nearly 63 million metric tons of wood waste material is generated in the manufacture, use, and disposal of solid wood products each year. Of that total, about 27.1 million metric tons (43 percent) is suitable for recycling or reuse.

In 1999, an estimated 299 million pallets were recovered for recycling. These recovered pallets were recycled into new pallets or related products, or were ground for fuel or mulch. Less than 1 percent of recovered pallet material was returned to the landfill. Thus, nearly 7 million metric tons of pallet material was diverted from the MSW stream.

## 16. Janitorial Cleaners

The cleaning industry employs 2 to 3 million janitors. U.S. demand for janitorial services and supplies grew 5.6 percent (including price increases) to \$37 billion in 2005 (Informa).

The cleaning supply industry will offer strong growth opportunities for biobased products, driven by demand for commercial cleaning equipment (Freedonia, 2001). Yellowstone is the first park in the country to replace existing cleaning and janitorial products used by park and concessionaire personnel with environmentally preferable

cleaning products. This amounted to more than 130 products with health or environmental risks being replaced by fewer than 10 products that are environmentally sound. This is an example of work done by the Office of the Federal Environmental Executive (OFEE) and of the Office of Federal Procurement Policy (OFPP) which has encouraged agencies to buy and test biobased products to see if they meet the agencies' needs.

## **17. Sorbents**

Absorbents and adsorbents (referred to as “sorbents”) are used in environmental, industrial, agricultural, medical, and scientific applications to retain or release liquids and gases. The U.S. sorbent products market (the types used to clean up oil and solvent spills) is \$400-\$500 million a year (Informa).

The forest products industry is an important supplier of the sorbents industry. Recovered sawdust is commonly used for sorbent products, particularly animal bedding. Sorbents can also be manufactured using recovered paper, textiles, plastics, wood, and other materials.

## **18. Transformer Fluid**

Transformer oil is a highly refined mineral oil that is stable at high temperatures and has excellent electrical insulation properties. Most electricity passes through petroleum oil-filled power and distribution transformers. More than a billion kilowatt-hours of electricity is conducted each year for U.S. residential purposes alone. The Tennessee Valley Authority (TVA) estimates that 151.4 million liters (40 million gallons) of transformer oil are used each year.

Public awareness has grown about PCB based transformer oils and their environmental hazard from damage or leak. FR3<sup>20</sup>, with soy oil as its base, is becoming an environmentally preferred solution for cooling electrical transformers.

In 2004, Cooper Power partnered with Cargill to develop vegetable based transformer oil. A three-way collaboration (Cargill Industrial Oils and Lubricants, Electric Research and Manufacturing Cooperative (ERMCO), and Waverly Light and Power) will provide to electric utilities an earth-friendly alternative to petroleum based transformer oil.

Most PCB oil-filled transformers have been collected or replaced with PCB-free mineral oil or alternate fluids. One company, Acme Electric Corporation, has eliminated liquids altogether and now only use a silicon based substance in their transformers.

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<sup>20</sup> FR3 fluid is a soy based, fire-resistant fluid and is PCB-free. FR3 fluid is the only non-silicone fluid that meets both the National Electric Code (NEC) and National Electric Safety Code (NESC) standards for less-flammable formulation as well as the UL listing requirements for use in electrical transformers (EOVK listing).

## F. The Market for Pharmaceuticals and Nutraceuticals

### 1. Background

Pharmaceuticals and nutraceuticals are discussed separately because of the considerable differences between the two categories. The primary difference is whether a product has been subjected to rigorous regulatory procedures. Pharmaceuticals are put through lengthy and expensive tests and are regulated by such agencies as the U.S. Food and Drug Administration, whereas nutraceuticals encompass a large universe of diverse unregulated products ranging from foods to dietary supplements.

Sharp shifts in demand and supply of new pharmaceutical, nutraceutical, and industrial products using biobased materials may have as much impact on the structure of agriculture as did many of the major events and discoveries of the last century - including plant breeding and new information and communication technologies. Demand for new pharmaceutical, nutraceutical and industrial products is being driven by fundamental shifts in demand for improved health and quality of life and renewed concern about the long-term availability of petroleum based products that replaced biobased materials in the last century.

Agricultural producers and research organizations can be expected to respond to markets and manufacturers' demand for more differentiated products with more consistent content for more sharply segmented markets. There will be increasingly differentiated products for polarized market segments, driven by the demand of various consumer groups, each motivated by different priorities such as health benefits, cost, ecological benefits, ethical issues, food safety, and sustainability of supply.

New farm management challenges will arise from the demand for improved product quality with increased nutrient content, which new technology and expert farm management may be able to deliver at lower cost and prices. Demand for natural products as raw material for new pharmaceutical, nutraceutical and industrial products seems assured, but there will also be increased interest in the composition and active ingredients of materials for specific end uses. New technologies that offer specific and reliable traits for specific end uses will lead offer a competitive advantage for those enterprises ready to adopt them when they become available. Traditional, organic, and GMO production systems may all participate in these markets.

Products for the cardiovascular market stand at \$30 billion/year, with potential to be supplied by plants such as *Digitalis* spp., *Strophanthus fratus*, *Cinchona* spp. and *Rauwolfia serpentina*. Nutraceuticals *Ginkgo biloba*, ginseng, garlic, and echinacea are likely to continue to experience strong growth in Europe and the United States.

### 2. Pharmaceuticals

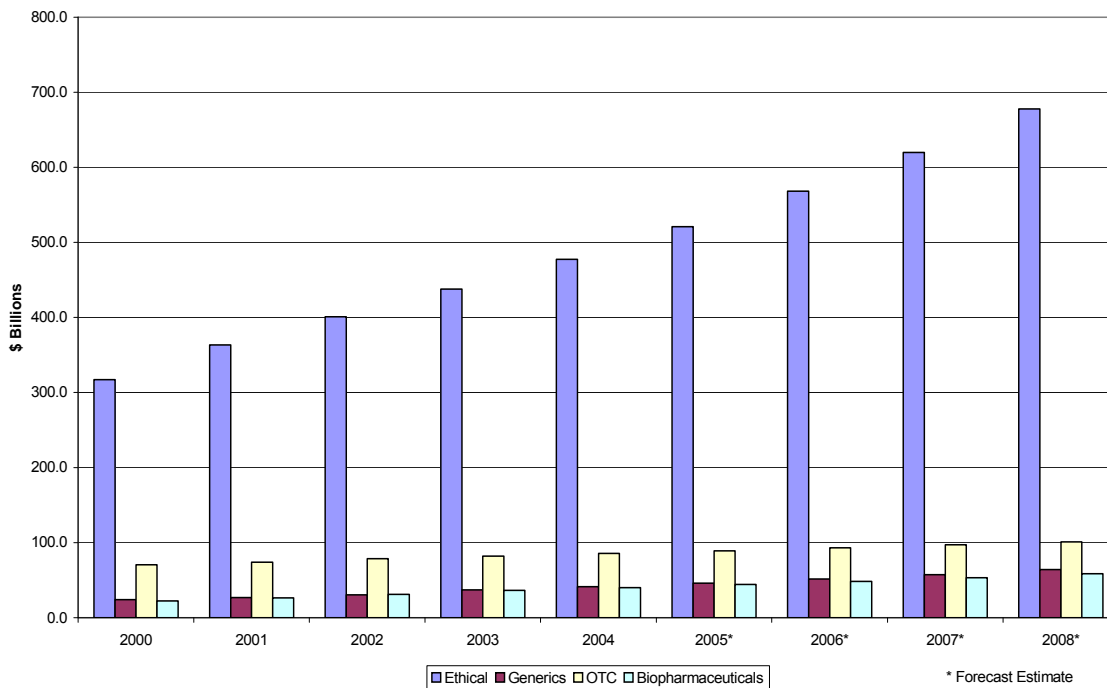
The world pharmaceutical industry stood at \$593 billion in 2003, or 24 percent of the healthcare sector. This market is expected to reach \$901 billion in 2008, growing at a

compound annual rate of 8.8 percent (Figure 35). A biopharmaceutical is a pharmaceutical produced by biotechnology and especially by genetic engineering.

Ethical pharmaceuticals (available by prescription only and name brand as opposed to generic) account for 74 percent of the market. This sector is under increasing pressure from generics and biopharmaceuticals. The generic industry is expected to increase its penetration in the world market to 7 percent by 2008, reaching \$64 billion. Biopharmaceuticals are growing at double the rate of the ethical sector, and were valued at \$40.1 billion in 2004.

The market share of the top 10 pharmaceutical companies grew from 28 percent in 1990 to 46 percent in 2002. Companies are increasingly focusing on mergers and acquisitions, in-licensing activities, co-development, and co-marketing activities. Biopharmaceutical companies like Amgen and Genentech are competing head-on with the big pharmaceuticals in the market place. Ethical pharmaceutical companies are increasingly venturing into biopharmaceuticals and generics to sustain growth.

**Figure 35: Worldwide Pharmaceutical Market by Sectors, Through 2008**



Source: Business Communications Company, 2004

The WTO/GATT implementation in 2005 is aligning the world pharmaceutical market into one global market. North America alone accounts for half of the world pharmaceutical market. The 10 leading world markets cover 70 percent of the ethical pharmaceutical market. Some key markets like Japan and Latin America are declining

in market share due to ongoing economic crises. Asia, on the other hand, is emerging as a leading pharmaceutical market.

The main categories of disease, in terms of drug sales, are cardiovascular, alimentary or metabolic, central nervous system (CNS), respiratory, and infectious diseases.

Twenty five percent of the active components in drugs prescribed in 1996 had their origins in higher (flowering) plants, with an additional 10 percent derived from fungi. In 1980, none of the top 250 pharmaceutical companies had research involving higher plants; by the early 1990s, more than half had introduced such programs. Drugs with botanical origins include established products, such as the cardiotonic digitoxin, and newer drugs such as the taxoids from *Taxus* spp or artemisinin and its derivatives from *Artemisia* spp (Table 37). The growing demand for natural medicines will continue to erode the existing (largely synthetic) drug market.



**Table 37: Classic Plant Drugs Obtained from Higher Plants**

Drug	Clinical action or use	Primary botanical origin
Atropine	Anticholinergic	Atropa belladonna
Caffeine	CNS stimulant	Camellia sinensis
Camphor	Rubefacient	Cinamomum camphora
Chymopapain	Chemonucleolysis	Carica papaya
Cocaine	Local anaesthetic	Erythroxylum coca
Codeine	Analgesic/anti-tussive	Papaver somniferum
Colchicine	Anti-gout	Colchicum autumnale
Digitoxin	Cardiotonic	Digitalis purpurea
Digoxin	Cardiotonic	Digitalis lanata
Emetine	Amoebicide	Cephaelis ipecacuanha
Ephedrine	Sympathomimetic	Ephedra sinica
Galanthamine	Cholinesterase inhibitor	Lycoris squamigera
Gossypol	Male contraceptive	Gossipium spp.
Hyoscamine	Anticholinergic	Hyoscamus niger
Kawain	Tranquiliser	Piper methysticum
Levodopa	Anti-Parkinsonian	Mucuna deeringiana
Menthol	Rubefacient	Mentha spp.
Methoxsalen	Psoriasis/vitiligo	Ammi majus
Methyl salicylate	Rubefacient	Gaultheria procumbens
Morphine	Analgesic	Papaver somniferum
Nordihydroguaiaretic acid	Antioxidant	Larrea divaricata
Noscapine	Anti-tussive	Papaver somniferum
Ouabain	Cardiotonic	Strophanthus fratus
Physostigmine	Cholinesterase inhibitor	Physostigma venenosum
Pilocarpine	Parasympathomimetic	Pilocarpus jaborandi
Podophyllotoxin	Topical treatment for condylomata acuminata	Podophyllum peltatum
Quinidine	Anti-arrhythmic	Cinchona ledgeriana
Quinine	Anti-malarial	Cinchona ledgeriana
Reserpine	Antihypertensive	Rauwolfia serpentina
Scopolamine	Sedative	Datura metel
Sennosides A and B	Laxative	Cassia spp.
Taxol	Antineoplastic	Taxus Baccata
Tetrahydrocannabinol	Antiemetic	Cannabis sativa
Theophylline	Bronchodilator	Camellia sinensis
Tubocurarine	Muscle relaxant	Chondodendron tomentosum
Vinblastine	Anticancer	Catharanthus roseus
Vincristine	Anticancer	Catharanthus roseus
Yohimbine	Aphrodisiac	Pausinystalia yohimbe

Source: Rural Industries Research and Development Corporation.

### 3. Nutraceuticals

The term “nutraceutical” was coined in the 1980s, and has been used interchangeably with “functional food” or, less commonly, “pharmafood.” Nutraceuticals were defined in 1994 by the Institute of Medicine’s food and nutrition board as “any food or food ingredient that may provide a health benefit beyond the traditional nutrients it contains.” The broader use includes both foods and processed products but in a modified version Health Canada has defined a *nutraceutical* as: “a product isolated or purified from foods, and generally sold in medicinal forms not usually associated with food and demonstrated to have a physiological benefit or provide protection against chronic disease. A nutraceutical is usually sold in pill, powder, potion, or other medicinal form.

Minerals and nutrients, vitamins, and herbal extracts are the largest product categories that make up the nutraceutical group.

For nutraceuticals, genetic engineering may increase the nutritional value of certain plants and, regulations permitting, this may accommodate a high-growth market. The development of “golden rice,” a genetically modified rice with high levels of beta-carotene and other carotenoids that the body turns into Vitamin A as needed, is a current example. The underlying desire for better health, improved quality of life, and concern about the availability of nonrenewable resources is driving this demand.

The quality and content of information about products and processes is likely to have a significant influence on this developing market. For example, scientific research suggests that 400 - 1200 IU of vitamin E per day will help reduce heart attacks, control diabetes, improve immunity, and reduce the risk of cancer. This level of intake is 40 times higher than the recommended dietary intake of 10 IU. Some health professionals argue that complete nutrition is best obtained from diet alone, and many physicians remain skeptical about a whole range of nutritional supplements including vitamins, minerals, amino acids, and herbs. But supplement manufacturers claim it is impossible to consume the optimal amount of 450 IU of vitamin E through diet alone without upsetting the overall balance of nutrients required.

Some of the factors leading to increased consumption of nutraceuticals include the positive research results from nutrient supplements, increased clinical studies being performed to establish the efficacy of natural remedies, increased distribution and promotion by retailers, and growing interest in alternative medicine and self-medication. Demand is also being fueled by growing awareness of the role of antioxidants in enhancing quality of life and reducing the prevalence of degenerative diseases.

Agricultural plants are the essential source of raw material in the manufacture of anti-oxidants, which typically contain vitamin C, vitamin E, and beta-carotene in balanced product formulations. Antioxidant sources range from grains to horticultural crops such as cabbage, broccoli, and grape seeds. The growing awareness of the need to limit consumption of foods with high levels of saturated fats is creating opportunities for plant seeds such as canola, which are relatively low in saturated fat and genetically modified plants with high levels of saturated oil in their natural state, such as peanuts. There has been great focus on phytochemicals - biologically active chemicals such as glucosinolates in cruciferous vegetables (cole crops), lycopene in tomatoes, limonoids in citrus fruits, lignins in flaxseed and catechins in tea - all purported cancer fighters.

The fastest growing nutraceutical market is weight-loss products. With more than 120 million overweight Americans and 17 million diabetics, demand is growing for foods or supplements that increase metabolism, suppress or satiate appetite, and control blood sugar.

While many claims have not been replicated in clinical trials, research facilities are going up around the country to study the medicinal qualities of food components.

The president of California Functional Foods states “The functional food and beverage market is continuing to grow, including the FOSHU (Foods for Specified Health Uses) category” (Informa Economics).

Interest in health-promoting foods has a long history. Nutraceuticals can be seen as the latest trend in a succession of health food concepts. An historical overview of the stages of nutraceutical product development is presented in Table 38.

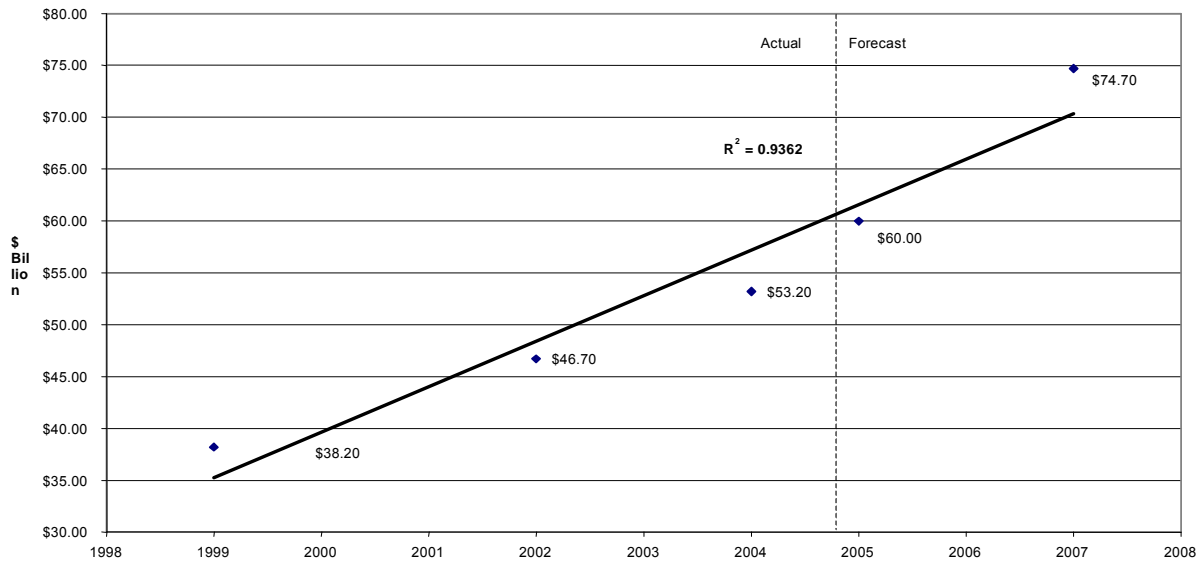
**Table 38: Historical Overview of Nutraceutical Product Evolution**

Era	Food-health concept/catalyst for change	Effect on attribute or product type
1950's-1960's	“Refined”	Fiber Cod liver oil
1970's	“Green”	“Natural” ingredients Pesticide-free
1980's	“Low” and “Lite”	Calorie intake Fat/salt/sugar Fish oils Cholesterol
1990's	“Nutraceuticals”	Dietary fibers Oligosaccharides Polyunsaturated fatty acids Cholines/phospholipids Glycosides Dietary vitamins/minerals Peptides Lactic acid bacteria
Until 2010	Disease-fighting foods  Health-optimizing foods	Genetically engineered plants and fruits, e.g., bananas to give pediatric vaccines Tomatoes with elevated nicotine content to aid smoking cessation Foods with disease prevention function; studies on modes of action and benefits, e.g. terpenes, carotenes, limonoids, xanthophylls, phytosterols, isoflavones, oligosaccharides and vitamin enriched foods

Source: Mertens/Financial Times Healthcare.

The precise market value for nutraceuticals is not clear, reflecting the difficulty with defining the market. If the term nutraceutical is taken in its broadest sense, including health foods, dietary supplements, and natural foods, the global market has been put at \$504 billion, with \$500 billion split equally between the United States and Europe. If defined in a stricter sense, as dietary and nutritional supplements only, the U.S. nutraceuticals market was \$46.7 billion in 2002, and is expected to reach \$74.7 billion in 2007 (Figure 36).

**Figure 36: U.S. Nutraceutical Market**



Source: Rural Industries Research and Development Corporation, Business Communications Company, Informa Economics (forecast).

There are more than 85 U.S. supplement manufacturers. The top five manufacturers and sales in 2000 are as follows.

- Royal Numico \$939 million
- American Home Products \$480 million
- Leiner Health Products \$463 million
- Unilever (Slim Fast) \$385 million
- Pharmavite \$360 million

A huge diversity of herbal products, including teas, exists for self-medication, covering a wide range of complaints. Following are some of the best selling plant species used in herbal preparations.

- Garlic (*Allium sativum*) is primarily used to combat infections, reduce cholesterol levels, and treat circulatory disorders, including high blood pressure and high blood sugar levels. Garlic sales accounted for 16 - 18 percent of the U.S. herbal market during 1996 - 99. Approximately 1,000 tons of fresh garlic, sourced exclusively from China, is required annually for the production of Kwai® N, Lichtwer Pharma AG.
- Ginkgo (*Ginkgo biloba*) is taken to improve microcirculation, especially to the brain and central nervous system, with the aim of improving mental function and concentration, especially in cases of dementia and Alzheimer's disease. Ginkgo is the most popular herbal remedy, and accounts for 19 - 21 percent of herbal sales.

- Ginseng (*Panax ginseng*) is most commonly taken as a general tonic, an adaptive (helping the body to combat stress, fatigue, and cold), and stimulant. Ginseng is frequently among the top three most commonly purchased herbs, accounting for 12 - 20 percent of the herbal market between 1996 and 1999.
- Spirulina (*Spirulina platensis*) is a microalga, containing high concentrations of gamma-linolenic acid, vitamins B12 and E, provitamin A (beta-carotene), and protein. Claims made for Spirulina include immunostimulant activity, stabilization of blood sugar, anti-allergen, appetite suppressant, and cancer preventative.
- German Chamomile (*Chamomilla recutita*, syn. *Matricaria recutita*) and Roman Chamomile (*Chamaemelum nobile*, syn. *Anthemis nobilis*) are used interchangeably to treat digestive problems, combat tension, and reduce irritation (such as sore skin and eczema).
- A European native, St. John's Wort (*Hypericum perforatum*), is among the most extensively studied plants in herbal medicine. It is mainly taken to counter depression, and has been used as a natural alternative to synthetic anxiolytics, such as Prozac. This herb accounted for 11 - 14 percent of herbal sales in Europe and the United States between 1996 and 1999.
- Echinacea (mainly *Echinacea purpurea*, but also *E. angustifolia* and *E. pallida*) is widely used as an immunomodulator, for treatment and prevention of upper respiratory tract infections.
- The primary claim made for saw palmetto (*Serenoa repens*) is for the treatment of benign prostatic hyperplasia (BPH), a condition likely to increase in incidence with the aging of the population. Sales range from 4 to 6 percent of the herbal market.

Lycopene, found mainly in tomatoes (and also red peppers and red cabbage), is one of the major carotenoids in Western diets. It may become a major player in the nutraceutical market if studies continue to show it to be anticarcinogenic. This benefit is thought to arise from the antioxidant properties of the carotenoid, which decrease oxidative damage to DNA. Currently, the only supplier of lycopene to the nutraceutical market is the Israeli company LycoRed Natural Products.

Another emerging antioxidant is resveratrol (3,5,4-trihydroxystilbene), which is found in green vegetables, citrus fruit, and particularly in red wines. Resveratrol may be responsible for the health benefits attributed to drinking red wine: antioxidant, anticarcinogenic, and anti-inflammatory.

Materials like distillers' dried grains (DDG), an ethanol byproduct, can yield such high-value extracts as:

- Xylose: a low-calorie sweetener and fluoride replacement.

- L-arabinose: used in a Hepatitis-B treatment and as a sucrose inhibitor for diabetic and weight loss applications.
- Galactose: plant based low-calorie sweetener and an energy additive in sport drinks and bars.

## **G. Future Projections for Biobased Chemicals and Materials**

The chemical process industry uses 7.7 percent of all energy resources, with half of that used as chemical feedstocks. Even with the relatively minor use of fossil fuels in the chemical industry, the sustainability of producing and transforming hydrocarbon into useful feedstocks will be challenging. Current biobased feedstocks can meet the existing needs of the chemicals and materials industry; however, the long-term economic sustainability of a bioeconomy will require the use of nonstarch feedstocks such as plant oils and cellulose.

The integration of biofuels production with the production of biochemicals will be needed to provide economies of scale for feedstock development, refining, and production of biochemicals (as in the petrochemical industry). State-of-the-art technologies are being deployed to process biomass into useful fermentation and biocatalytic feedstocks, and fermentation systems are available to produce biochemicals and materials.

The chemical industry will grow to over \$2 trillion a year when biobased products replace existing products and provide new revenue sources amounting to more than \$500 billion a year. Significant growth in biobased chemicals and materials will come from new platform chemicals like succinic acid, as well as new fine chemicals and specialty chemicals. Over half of the chemicals in these categories will come from renewable feedstocks.

Over the past 30 years, the chemical industry has enjoyed a 12.5 percent compound annual growth rate. During this time period, the industry has gone through two historical peaks and three historical lows, and is currently emerging from a 5 year period of low profitability. To improve chemical industry performance, company CEOs identified the following drivers of change for the industry over the next 20 years:

- Feedstock prices.
- Innovation.
- Asia.
- Service offerings.

Increasing hydrocarbon feedstock prices are driving companies to look to alternative strategies in pricing, purchasing, and research and development. Dependence on oil producing countries and consumer concerns over the environment, waste management, and global warming are further pressuring the chemical industry. Many industry leaders see biotechnology as a potential solution to escalating feedstock prices and as a source of innovation.

Market expansion and manufacturing in China and India will continue to be a high priority for chemical companies. Vast agricultural resources in both countries make them suitable sites for biobased chemicals and materials production (and markets). Chemical companies will likely look to establishing areas where margins can be grown, especially in the fine chemical sector.

Biotechnology may transform the chemicals and materials industry over the next 20 years. Biobased feedstocks have grown less costly over the last two decades (on an inflation-adjusted basis). While the costs of biobased feedstocks such as corn starch, soybean oil, and cellulose will likely rise, they should maintain their advantage over petroleum and natural gas feedstocks. The economic sustainability of biobased feedstocks will be driven by the production and use of plant oils and cellulose at progressively lower cost. The production costs of source agricultural crops will likely grow modestly while the costs to process plant oils and cellulose into feedstocks will diminish (as in the petrochemical industry during the past 50 years).

Biotechnology offers the potential for new and innovative products and processes. For example, acrylamide monomer can be made via copper catalysis, but Mitsubishi Rayon was able to use an enzymatic process to reduce the costs of production and waste products. Energy consumption and carbon dioxide emissions were also reduced by 80 percent. In another example, Cargill developed an efficient fermentation//polymerization process to derive polylactic acid (PLA), the first new polymer in 40 years with wide application in textiles and disposable materials like cups, plates, and plasticware.

Biobased building blocks or platform chemicals are critical if biobased products are to penetrate the market for polymers, chiral drugs, resins, fine chemicals, high performance chemicals, and commodity chemicals. For example, biobased polyols provide inroads into polyurethane; succinic acid into acrylonitrile-butadiene-styrene resins, nylon 6,6, and unsaturated polyester resins; and 3-hydroxypropionic acid into acrylonitrile and acrylamide.

In 2003, DuPont reported its intent to generate up to 25 percent of its 2010 revenues from biomaterials, which could exceed \$7.5 million. The company also stated that it expects that its second generation high performance polymer, Sorona, will be produced directly from cellulosic biomass. Cargill, through its wholly owned subsidiary, NatureWorks, has been producing polylactic acid since 2002.

Futurists project that the fusion of biotechnology and nanotechnology will produce composites tailored at the molecular or atomic level. Smart materials ranging from diagnostics and repair systems to multi-level syntheses producing cocktails of drugs, flavors, or other functional properties are well within the range of technological possibilities. On a more immediate front is the pending emergence of the cosmeceuticals industry (combination of cosmetics and pharmaceuticals) and a shift in the foods industry to functional foods (combination of nutritional sciences and functional genomics). Anti-aging creams and energy drinks are already on the market.

This portion of the report addresses the potential for biobased chemicals and materials to replace traditional petrochemicals and to create new molecules with new functionalities. Industrial biotechnology is expected to contribute over 70 percent of chemical industry growth over the next 20 years, primarily in the specialty and fine chemicals markets.

Factors considered for assessing the potential impact of biobased chemicals on the economy from 2006 to 2025 include:

- Technological barriers.
- Feedstock availability and cost.
- Petrochemicals availability and cost.
- Government policy.
- Regulatory climate.
- Public acceptance.
- Freedom to operate.
- Industrialization of China and India.

## 1. Segment Analysis

Biobased products are perhaps best positioned to create value in the production of raw materials (such as transitioning from oil to corn or corn stover), reduction of process costs (reduced process steps, increased yield), reduction of risk (reliable and stable supply), value-added processes (shorter time to market, “natural” label), and new businesses (routes to compounds not accessible through classical chemistry). With the exception of commodity chemicals, a significant portion of value-creation potential in biotechnology will be driven by increases in revenue.

Table 39 shows the projected world market penetration of biobased chemicals by 2010 and 2025. The projected growth of different chemical sectors from 2005 to 2025 is shown in Table 40. The global market for biobased chemicals and plastics is projected to reach \$160 to \$280 billion by 2010 (Bachmann, 2003). By 2025, biobased chemicals likely will contribute over \$500 billion annually to the chemical and materials industry.

**Table 39: World Biobased Market Penetration 2010 - 2025**

<b>Chemical sector</b>	<b>2010</b>	<b>2025</b>
Commodity chemicals	1-2 percent	6-10 percent
Specialty chemicals	20-25 percent	45-50 percent
Fine chemicals	20-25 percent	45-50 percent
Polymers	5-10 percent	10-20 percent

Sources: Bachmann, 2003; Cygnus Business Consulting & Research; Informa Economics et al., Biobased Multi-Client Study, March 2006.



**Table 40: Projected Value of World Chemical Production: 2005, 2010, and 2025 \***  
(in billion \$US)

Chemical sector	2005		2010		2025	
	Total	Biobased	Total	Biobased	Total	Biobased
Commodity	475	0.9	550	5-11	857	50-86
Specialty	375	5	435	87-110	679	300-340
Fine	100	15	125	25-32	195	88-98
Polymer	250	0.3	290	15-30	452	45-90
<b>Total</b>	<b>1200</b>	<b>21.2</b>	<b>1400</b>	<b>132-183</b>	<b>2183</b>	<b>483-614</b>

\* The value of pharmaceuticals is excluded.

Sources: Bachmann, 2005; Cygnus Business Consulting & Research; Informa Economics et al., Biobased Multi-Client Study, March 2006.

The impact of rising petroleum prices on the bioeconomy cannot be overstated. Historically, petrochemical processing costs exceeded feedstock costs. Processing efficiencies have increased and costs have decreased dramatically, but are reaching a point of limited returns. The cost of petroleum based materials will continue to increase as supplies tighten, resulting in significant pressure on profitability.

Processing is the dominant cost of biomaterials today. Biobased raw materials should increase modestly in cost, based on corn starch as the primary feedstock. Over the long term, biobased raw materials may grow even cheaper as cellulosic and/or plant oil feedstocks come on line. Biotechnology will be the dominant driver in reducing processing costs during the next decade contingent on new technologies that depart from the petroleum based chemical industry.

New biobased chemicals and materials will most likely be concentrated in the fine chemicals sector. This underlies the argument that biotechnology's contribution to value in this segment will be driven by new revenue growth as opposed to cost savings for the processing of existing products (Table 41).

**Table 41: Estimated Biotechnology Impact on World Costs and Revenues**

Chemical segment	Cost reduction (process improvements)	Revenue or new value creation
Commodity Chemicals	100 percent	0 percent
Specialty Chemicals	75 percent	25 percent
Fine Chemicals	35 percent	65 percent
Polymers	40 percent	60 percent

Sources: Bachmann, 2003; Informa Economics et al., Biobased Multi-client Study, March 2006.

The global chemical market, excluding pharmaceuticals, is approximately \$1.2 trillion (Table 40). Commodity chemicals and polymers contribute 60 percent of the total, followed by specialty (30 percent), and fine chemicals (10 percent). Commodity

chemicals are manufactured in extremely large volume, typically more than 3 million tons a year. Specialty chemicals are for special uses or intermediates and are also produced in large volumes. Fine chemicals are manufactured in smaller batches and intended mainly for pharmaceutical intermediates, enzymes, flavors/fragrances, and polymers.

The chemical industry is expected to grow 3 to 6 percent through 2025. Biobased chemicals are expected to grow from 2 percent of the total chemical market to at least 10 percent by 2010 and 22 percent by 2025 (Table 40).

Commodity chemicals alone represent a \$475 billion market; the biobased share is projected to increase from 0.2 percent to 6 - 10 percent by 2025. This growth will be driven by the replacement of petrochemical platform or building block chemicals with biobased alternatives, which will grow more competitive if petroleum and natural gas prices continue to rise. Environmental benefits of biobased chemicals will also favor adoption. Biobased commodity chemicals, due to their large volumes, will have the greatest positive impact on the environment among all biobased chemicals and materials.

Specialty chemicals represent a \$375 billion global market. Specific sectors of this market are expected to show noteworthy growth over the next few years, including pharmaceutical intermediates (above 5 percent), dyes and pigments (10 - 15 percent), specialty polymers (5 - 6 percent), thermoplastics (6 percent), and specialty coatings (6 - 8 percent) (SRI Consulting, 2005). The biobased share of the market is expected to increase from 1 percent to 45 - 50 percent by 2025.

The market for fine chemicals was an estimated \$100 billion in 2005 (Bachmann, 2005), and is expected to reach \$195 billion by 2025. The biobased share is projected to grow from the current 15 percent to as much as 50 percent by 2025.

Substitution of biobased resins for petrochemical products will be determined by the cost of oil and energy and the ability of biobased resins to compete in performance. In many cases, biobased components in polymers (without the complete substitution of all petroleum based carbon with biobased carbon) such as in DuPont's Sorona polymer, is the more likely scenario. The combination of bio- and petrobased chemicals is often essential for product performance. Similarly, one can hypothesize that bionylon 6,6 could be made with biobased adipic acid, while the hexamethylene diamine could be sourced from petrochemicals. New polymers like PLA, solely derived from biobased lactic acid, should make significant inroads into the polymers segment.

The global polymer market is estimated at \$250 billion and is predicted to exceed \$450 billion by 2025; the biobased share is expected to increase from the current 0.1 percent to 10 - 20 percent by 2025. The maximum substitution potential has been estimated to be about 33 percent of total polymer production, although diminishing supplies and higher prices for petroleum feedstocks could elevate that share.

## 2. Platform Chemicals

In 2004, a USDOE report, *Top Value-Added Chemicals from Biomass*, identified 12 chemicals or chemical classes that could be produced from sugars by either chemical or biological methods. These are considered building blocks or platform chemicals from which many value-added chemicals may be derived (Table 42). The USDOE (2004) is focusing its funding toward development of technology for the conversion of biomass to these biobased chemicals/products.

In this study we use these chemicals as examples of existing and emerging technologies that could have a significant impact on biobased chemical production. The potential of each chemical to become a platform chemical (i.e., high volume, with potential for the production of multiple derivatives), was assessed with the following parameters:

- Strategic fit.
- Market/Customer.
- Technical feasibility and risks.
- Competitive advantage.
- Legal/Regulatory compliance.
- Critical success factors.

**Table 42: Top Value-Added Chemicals from Biomass**

Chemicals	Carbon number	Base technology stage	Platform chemical stage
1,4 diacids succinic, fumaric and malic	4	Commercial	Development
3 hydroxypropionic acid	3	Development	Development
levulinic acid	5	Commercial	Development
glutamic acid/MSG	5	Commercial	Detailed investigation
sorbitol	6	Commercial	Detailed investigation
xylitol/arabinol	5	Commercial	Detailed investigation
2,5 furan dicarboxylic acid	6	Preliminary investigation	Preliminary investigation
aspartic acid	4	Detailed investigation	Preliminary investigation
glucaric acid	6	Preliminary investigation	Preliminary investigation
itaconic acid	5	Commercial	Preliminary investigation
3-hydroxybutyrolactone	4	Commercial	Preliminary investigation
glycerol	3	Commercial	Preliminary investigation

Base technology stage = current technology status; commercial production is low volume, specialty or fine chemicals.

Platform chemical stage = Status with regard to production as a high volume, commodity or platform chemical with potential for further production of multiple products.

Source: U.S. Department of Energy, 2004.

Table 42 shows the stage of commercial development for these chemicals as they exist currently (as specialty or fine chemicals), and, or, the potential they hold as platform chemicals. At the base technology stage these chemicals are produced in low volumes

for specialty and fine chemicals. At the platform chemical stage they hold potential for high volume production.

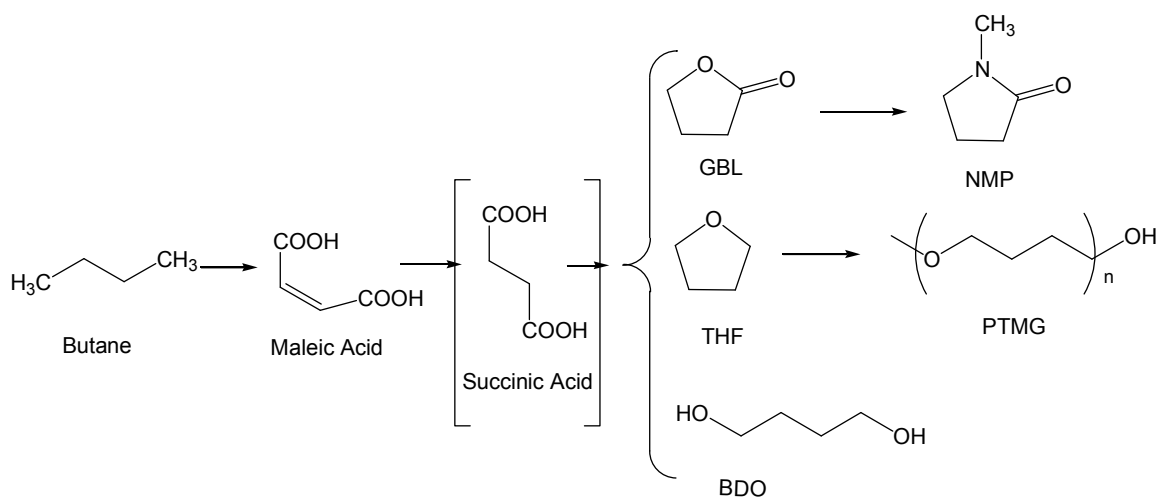
In order to reach commercial development, new products typically pass through five stages:

- **Preliminary investigation.** This step involves a preliminary technical and market assessment of the proposed project.
- **Detailed investigation.** Work must show the unique capabilities of the technology and demonstrate unproven steps in a laboratory setting. A business case should be developed that fully illustrates the market and route to commercialization.
- **Development.** Progress includes prototype demonstration of unit operations, demonstration of simulated integration in real processing conditions, and development of engineering scale-up data.
- **Testing and Validation.** Demonstration scale testing of the product/process begins. The information should be sufficient to support a decision on investment in commercial-scale production.
- **Commercial.** Full production and market launch.

#### a) 1,4 Diacids (Succinic, Fumaric and Malic)

Succinic, fumaric, and malic acids are 4-carbon dicarboxylic acids that are widely found in nature and are key metabolic intermediates (Krebs Cycle) in plants, animals, and bacteria. Succinic acid is the more reduced of the three acids and will be used as the primary example in the following discussion. When chemically synthesized, succinic acid is currently used as a flavoring agent and a pharmaceutical additive. The market for these purposes is a “niche market” (20,000 tons in 2004). Figure 37 illustrates the production of petrochemically derived succinic acid from butane.

Succinic acid can also be produced by fermentation of glucose and other sugars. Figure 25 has already shown a simplified illustration of the bioroute to succinic acid involving phosphoenolpyruvate (PEP), including byproducts (ethanol, lactic acid, and potentially pyruvic acid and fumaric acid).

**Figure 37: Petrochemical Route to Succinic Acid and Succinic Derivatives**

Source: Michigan Biotechnology Institute

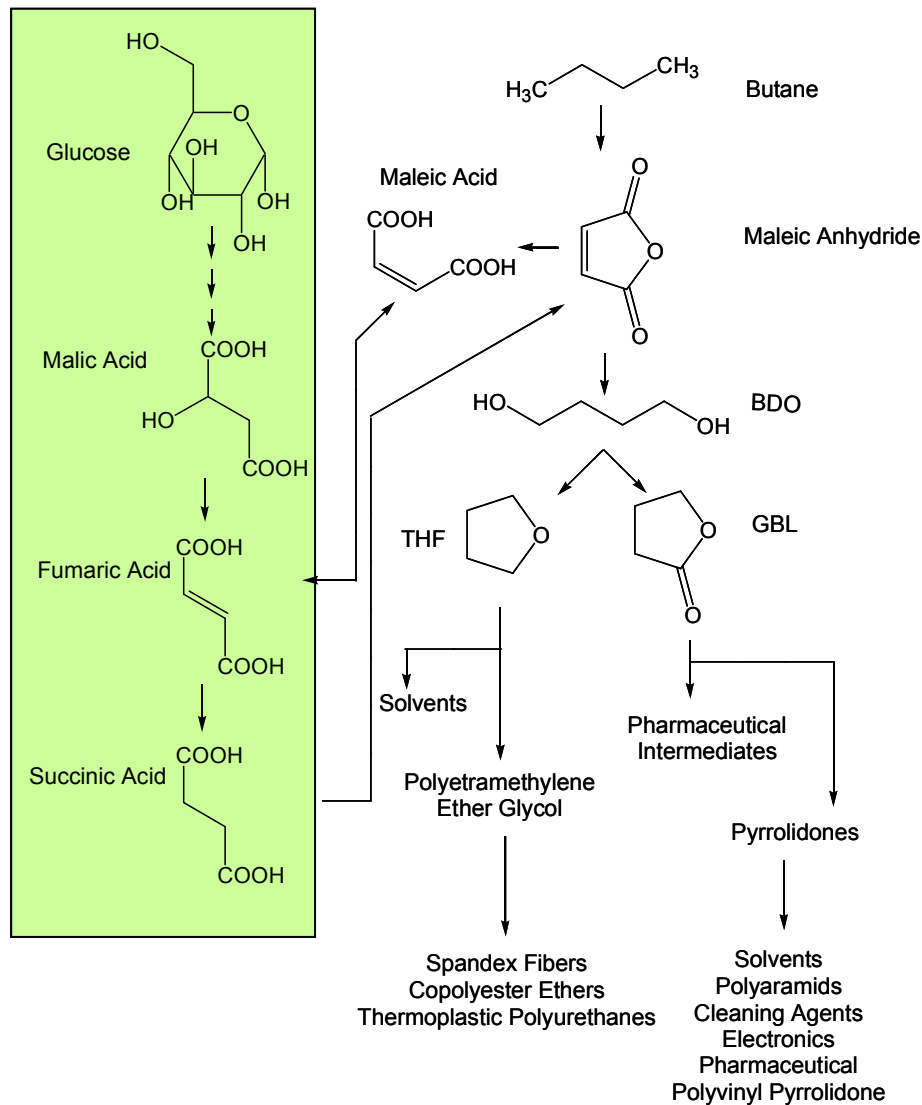
### Potential Derivatives and Products

Figure 38 shows the potential use of these acids as platform chemicals for the production of additional chemicals and products. A chemical industry strategy can be developed using succinic acid for all four carbon molecules and repeating polymer products. Current worldwide value for the C4 platform is estimated to exceed \$5 billion annually, largely driven by the expanded use of Spandex fibers and polybutylene terephthalate.

The primary targets for biobased succinic acid are as a direct replacement for feedstocks used to produce 1,4 butanediol (BDO). BDO is currently produced from acetylene (using the Reppe process), maleic acid (using the BP/Lurgi/Geminox process), maleic anhydride (using the Kvaerner [Davy] process), butadiene/acetic acid, allyl alcohols, or propylene oxide.

The prices of petrochemical feedstocks, and consequently BDO, have risen sharply over the past few years. BDO prices increased by more than 50 percent from 2004 to 2005.

BDO is the single largest segment of the C4 platform and is primarily used in the high-quality plastic materials, but it is also processed to yield tetrahydrofuran (THF) and gamma-butyrolactone (GBL), as well as three types of pyrrolidones. These intermediates are used widely as solvents, additives and bases from which other end-products (such as Spandex fibers) are made.

**Figure 38: Four Carbon 1, 4-diacids as Chemical Platforms**

Note: Green shading highlights biobased steps in succinic acid production.

Source: Michigan Biotechnology Institute.

The market for maleic anhydride (MA), maleic acid, and BDO and related intermediates is growing at above-GDP rates. U.S. demand for BDO grew from 850 million pounds in 2003 to 900 million pounds in 2004 (*Chemical Market Reporter*). Demand is projected to grow as much as 6 percent a year. Certain product segments (notably polymers) are forecast at higher growth levels, while THF and GBL are expected to grow more slowly (less than 2.5 percent).

Worldwide production capacity for MA was about 1.65 million tons in 2004 (*Chemical Market Reporter*), with 18 percent of the total (290,000 tons) from North America. Several companies are planning significant expansion of production during the next few years. About half of MA production is used for unsaturated polyester resins, 14 - 20

percent for BDO, and 7 percent for THF. Worldwide MA demand is anticipated to grow 7 percent for the next few years and reach 2.2 million tons in 2008. Due to the enormity of this market, the ultimate target for succinic acid is the replacement of MA, which would create over \$4 billion in value.

### Technical Barriers

The issue of productivity is critical to production of commodities and requires more than the right metabolic pathways. Very few microorganisms are known to produce succinic acid in sufficiently high concentrations to permit economical production processes. A review of the patent literature reveals three well-studied organisms for which claims of useful succinic acid production have been allowed; *E. coli* ATCC 202021 (Donnelly et al.), *Anaerobiospirillum succiniciproducens* for which two strains are patented, ATCC 29305 (Guettler and Jain) and ATCC 53488 (Datta), and *Actinobacillus succinogenes* ATCC 55618 (Guettler et al.). Of this list of organisms, the *A. succinogenes* organism is unique in its ability to use both hexoses (glucose) and pentoses (xylose and arabinose) simultaneously, and is thus well-suited for the biobased production of succinic acid from lignocellulosic feedstock. Production of succinic acid by fermentation for commodity use is in the development stage. Two groups - MBI International and Diversified Natural Products - are commercializing biobased succinic acid technology. Both companies expect to produce succinic acid at commercial levels in 2 - 3 years. The impact of succinic acid as a C4 platform chemical could easily exceed \$1 billion a year by 2015.

### **b) 3-Hydroxypropionic Acid (3-HPA)**

Low-cost fermentations must be developed for 3-HPA to have utility as a commodity platform chemical. There is no viable petrochemical production route to 3-hydroxypropionic acid, although several of the derivative chemicals are produced from petroleum feedstocks (Energetics, Inc., 2003). Cargill teamed with the Pacific Northwest National Laboratory and Codexis, Inc., to develop a process for production of 3-hydroxypropionic acid from glucose (Informa Economics et al., Biobased Multi-client Study, March 2006).

### Potential Derivatives and Products

3-hydroxypropionic acid is a platform chemical for several commercially valuable chemicals, including 1,3-propanediol, malonic acid, acrylic acid and acrylamide (Figure 39). These are high-volume chemicals used to manufacture polymers, resins, plastic packaging, fibers, and adhesives. The market for acrylic acid derivatives is an estimated \$950 million and the market for acrylamide derivatives is an estimated \$370 million (Informa Economics et al., Biobased Multi-client Study, March 2006).

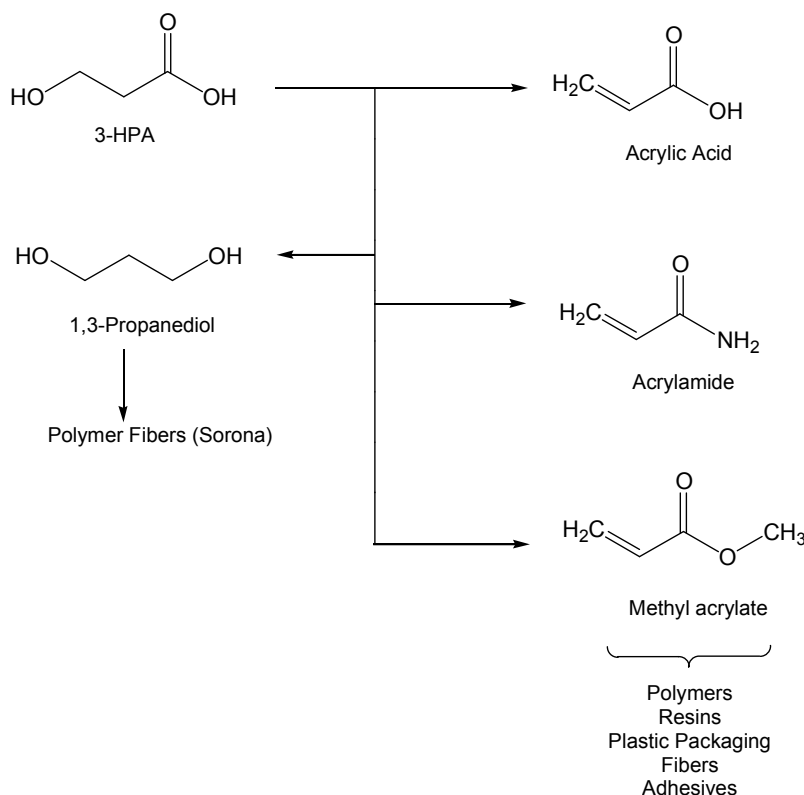
Cargill aims, through the fermentation of carbohydrates to make 3-HPA, to generate important chemicals such as acrylic acid, 1,3-propanediol, and plastics. In order to develop an effective fermentation organism and process for 3-HPA productions, Cargill will work to optimize organisms for efficient industrial-scale production and to develop a viable catalyst for downstream conversion of 3-HPA to valuable products. Eventually, Cargill hopes to finalize a process design that will be suitable for pilot testing and industrial production. Since the project's beginning, 33 percent of the \$6 million

requested for the project has been obligated. Major accomplishments to date include the selection of a suitable strand; the identification of reactor configuration, catalyst, and operating conditions; the successful development of the enzyme assay and demonstration of enzyme production; and the improvement of the key enzyme in the 3-HPA pathway. 3-HPA is estimated to be 2 to 3 years away from a pilot demonstration and 7 to 8 years from large-scale commercial launch. The impact of 3-HPA at maturity is projected to be greater than \$1 billion a year in 2025.

### Technical Barriers

The fermentation route to 3-HPA is being developed by Cargill. It remains to be seen if productivity is sufficient and if production costs are low enough to enable the production of the described products. Production of 3-HPA and its derivatives will require the development of new catalysts.

**Figure 39: 3-Hydroxypropionic Acid as a Platform Chemical**



Source: Michigan Biotechnology Institute.

### **c) Levulinic Acid**

Treatment of hexose sugars or lignocellulosics with acid is used to produce levulinic acid (LA). It can also be produced from pentose sugars (C5) by using a reduction step following acid treatment. Levulinic acid can be used as an acidulant in foods and

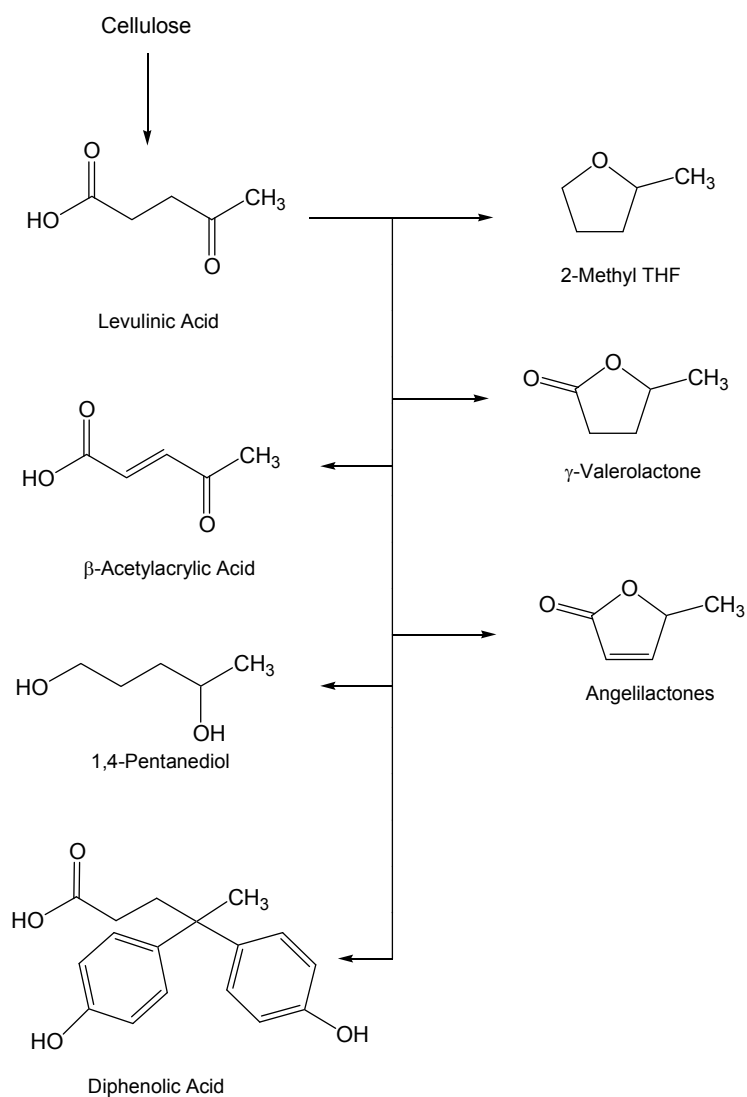


beverages. It is also used as an intermediate to manufacture synthetic fibers, pharmaceuticals, pesticides, and plastics. Levulinic acid and its esters are used as plasticizers and solvents in polymers, textiles, and coatings.

### Potential Derivatives and Products

Potential products from LA include diphenolic acid,  $\beta$ -acetylacrylic acid, 1,4-pentanediol, angelilactones,  $\gamma$ -valerolactone and 2-methyl-THF (Figure 40). Target markets include the production of acrylic and polycarbonate polymers.

**Figure 40: Levulinic Acid as a Platform Chemical**



Source: Michigan Biotechnology Institute.

### Technical Barriers

The current process for production of levulinic acid from low-grade cellulose results in only a 70 percent yield. Improving the yield is critical to reducing the production cost in a commodity market. Other technical barriers include technology for selective oxidation of LA to succinic and acrylic acid. The development of selective reduction technologies could enable the production of lactones and methyltetrahydrofuran for fuels. The development of diphenolic acid as a replacement for biosphenol is of industrial importance. The development of levulinic acid as a commodity chemical is in the development stage. A pilot plant (1 ton/day) was constructed in South Glens Falls, NY, to provide feedstock for methyltetrahydrofuran (MTHF) and delta-aminolevulinic acid (DALA).

### **d) Glutamic Acid**

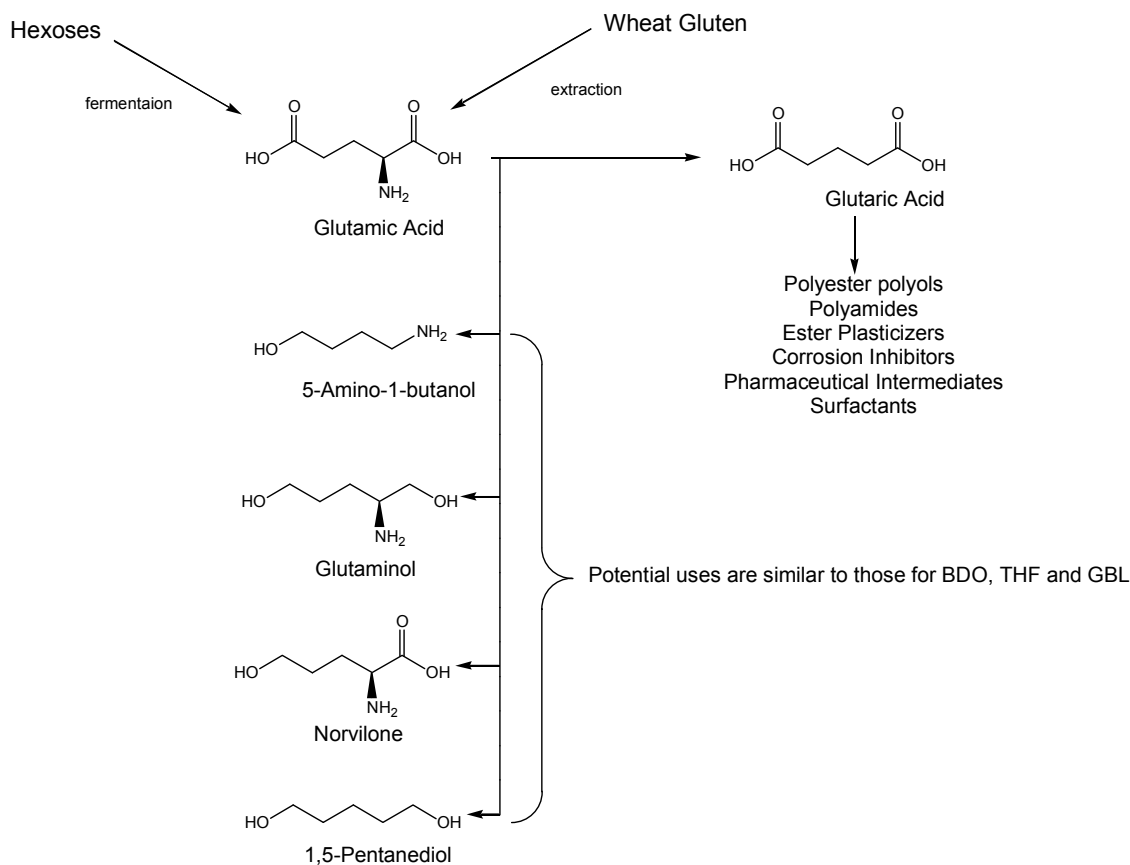
Glutamic acid is produced primarily by fermentation using the microorganism *Corynebacterium* (there are patents for processes using *Brevibacterium* also). It can also be produced directly from wheat gluten. Wheat gluten has the highest concentration of L-glutamic acid among industrial raw materials. The vast majority of glutamic acid is used to produce monosodium glutamate (MSG), a food flavoring agent. Glutamic acid is also used in pharmaceutical applications, such as ophthalmic preparations and nasal solutions, as well as industrial applications such as surfactants and fabric coatings. The worldwide demand for monosodium glutamate (MSG) is 1.1 million tons per year. Primary producers are Ajinomoto, Kyowa Hakko, and CJ Corp, although Chinese manufacturers are now entering the market as well (Informa Economics et al., Biobased Multi-client Study, March 2006).

### Potential Derivatives and Products

If production costs can be lowered, glutamic acid has the potential to be used as a major building block for a variety of derivatives including glutaminol, 5-amino-1-butanol, 1,5-pentanediol, and norvoline (Figure 41). This could lead to the production of analogs to BDO, THF, and GBL that would affect similar products and markets (see Succinic Acid).

### Technical Barriers

Technical hurdles in the commodity production of glutamic acid include increased productivity in the fermentation and reduction in fermentation media costs. Selective reductions in aqueous media need to be developed for the conversion of glutamic acid to BDO, THF, and GBL. New catalyst systems that eliminate side reactions, while not being inhibited by impurities in the fermentation, are also essential. While glutamic acid is produced commercially, development of technology suitable for commodity production is in a detailed investigation stage. It also likely that biobased succinic acid will compete directly with this potential platform chemical.

**Figure 41: Glutamic Acid as a Platform Chemical**

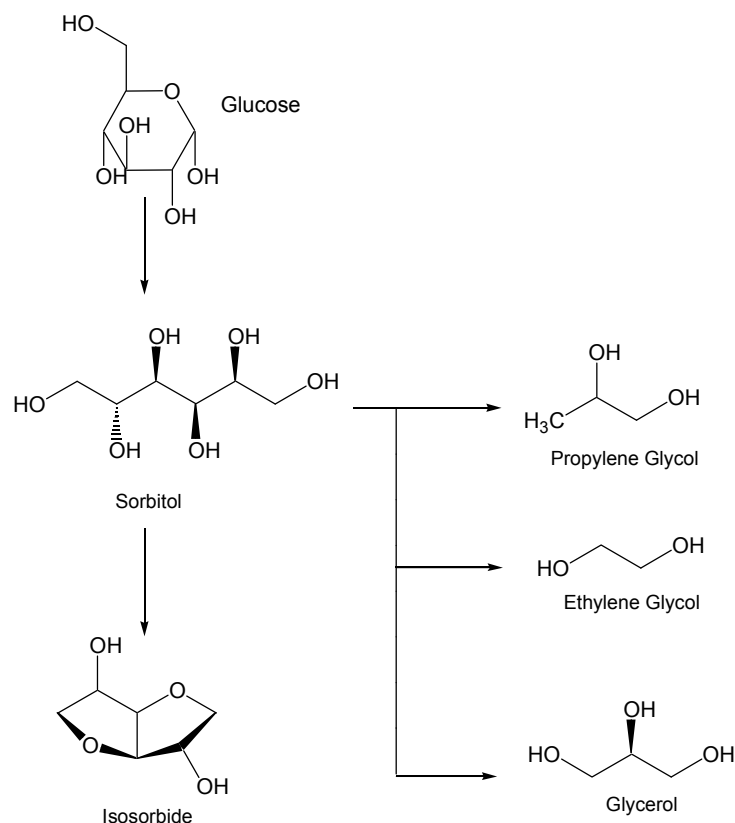
Source: Michigan Biotechnology Institute.

### e) Sorbitol

Sorbitol is produced commercially using Raney nickel as the catalyst in the hydrogenation of glucose in a batch process. The United States, Western Europe, and Japan consume 690,000 metric tons a year, with a value of \$420 - \$520 million (SRI Consulting, 2005a). Compound annual growth has been 1 - 2 percent since 1997, and is expected to be 1 percent through 2010. Current uses are primarily in the food industry. Production of sorbitol as a commodity building block would require the use of a continuous process. This has been demonstrated with 99 percent yields.

#### Potential Derivatives and Products

Potential derivatives include isosorbide, glycerol, ethylene glycol, and propylene glycol (Figure 42). Sorbitol could also be used as a direct copolymer with other glycols. Isosorbide has utility in producing polymers such as polyethylene isorbide terephthalates that would have properties similar to PET.

**Figure 42: Sorbitol as a Platform Chemical**

Source: Michigan Biotechnology Institute.

### Technical Barriers

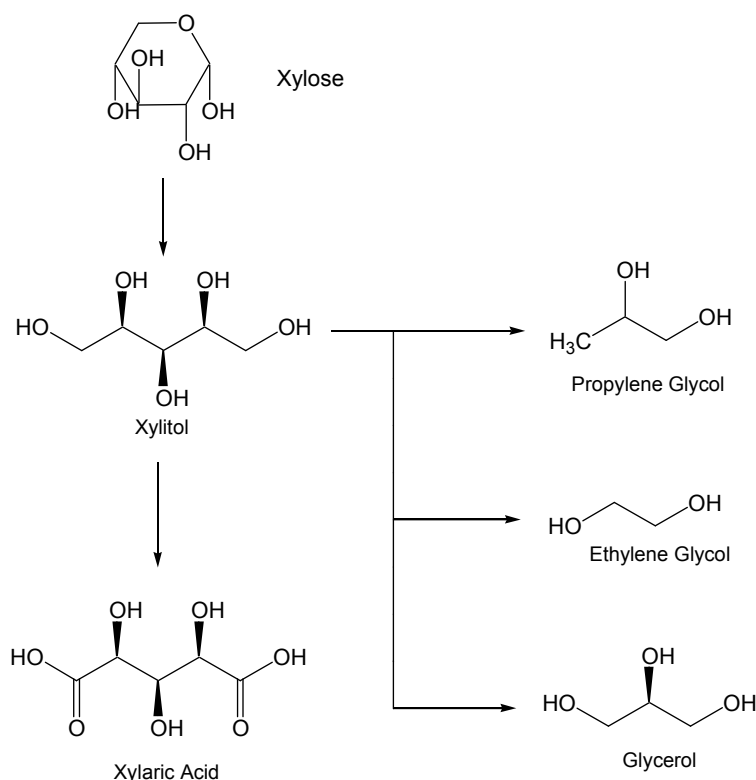
Production of sorbitol is well developed. Development of a continuous process from glucose has been demonstrated with a ruthenium-on-carbon catalyst and could offer reductions in production costs. Technologies for dehydration catalysts for the production of isosorbide and the hydrogenolysis of sorbitol to glycols to improve yields need further development. Efforts in this area are in the detailed investigation stage.

### **f) Xylitol/Arabinitol**

Xylitol is currently used as a non-nutritive sweetener and is produced commercially with high yield. It is produced by chemical reduction of xylose or hemicellulose and/or by microbial fermentation.

### Potential Derivatives and Products

Potential derivatives include xylaric acid, propylene glycol, ethylene glycol, and glycerol (Figure 43). Market potential is similar to that for sorbitol. The primary opportunity is probably the copolymerization with other glycols for production of unsaturated polyester resins.

**Figure 43: Xylitol as a Platform Chemical**

Source: Michigan Biotechnology Institute.

### Technical Barriers

There are no significant technical barriers to using xylitol as a building block other than the demonstration of low-cost continuous production. Biotechnology may soon enable complete production of sugar polyols through the use of microbes and microbial enzymes in an effort to eliminate chemical hydrogenation. ZuChem is developing fermentation pathways to the production of mannitol and xylitol. Efforts to produce xylitol at commodity scale are in the detailed investigation stage.

### **g) 2,5-Furan Dicarboxylic Acid (FDCA)**

2,5-furan dicarboxylic acid (FDCA) is a furan that can be synthesized from the oxidation of 2,5-disubstituted furans or the catalytic conversion of various furan derivatives. A biobased route is the oxidative dehydration of glucose by using either oxygen or electrochemistry (Lewkowski). FDCA can also be produced by the oxidation of 5-hydroxymethylfurfural, an intermediate in the production of levulinic acid from hexose sugars.

### Potential Derivatives and Products

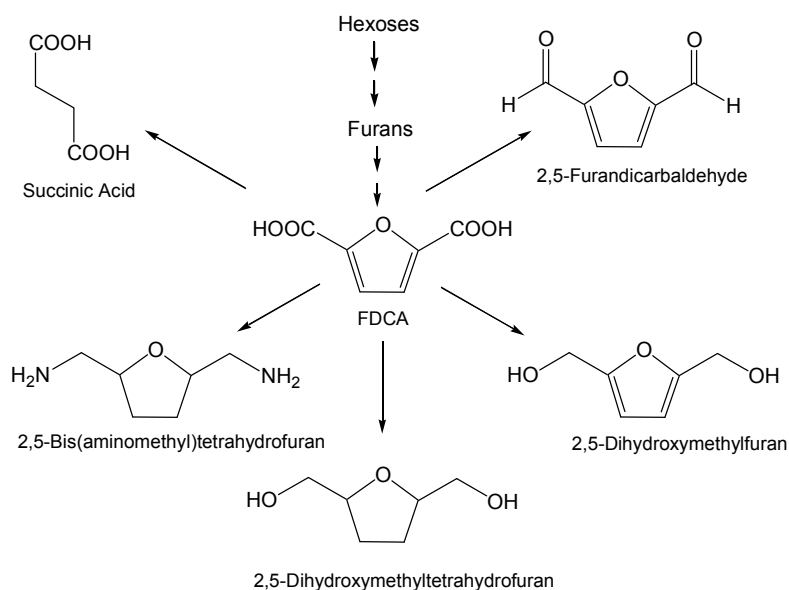
Figure 44 shows the potential chemicals that may be derived from FDCA. FDCA is potentially a replacement for terephthalic acid, which is used in the production of polyesters such as polyethylene terephthalate (PET) and polybutyleneterephthalate (PBT). The annual market size for PET and PBT is 4 billion pounds and 1 billion pounds, respectively. The U.S. market for PET resins is approaching 7 billion pounds. Current compound annual growth for both PET and PBT resins is an estimated 7 percent (Plastics Technology). Both PET and PBT are used extensively in the packaging industry.

The reaction of FDCA with diamines or the conversion of FDCA to 2,5-bis(aminomethyl)tetrahydrofuran could be used to produce new nylons. The market for these types of products is estimated at 9 billion pounds a year, with prices ranging from \$0.85 to \$2.20 pound.

### Technical Barriers

The primary technical barrier to production of FDCA is the development of effective dehydration technology for sugars, a process not well understood, and the appropriate oxidation technology that is compatible with the dehydration process. For use in polymers, appropriate esterification technology must be developed.

**Figure 44: 2,5-Furandicarboxylic Acid as a Platform Chemical**



Source: Michigan Biotechnology Institute.

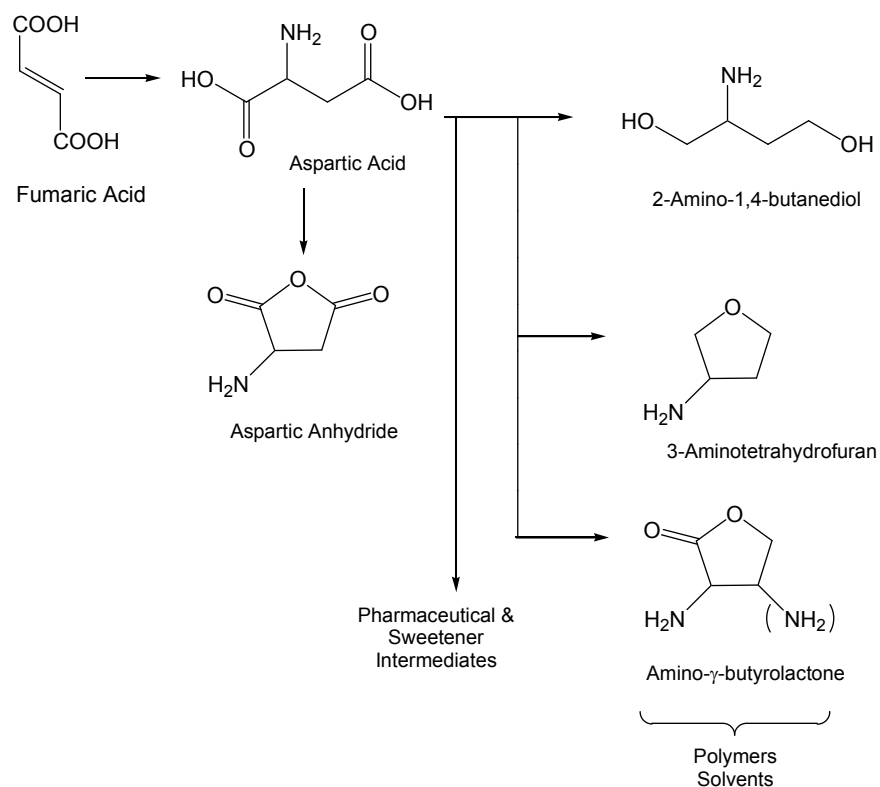
## h) Aspartic Acid

The four-carbon amino acid, aspartic acid, is used for the production of the artificial sweetener aspartame. L-aspartic acid can be produced by (1) enzymatic conversion; (2) protein extraction; (3) chemical synthesis; or (4) fermentation. It is currently produced by the reaction of fumaric acid with ammonia catalyzed by an aspartase enzyme.

### Potential Derivatives and Products

Other chemicals that may be produced from aspartic acid include aspartic anhydride, 2-amino-1,4-butanediol, 3-aminotetrahydrofuran, and amino- $\gamma$ -butyrolactone (Figure 45). The amino analogs of four carbon dicarboxylic acids have application in the polymer and solvent industries. Applications for aspartic acid polymers include detergents, absorbent polymers, corrosion inhibitors, and water treatment systems. Aspartic acid can be made by chemical synthesis, fermentation, protein extraction, and enzymatic conversion (the primary method). The market for L-aspartic acid is expected to grow 2 to 3 percent annually for the next few years.

**Figure 45: Aspartic Acid as a Platform Chemical**



Source: Michigan Biotechnology Institute.

### Technical Barriers

Reducing the cost of fumaric acid would significantly reduce the cost of enzymatic production and could build on the existing production infrastructure. A direct fermentation route to aspartic acid from sugar could be advantageous as well. High productivity and yields will be necessary to enable efficient and inexpensive production. The enzymatic production results in high concentrations of aspartic acid that can be separated by crystallization. New separation and purification strategies may be necessary for fermentation production of aspartic acid. Genetic engineering and/or traditional strain improvement technologies will be the primary drivers of the fermentation route. This technology is in a detailed investigation stage.

### **i) Glucaric Acid**

Glucaric acid is a sugar acid derived from D-glucose in which both the aldehydic carbon atom and the carbon atom bearing the primary hydroxyl group are oxidized to carboxylic acid groups. It can be prepared by the nitric acid oxidation of starch with about 65 percent yield; however, there is no efficient method to manufacture glucaric acid on an industrial scale.

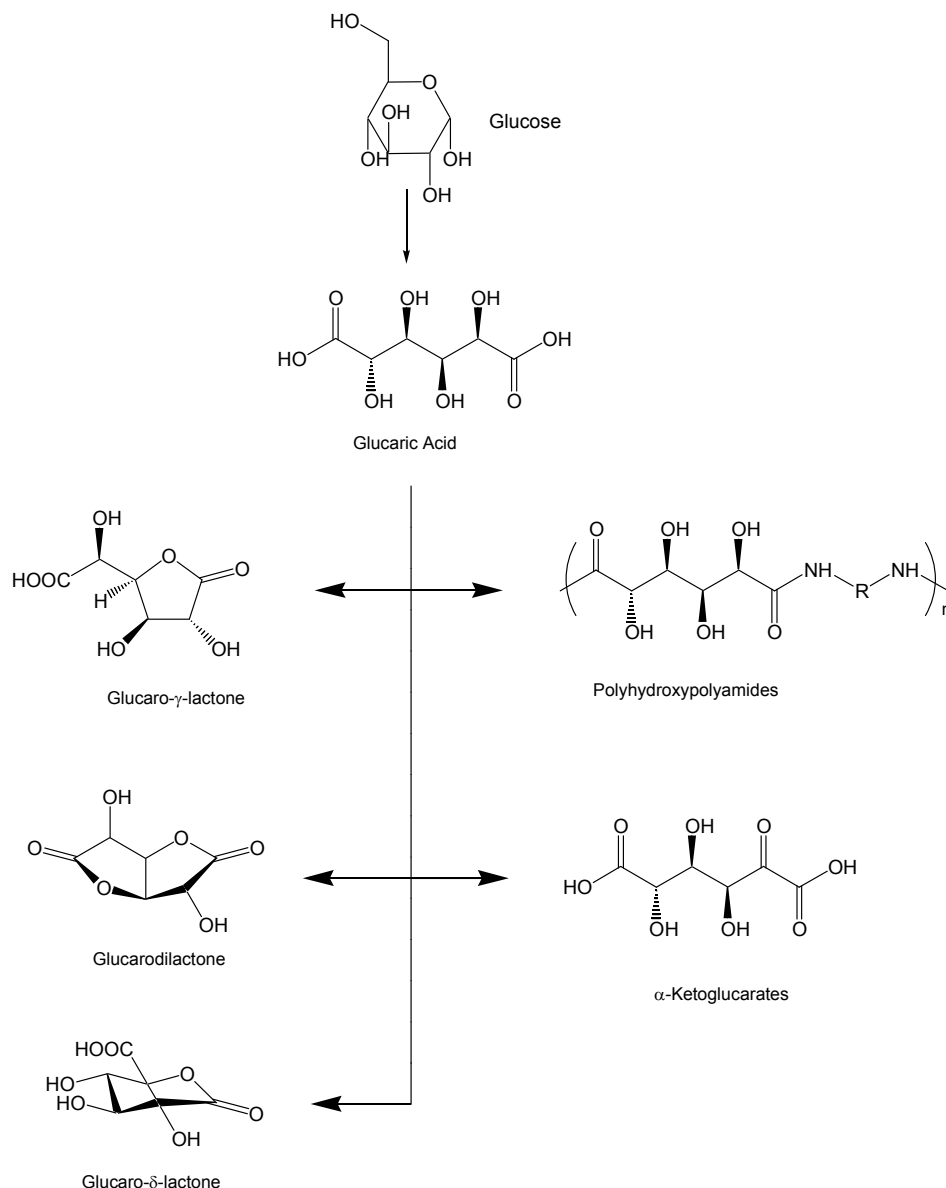
### Potential Derivatives and Products

The potential value of glucaric acid production from biomass sugars resides in the production of large-volume products including polyhydroxy-polyamides, glucarodilactone, glucaro- $\delta$ -lactone, and glucaro- $\gamma$ -lactone (Figure 46). Potential products from these chemicals include nylons, hyperbranched polyesters, and detergent surfactants.

### Technical Barriers

Technology barriers include selective glucose oxidation as well as development of technologies for selective sugar dehydration for transformation of glucaric acid to sugar lactones. Development of these technologies would have applications for other platform chemicals such as xylaric and arabinaric acids. This technology is in a preliminary investigation stage.



**Figure 46: Glucaric Acid as a Platform Chemical**

Source: Michigan Biotechnology Institute.

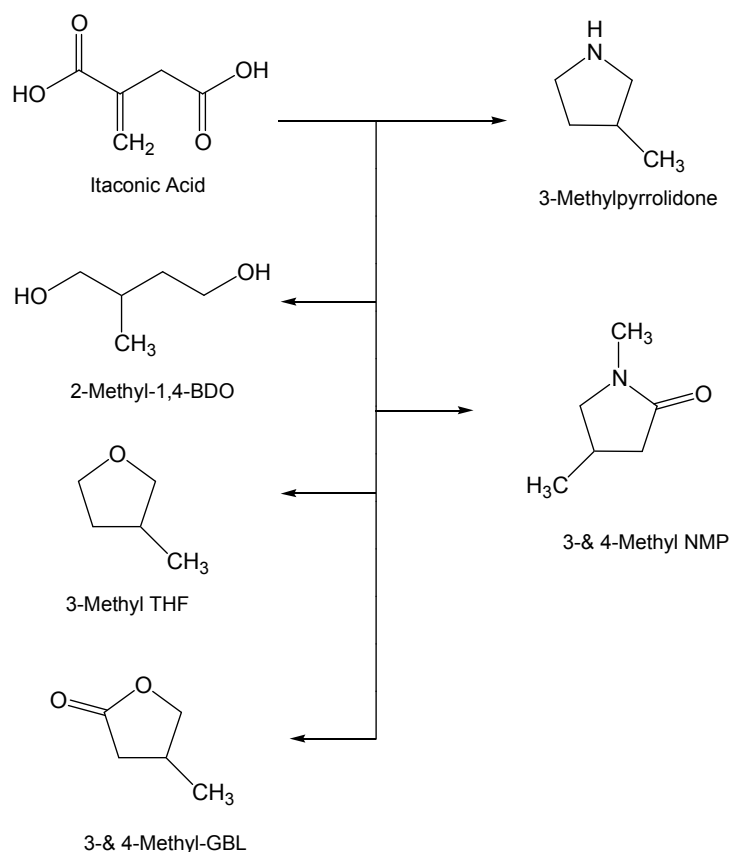
### j) Itaconic Acid

Also known as methyl succinic acid, itaconic acid is a five-carbon dicarboxylic acid. It is currently produced by fermentation (fungal) and is used as a specialty monomer. Itaconic acid and its esters are used in polymer resins, lubricant oil, carpets, adhesives, coatings, paints, emulsifiers, surface-active agents, pharmaceuticals, and printing chemicals. Fermentation cost currently limits its industrial use.

### Potential Derivatives and Products

With a similar chemistry to maleic anhydride, itaconic acid is expected to be amenable to the production of BDO, THF, and GBL analogs as well as pyrrolidones (Figure 47). The market potential of these compounds was detailed in the discussion of succinic acid. Itaconic acid could compete with methyl methacrylate and other acrylates: the market for these compounds is over \$1 billion a year.

**Figure 47: Itaconic Acid as a Platform Chemical**



Source: Michigan Biotechnology Institute.

### Technical Barriers

The development of potential derivatives is dependent on significantly lower fermentation production costs of itaconic acid. Additionally, hydrogenation/oxidation chemistry for production of the itaconic acid derivatives will need to be developed, as well as new catalysts that can function amid fermentation impurities. While itaconic acid can be produced from glucose and sucrose, the production from xylose could offer economic benefit. A more economical fermentation would greatly increase itaconic acid use in the plastics, paints, and automotive industries. The development of itaconic acid as a platform chemical is in a preliminary investigation stage and considered a long-term effort.

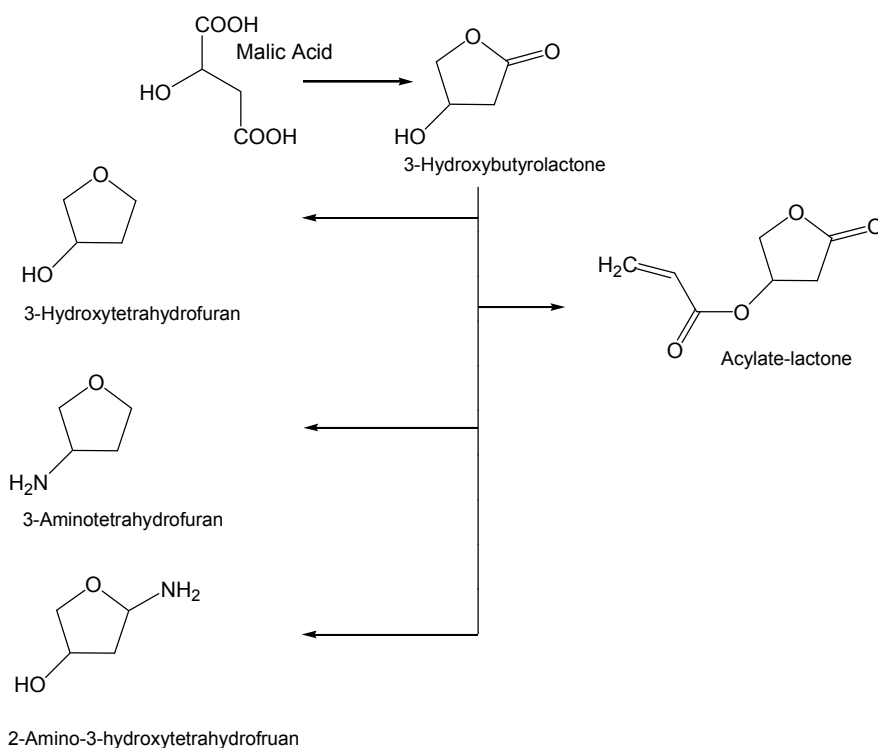
### k) 3-Hydroxybutyrolactone

3-hydroxybutyrolactone (3-HBL) is a cyclic four-carbon compound produced by chemical transformation and is used in pharmaceutical production. There is currently no fermentation route to 3-HBL. It will more likely be produced by the cyclization of biobased malic acid to form hydroxysuccinic anhydride, which can be reduced to hydroxybutyrolactone.

#### Potential Derivatives and Products

Possible derivatives of 3-HBL include analogs of succinic acid by ring opening, gamma-butenyl-lactone by dehydration, and acrylate-lactone by esterification (Figure 48). The primary uses of these derivatives would be as solvents and amino analogs to lycra fibers.

**Figure 48: 3-Hydroxybutyrolactone as a Platform Chemical**



Source: Michigan Biotechnology Institute.

#### Technical Barriers

Since 3-HBL is a specialty chemical with high-value use, there is little incentive at this point to develop it for use as a commodity chemical. Development as a commodity chemical is considered to be in the preliminary investigation stage.

## I) Glycerol

Glycerol is produced either from propylene or as a byproduct from the oleochemical and biodiesel industries. In 2004, production was 1 million metric tons a year (SRI Consulting, 2005b). Approximately 75 percent of glycerol production is biobased and 25 percent synthetically produced. As biodiesel production increases, there will be a substantial increase in production of glycerol (additional 800 million pounds a year by 2012), which is expected to significantly lower the price. As the price decreases, significant markets for polymers, ethers, and other compounds would become available for glycerol derivatives.

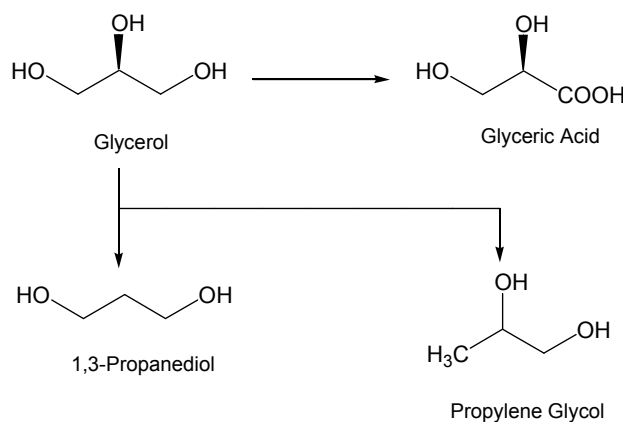
### Potential Derivatives and Products

Potential derivatives include glyceric acid, 1,3-propanediol, and propylene glycol (Figure 49). Potential products are numerous and include a broad area of polymers (polyesters, polyurethanes, and nylons). Polyesters have markets of 2 to 3 billion pounds a year at prices between \$1.00 and \$3.50 a lb. Nylons are priced between \$0.85 and \$2.20 a pound, with global production of 9 billion pounds a year.

### Technical Barriers

Selective oxidation technologies and hydrogenolysis technology will be required to realize the potential of glycerol as a building block chemical. Catalysts that can differentiate between C-C and C-O bonds will also need to be developed. While increasing production of glycerol will likely drive the price into the commodity range, the development of technologies to enable its use as a platform chemical is still in the preliminary investigation stage.

**Figure 49: Glycerol as a Platform Chemical**



Source: Michigan Biotechnology Institute.

## 3. Other Chemicals of Interest

The development of biocatalysts is one of the primary drivers for development of biobased chemicals and fuels. Industry experts have predicted that by 2020, the development time for new whole cell biocatalysts will be reduced from 10 years to 2

years and that the product cycle time for biocatalysts created by protein engineering will be reduced to less than 6 months (Energetics, Inc., 1999). Maxygen believes that 6 percent of the global commodity, specialty, and fine chemicals market can be addressed by current biobased technologies, and that by 2025 an additional 25 percent may be produced by biobased processes (Thayer). The development of new biocatalysts and metabolic engineering has enabled researchers to create new production systems for fine chemicals. The following are examples of new commodity and fine chemicals in the product development pipeline.

#### **a) Caprolactam**

Caprolactam is a monomer used in the production of polyamide-6 (Nylon 6) for use in the artificial fiber industry. It is also a structural material in the automotive and electronics industries. BASF and DSM together produce over a billion pounds a year, using cyclohexane as the feedstock. New technologies are being developed that produce caprolactam from L-lysine (Informa Economics et al., Biobased Multi-Client Study, March 2006).

#### **b) Shikimic Acid**

Shikimic acid is a six-member carboxylic ring that is naturally produced in plants and microorganisms. Presently, the shikimic acid is harvested from the fruit of *Illicium* plants (Chinese star anise), a tedious multistep process that precludes its use in large volumes. The lack of sufficient sources of shikimic acid to support large-scale production has made production of the chemical by fermentation an attractive alternative.

A process for producing shikimic acid from glucose was patented in 2002 (Frost and Knop) and licensed nonexclusively to Roche, which used the process to produce 8,000 kg for Tamiflu® manufacture (John Frost, personal communication). The market for Tamiflu® is estimated at more than \$1 billion annually. It is considered a strategic asset in control of pandemic outbreaks of influenza. Acid catalyzed dehydration of shikimic acid yields p-hydroxybenzoic acid, a precursor to parabens and an intermediate in the production of liquid crystal polymers.

#### **c) Quinic Acid**

Quinic acid can also be produced from glucose in a scheme similar to the Frost shikimic acid route. Quinic acid is used in the production of pharmaceuticals. With the Frost technology, hydroquinone may be produced from quinic acid (Informa Economics et al., Biobased Multi-Client Study, March 2006).

#### **d) Vanillin**

Vanillin has an annual market volume of 12 million kg and is second only to aspartame as a chemical flavoring. While current manufacture is based on the conversion of

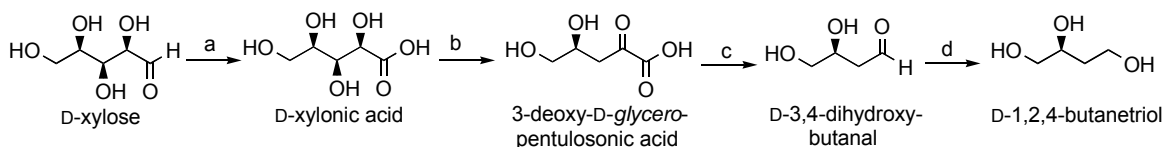
ferrulic acid to vanillin, technologies are being developed to produce vanillic acid from glucose, using a microbe-catalyzed process, with subsequent reduction to vanillin catalyzed by aryl-aldehyde dehydrogenase isolated from *Neurospora crassa* (Informa Economics et al., Biobased Multi-Client Study, March 2006).

### e) Feedstocks for Energetic Materials

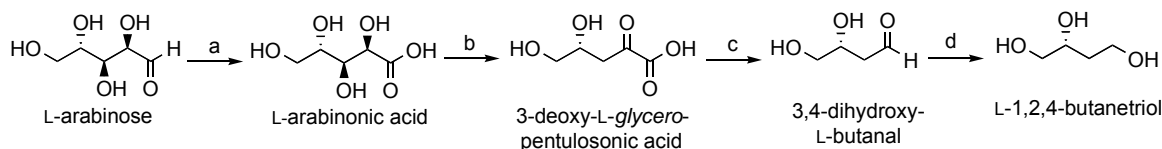
1,2,4-butanetriol (BT) is a polyol intermediate that can be nitrated to produce 1,2,4-butanetriol trinitrate (BTTN), a compound that is thermally more stable, has a lower shock sensitivity, and is less volatile than nitroglycerin (Figure 50). BTTN can be used as a coplasticizer in castable explosives. BT is currently derived from petrochemical feedstocks. The cost of racemic BT (\$30 - \$40/lb) currently limits its use in the production of BTTN (Informa Economics et al., Biobased Multi-Client Study, March 2006).

Dr. John Frost (Michigan State University) has developed a synthesis of BT that uses microbial catalysis and renewable carbohydrate feedstocks (Informa Economics et al., Biobased Multi-Client Study, March 2006). In this process, D-BT is produced from D-xylose and L-BT is derived from L-arabinose.

**Figure 50: Biobased Production of Butanetriol**



a. D-xylose dehydrogenase; b. D-xylonate dehydratase;  
c. 2-ketoacid decarboxylase; d. alcohol dehydrogenase.



a. L-arabinose dehydrogenase; b. L-arabinonate dehydratase;  
c. 2-ketoacid decarboxylase; d. alcohol dehydrogenase.

Source: Michigan Biotechnology Institute.

While the market for BTTN explosives/propellants is relatively small, it is anticipated that BTTN could also replace nitroglycerin as a vasodilator for the treatment of angina. Advantages over nitroglycerin include BTTN's resistance to degradation by nitrate reductase and the ability to produce chirally pure D-BTTN and L-BTTN, minimizing the number of metabolites generated from degradation by nitrate reductase.

Other possible derivatives of BT include the chiral intermediates D-3,4-dihydroxybutanoic acid, L-3,4-dihydroxybutanoic acid, D-3,4-dihydroxybutanal, and L-3,4-dihydroxybutanal. Crestor®, a cholesterol-lowering drug manufactured by Astra Zeneca, is derived from D-3,4-dihydroxybutanoic acid.

Another intermediate with potential for production of propellants/explosives is phloroglucinol, which could be used in the synthesis of 1,3,5-trinitro-2,4,6-triaminobenzene (TATB), a stable energetic material used by the U.S. military. The current manufacture of phloroglucinol involves oxidation of 2,4,6-trinitrotoluene (TNT), a process that presents an explosion hazard, and generates carcinogenic chromates as well as other waste streams. Phloroglucinol can also be used in the synthesis of resorcinol, widely used to produce resins used in adhesive applications for products including tires and plywood.

#### f) Antioxidants

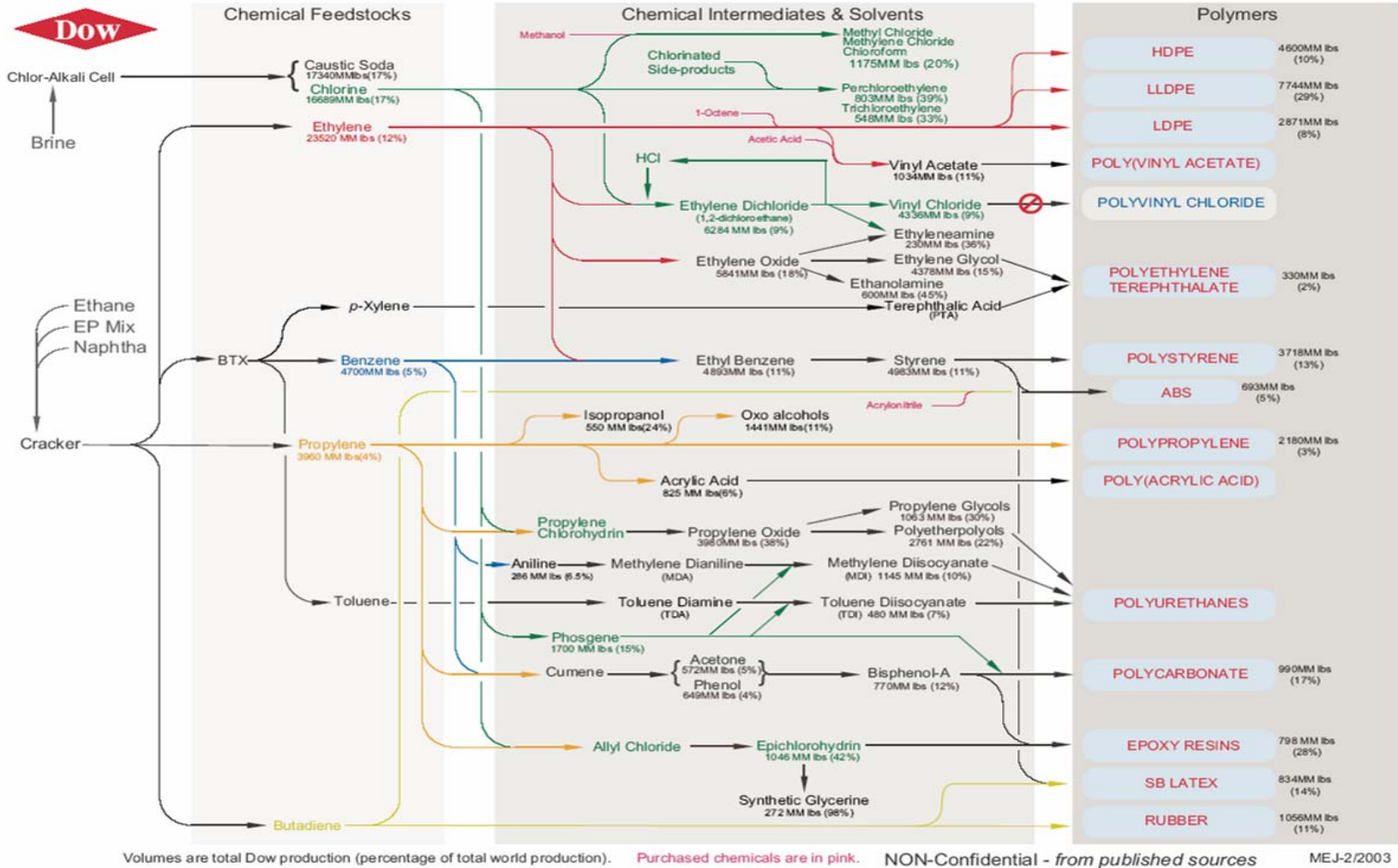
Gallic acid and pyrogallol are aromatics that have high oxygen content. These chemicals are ideal candidates for synthesis of such products as trimethoprim, gallamine triethiodide, and trimetazidine. Propyl gallate is used in food applications as an antioxidant. The market for gallic acid is 170,000 kg annually. The market for pyrogallol is 200,000 kg annually. Gallic acid is currently isolated from insects and pyrogallol comes from the seed pod of a tree native to Peru. Gallic acid can be produced by fermentation of biomass-derived carbohydrates using a recombinant *E. coli* (Informa Economics et al., Biobased Multi-Client Study, March 2006). Gallic acid can be converted to pyrogallol via decarboxylation by another recombinant *E. coli* at a yield of 97 percent.

### 4. The Evolving Biobased Market

Important to a biobased economy in 2025 will be the development, scale-up, and commercialization of economically relevant technologies. These technologies must compete on cost and performance and should be readily used in the existing chemical industry infrastructure. In other words, the first significant impact of biotechnology in the chemicals and materials industry will be seen with biobased replacements for existing chemicals and materials.

The integration of chemicals production with fuel production (ethanol or biodiesel) will help drive chemical costs down and generate new feedstocks in which biobased platforms replace petrochemical platforms. Figure 51 illustrates chemical production today in a typical chemical company using petrochemical feedstocks while Figure 52 represents a biorefinery of the future in which renewable resources are used as feedstocks. It is envisioned that such a refinery would include biological/enzymatic conversions, chemical conversions, and thermochemical conversions to enable the production of multiple products with utility in a variety of markets as illustrated in Figure 53.

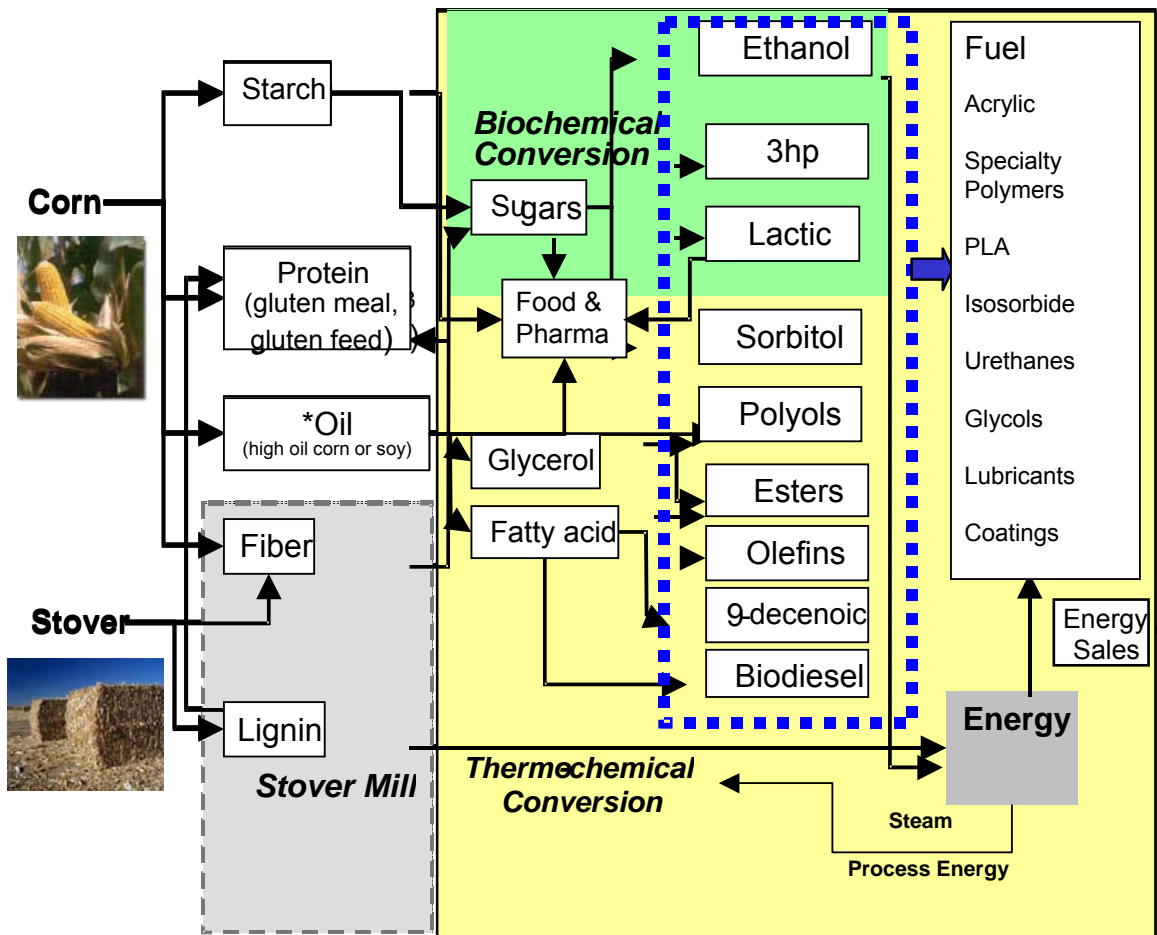
Figure 51: Chemical Industry Refinery



Source: Dow Chemical, Courtesy of Pat Smith.

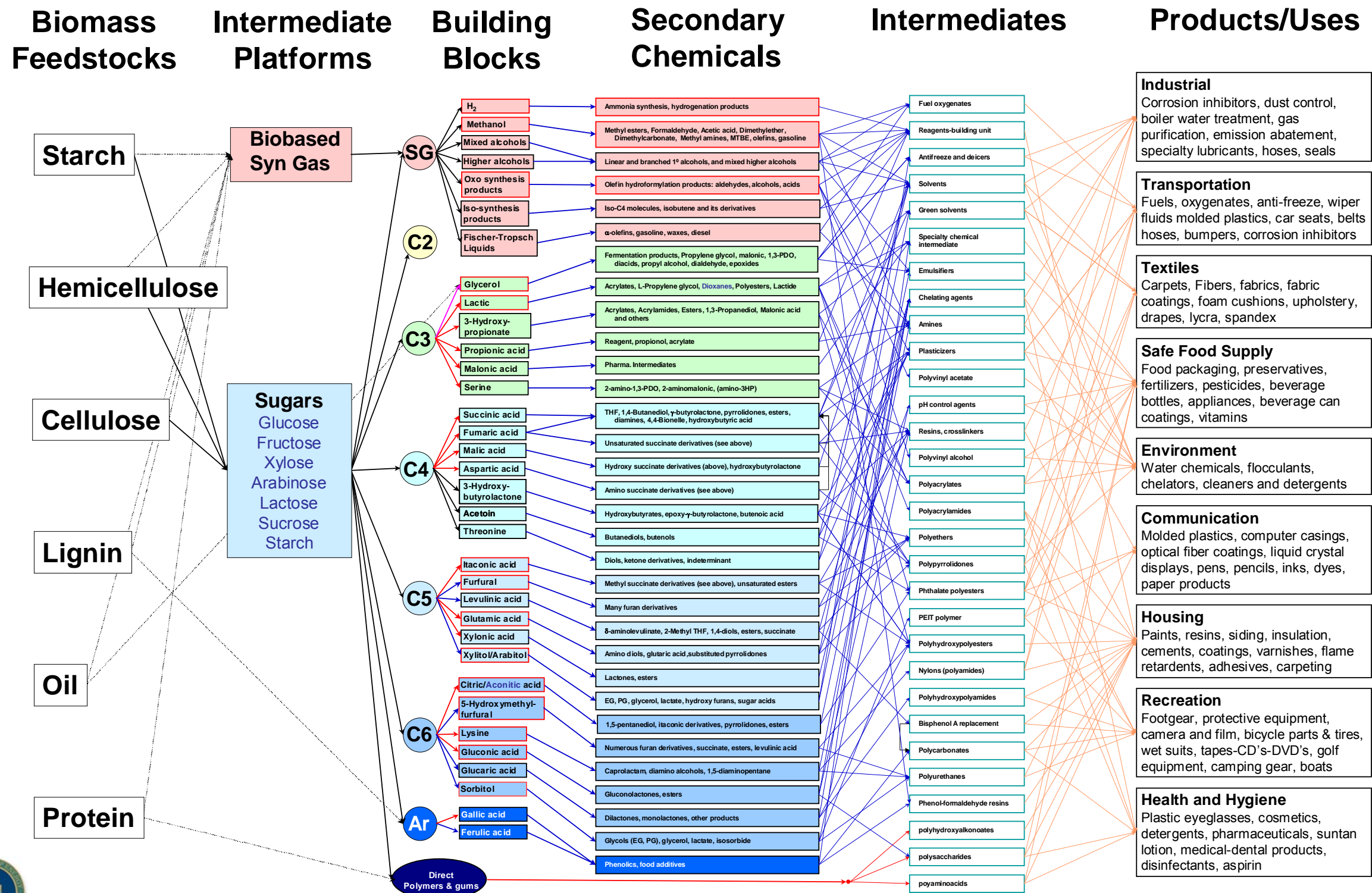


**Figure 52: Conceptual Biorefinery, Agricultural Feedstocks, Milling Operations, Biochemical and/or Thermochemical Conversions, Intermediates and Final Products**



Source: Informa Economics et al., Biobased Multi-Client Study, March 2006.

Figure 53: Pathway of Feedstocks to Markets, Biobased Industry of 2025



Source: U.S. Department of Energy.

## V. Biobased Process Technology

### A. Background

The emerging bioeconomy will drive the production of nontraditional products from biomass, such as fuels, chemicals, and materials currently produced from petroleum feedstocks.

Recent advances in biotechnology have eliminated many technical hurdles in the translation of lab-scale research into commercial-scale ventures. Research that was once slow and expensive has been accelerated through the use of molecular biology, genomics, proteomics, and metabolomics. Stability of the biocatalysts has been improved by genetic modification of more robust microorganisms and more finely tuned fermentation processes. Product yield in aqueous solution has been improved with advanced molecular biological techniques and the recovery of product has been facilitated by new aqueous separations systems and solvent extraction (Bachmann, 2003).

During the last 5 years there have been major advances in the production of biobased polymers. These include Cargill's production of polylactic acid polymers, DuPont's Sorona® polymer precursor, 1,3 propanediol, and Dow Chemical's BIOBALANCE™ soy based polymer used in carpet manufacture. These bioplastics are useful for many materials; however, they are marginal structural materials. Addition of reinforcing fibers can improve thermal, moisture and mechanical durability. An example of such biocomposite materials is a moldable board material under development by the U.S. Department of Agriculture Forest Service Laboratory that is composed of 70 - 80 percent wood flour combined with a conventional plastic. Another example is a soy based composite used by John Deere in the manufacture of their tractors. The reinforcing fiber is fiberglass. Research at Michigan State University and other institutions is directed at use of natural fibers from biomass as direct replacements of fiberglass in biocomposites (Knudson and Peterson).

New developments in the automobile industry are showing biobased materials to be as good, or better, than the petrochemical based materials they are replacing. Goodyear has developed corn infused tires that have a lower rolling resistance (Goodyear). Honda is experimenting with wood fiber-reinforced floor panels that exhibit better dimensional stability than current materials. DaimlerChrysler and BMW Group have made the use of biobased materials a key part of their overall environmental strategy (Informa Economics et al., Biobased Multi-Client Study, March 2006).

## B. Fermentation Technology

### 1. Fermentation Systems

Fermentation is the core process technology for the production of biobased products, including ethanol. Fermentation is the use of microorganisms to generate products that are metabolites of the organism's physiological activity. Fermentation systems can be classified into three types: batch, fed-batch, and continuous. Batch fermentation is a single-stage fermentation where all feedstocks and growth supplements are added in one step prior to the fermentation. This fermentation is inoculated with the desired organism and operated at specified conditions for a specified length of time. Optional control systems may include temperature, pH, and dissolved oxygen. Advantages of this system are that it is a simple, well tested design; easy to operate; and relatively easy to prevent contamination. However, the growth cycle can be inefficient (if product is formed in only one growth phase). Also, batch fermentation requires a large volume of prepared medium, and extensive cleaning and sterilization time.

Production of ethanol is currently via batch fermentations. Development of either fed-batch or continuous fermentations could improve the efficiency and productivity of corn-to-ethanol production where product inhibition could be a problem, especially in high-density fermentations with increased starch loading (Taylor et al.).

Fed-batch fermentations use the staged feeding of a nutrient to precisely control fermentation conditions and the metabolic state of the production organism. This type of fermentation is widely used in biotechnological applications, particularly for recombinant organisms with engineered expression systems that achieve optimal production at low concentrations of a particular nutrient. It is also used when high substrate concentration may be inhibitory, such as in production of the enzyme amylase (high-starch concentration increases the medium viscosity and decreases mass transfer rates) or in the production of acetic acid from ethanol.

In continuous fermentations, cells and spent medium are continuously removed at the same rate as nutrient input. This allows the use of smaller bioreactors than with batch or fed-batch fermentation. Downtime is reduced and continuous fermentations yield more uniform product since the production organism is kept at the same physiological state during production. This is often referred to as a chemostat fermentation, and is useful for studying metabolic behavior under specific conditions (e.g., pH, cell density, substrate concentration, product concentration, specific growth rate). Disadvantages of continuous fermentations include the difficulty of maintaining sterile conditions; genetic instability of the production organism; and cell dilution or washout. Continuous fermentations are not typically suitable for production of recombinant products (potential back mutation to the parent strain) or for metabolites that are produced in stationary phase.

## 2. Traditional Products

The brewing, baking, and dairy industries (cheese making) have used microbial cultures for centuries to make commercial products that cannot be produced by any other method. Similarly, the commercial use of fermentation by bacteria and fungi originally isolated from the environment to manufacture therapeutic molecules (that would be prohibitively expensive if produced by classical organic chemistry) has been practiced since the middle of the 20th century (Table 43). The beta-lactam antibiotics penicillin and cephalosporin are both produced exclusively by fermentation, with annual global volumes of approximately 50 million kgs and 15 million kgs respectively (Visiongain, 2004). Other widely used antibiotics such as tetracycline, erythromycin, and gentamycin are all produced by fermentation and used directly as therapeutics, or as the essential starting material for improved therapeutics. These products are all made by biological processes, which work so well that the bulk pricing of these important medicinal molecules does not allow any nonbiological process to compete commercially. For example, the price of Penicillin G is now approximately \$10 a kg while the price of 6-aminopenicillanic acid (the penicillin nucleus from which all therapeutic penicillins are derived) is currently at \$35 to \$40 a kg (Visiongain). While pharmaceutical examples are of easily recognized value, less appreciated are the fermentation processes for the production of much more basic chemicals: mono-sodium glutamate (approximately 1 billion kgs a year, valued at \$1 billion), citric acid (approximately 1.5 billion kgs a year, valued at \$2 billion), and lysine (approximately 0.75 billion kgs a year, valued at \$1.5 billion).

Historically, commodity or industrial biotechnology has been applied to the production of solvents. Microbial acetone production was discovered in 1905 by Shardingier and organisms producing acetone and butanol were isolated independently by Fernbach and Weizmann. Their processes were patented in 1912 and 1915 respectively, and the Weizmann process dominated the industrial production of acetone and butanol until 1936. Between 1945 and 1950, 66 percent of n-butanol (over 45 million pounds) and 10 percent of acetone in the U.S. was produced by fermentation of molasses and starch. Other commodity products produced by fermentation in the first half of the 20th century include acetic acid, citric acid, lactic acid, itaconic acid, dextrans, vitamins, and antibiotics. Increased prices of the sugar feedstock and decreased prices of petrochemical feedstock ended the fermentive production of these solvents. With the current reversal of these trends, the further development of these processes by classical methods continues today.

**Table 43: Commodities Produced by Microorganisms in Fermentation Systems**

Pharmaceuticals	Amino Acids and Other Organic Acids	Enzymes	Solvents	Fuels	Food
Antibiotics	Lysine	Proteases		Ethanol	Diary products
Steroids	Glutamic acid	Amylases		Methane	Fermented meats
Human proteins	Gluconic acid	Cellulases			Bread
Vaccines	Citric acid				Alcohol beverages
Vitamins	Itaconic acid				Vinegar
	Gibberellic acid				Fermented vegetables
	Lactic acid				

Source: Informa Economics et al., Biobased Multi-Client Study, March 2006.

### 3. Applications of Biotechnology

The use of biological methods in industrial processes is not a new concept; such processes have a long history that is often overlooked in the current enthusiasm for industrial biotechnology. The brewing, baking, and dairy industries all use biological methods to produce high-volume low-price commodity products. Similarly, the production of food and feed ingredients such as amino acids and acidulants are commodities produced in large volumes using fermentation.

Recently, the tools and methods developed for the production of recombinant therapeutics and the elucidation of cellular process (for understanding diseases and identifying drug targets) have been applied to producing commodity fuels and chemicals from biomass. The difference between the biotechnology industry and the biocommodity (biorefinery) industry is not in the technology but in its application to problems posed by very different economic forces and in chemistry requirements of the molecules produced.

Bioprocesses are applied to fuels, chemicals and materials for different reasons than in the biopharmaceutical industry. The biopharmaceutical industry was created with a focus on therapeutics. Its products are expensive to develop and are priced based on market need and the immense risk associated with product development. Efficiencies of scale and manufacturing, cost of starting materials and competition in an established product marketplace are not necessarily primary considerations.

This is completely opposite to the forces affecting commodity manufacturing. Commodities are long-established high-volume products with well-known market requirements and easily measured competition and cost/price considerations. Success requires efficient production processes from low-cost feedstocks. For the commodities industry, the technical and economic forces are:

- Yield - the conversion of feedstock to product on a molecular basis.
- Productivity - the optimum use of equipment and avoidance of idle-time.

- Downstream processing - best summarized as purity and concentration.

While any manufacturing plant will be concerned with these forces, their mastery is essential for success in the production of commodities. A further distinction is that pharmaceutical processes are run as single batches, primarily for regulatory reasons. Processes for the production of commodity chemicals are often run continuously, and the adaptation of batch-process biotechnology to continuous-production processes remains a challenge.

#### 4. Limitations

Metabolic engineering (the use of molecular biological tools to manipulate the metabolic processes of an organism) for fuel and chemical production must address very different metabolic issues than pharmaceutically based biotechnology. Production of recombinant proteins generally requires the cell to produce very large amounts of ATP, which is used to run the synthesis of the protein for which a heterologous gene has been inserted. The consideration of metabolic pathways in the fermentation is limited to this single purpose (and possibly the need for post-translational processing, such as glycosylation). The production of small molecules requires consideration of energy efficiency and minimizing the production of ATP to only what the cell needs to live, the redox balance, and carbon flux within the available metabolic pathways. The balance of these concerns with that of the cell's own metabolism is the art of metabolic engineering.

Redox balance is an important chemical design issue, especially when starting from carbohydrates, which are approximately in the middle of the redox range available to carbon. Consider the single carbon atom; the simplest carbohydrate (formally) is formaldehyde,  $\text{CH}_2\text{O}$ , while the most reduced form of carbon (as a compound with a single carbon atom) is methane,  $\text{CH}_4$ , and the most oxidized form is carbon dioxide,  $\text{CO}_2$ . If a molecule with a redox potential lower (i.e., more reduced) than that of carbohydrates is desired, then some other carbon atoms must undergo oxidation, likely to  $\text{CO}_2$ . Petroleum is highly reduced relative to carbohydrates. To directly compete with commodity chemicals that are produced from petroleum feedstocks, a net reduction of carbon is required relative to carbohydrates, and this requires the cell to expend energy producing a pool of reducing equivalents rather than ATP, which would be required for synthesis of a recombinant protein. A net de-oxygenation of the carbohydrate starting material is required to reach the equivalent redox potential of hydrocarbon compounds. This is the central chemical issue in producing commodity chemicals from biomass, whether by biological methods or conventional chemical processes. For example, ethanol is more reduced than carbohydrates, so to provide the electron source for the net chemical reduction needed to produce ethanol from carbohydrates, some of the carbohydrate molecules are oxidized, and the fermentation produces  $\text{CO}_2$ . This is of particular concern for both biocatalysis (the use of single enzyme reactions) and metabolic engineering, as other cellular mechanisms are required to supply and remove the electrons needed to perform reductions or oxidations.

Adjusting the oxidation state of carbon always adds value in industrial chemistry. It is easy to oxidize in our oxygen atmosphere, so it is not surprising that of the target molecules identified in the USDOE Energy Efficiency and Renewable Energy (EERE) program, eight are more oxidized with respect to carbohydrate redox potential, while six are more reduced (USDOE, 2004). None have the same redox potential as the starting carbohydrate.

## **C. Biocatalysts**

Biocatalysts are whole-cell microorganisms or specific enzymes derived from microorganisms used in the biological production of industrial products. The biochemical pathways used by the organism to produce metabolites needed for its own survival is exploited to make products for human use. These biochemical pathways consist of a series of enzymatically catalyzed steps. The use of microorganisms to produce enzymes of specific interest - and the subsequent use of these enzymes to effect conversion of feedstock chemicals to desired products - is a modern twist on classic fermentation systems.

### **1. Production Strains and Strain Improvement**

Industrial production strains must be capable of providing consistent product over long periods of time. Microbial strains used for this purpose should have the following characteristics:

- Genetic stability.
- Limited or no need for vitamins and additional growth factors.
- Efficient production of the target product.
- Known route of biosynthesis of the target product.
- Utilization of a low-cost and readily available carbon source.
- Amenability to genetic manipulation.
- Nonpathogenic and nontoxic.
- Limited byproducts to ease subsequent purification.

Once a production strain has been selected, a cell banking system is usually established to ensure stability of the strain.

Isolation of naturally occurring strains and the use of classical mutagenesis have been used extensively for the improvement of useful microbial strains (Steele and Stowers). Organisms can be isolated from the environment using a technique known as enrichment, which engineers conditions that are selective for organisms with the desired metabolic activity. For example, a growth medium that contains only protein as a carbon source, a pH of 10.5, and an incubation temperature of 60° C can be used to isolate an organism that produces a thermostable protease that functions at high pH. The environmental source may be a highly alkaline hot spring to further increase the chances of isolating the desired organism.



Most natural isolates will lack the precise characteristics needed to isolate a production strain. It is usually necessary to improve the productivity of a natural isolate before it can be used for the economic production of a desired product. Mutagenesis, or the use of a mutagen to effect a change in genotype, has been widely used for strain improvement. Mutagens can cause mutation directly as a result of damaging DNA (pairing errors) and indirectly as a result of errors during the normal DNA repair process. Typical techniques include use of radiation (short- and long-wavelength ultraviolet, and ionizing gamma radiation) and chemical mutagens (ethidium bromide, mitomycin c, nitrosoguanidine, etc.). Organisms are then screened for the selection of desirable traits.

## 2. Enzymes as Biocatalysts

Biocatalysis differs from fermentation in its use of isolated, single enzymes in non-physiological conditions to catalyze desired chemical reactions that are unrelated to physiological processes. This field was pioneered by Jones, Whitesides, Sih, and Yamada in the 1970s and 1980s. Initially, biocatalysis was exclusively driven by the ability of enzymes to control chirality (and stereochemistry generally). This in turn was most applicable to molecules with biological activity. Thus, much of the early application of biocatalysis was in the pharmaceutical industry, but today it is applied more broadly across the chemical industry (Table 44). While most enzyme applications are in specialty and fine chemical production, several instances of large-volume applications exist:

- Acrylonitrile to acrylamide. Hydrolysis of acrylonitrile by *Rhodococcus* sp. nitrile hydratase at about 5 million kg annually.
- High-fructose corn syrup. Two-enzyme hydrolysis of starch (debranching with alpha-amylase, hydrolyze dextrans with glucoamylase), followed by a third enzyme step to isomerize glucose to fructose with glucose isomerase.
- Penicillin and cephalosporin. Enzymes are used to remove the sidechain of the naturally produced beta-lactam to give the commercial products 6-APA, 7-ACA, and 7-ADCA.

Once the utility of enzymes as individual catalysts was proven in industry, it was logical to extend this to a sequence of reactions. Combined with the capabilities of molecular biology, the concept of constructing reaction pathways by expressing a series of enzymes was the next step.

Today, the production of enzymes as catalysts for a wide range of applications is approximately \$2 billion annually. Of recent interest is the large-scale effort to develop commercial catalysts for biorefinery use; these are the cellulases and xylanses developed by Novozyme, Genencor, and others (van Beilen and Li).

**Table 44: Distribution of Enzyme Use by Industry**

• Textile processing	10 percent
• Grain processing	12 percent (HFCS)
• Food processing	18 percent
• Cleaning	44 percent
• Cattle feed	4 percent (cellulase, xylanase, phytase)
• Waste treatment	4 percent
• Specialty chemical	4 percent (diagnostic, chiral)
• Other	4 percent

Source: Michigan Biotechnology Institute

### 3. New Technologies

#### a) Molecular Biology and Genetic Engineering

“Molecular biology” or “biotechnology” was first applied to very high-value therapeutic materials with known (or presumed to be known) utility in healthcare: for example tumor necrosis factor (TNF), alpha-interferon, and insulin.

With the founding of Genentech in 1976, the tools of molecular biology moved from an academic to an industrial setting, with products maturing into off-the-shelf items. This has greatly reduced the need to “invent a new tool” to perform basic gene manipulation across a large variety of microorganisms. Today, it is not unusual that a microorganism with suitable characteristics for large-scale fermentation can be ordered from a list. The DNA sequence of desired genes can be found in a database and the actual gene synthesized chemically. The tools for inserting and expressing genes in an organism can be purchased from a catalog or provided as a contract service.

Further, if a microorganism is found with a desired metabolic activity but that organism has not been previously mapped, it is now possible to obtain the sequence of the genome in 3 to 4 days within one’s own lab. In fact, mass-market software can search and annotate this information. This software provides not only the desired genes but also the entire expression vector synthesized for a fee-for-service.

The initial application of biotechnology to the chemical industry was analogous to recombinant therapeutics; the use of (now conventional) techniques allowing the heterologous overexpression of enzymes one at a time, plus the ability to perform site-directed mutagenesis in attempts to alter the catalytic activity of the given enzyme. The enzymes expressed could either be isolated and used as discrete reagents, or simply left within the microorganism and the entire biomass used to catalyze the desired chemical reaction. Since the single enzyme of interest is usually so highly overexpressed and composes such a large amount of the cell mass, potential interference of naturally occurring enzymes is not a major practical problem. This may actually be considered an example of “metabolic pathway

deconstruction” since the desired single enzyme activity is arranged to overwhelm existing metabolic routes in the cell.

Generally, enzymes such as lipases, esterases, and proteases are isolated as purified or partially purified preparations of the single protein molecule, again using the techniques applied in conventional biotechnology for protein purification. Enzymes that perform redox reactions are more generally used as preparations of intact cells, since the additional cellular components needed to provide or remove electrons during the redox reaction are already present in the cell. Usually in such cases, two enzymes are overexpressed: one to catalyze the reaction of interest and a second to catalyze the redox reaction of another chemical to provide the corresponding source, or sink, of the electrons. For example, the reduction of a ketone to a secondary alcohol requires the addition of two electrons (a net reduction, provided formally as a full molecule of hydrogen). These electrons (formally as a molecule of hydrogen and most generally termed a “reducing equivalent”) are provided by the oxidation of another molecule, preferably a common and inexpensive one such as glucose. Glucose dehydrogenase catalyzes the oxidation of glucose to gluconolactone and provides the necessary reducing equivalent through the existing cellular machinery. This allows the overexpressed enzyme to perform the desired redox reaction. Many dehydrogenases are known, and such reaction systems are well established industrially.

The overexpression of heterologous enzymes must also satisfy yield and productivity requirements for the reaction to be of economic utility, as well as any requirements of the downstream processing necessary to isolate the desired reaction product. Here too, the now-conventional biotechnology tools of site-directed mutagenesis, for altering and improving specific properties of enzymes, are used. For single enzymes, such properties are:

- Thermal stability and the ability to operate outside the range of normal physiological conditions.
- Ability to operate in nonaqueous environments, and extremes of pH or salinity.
- Alteration of catalytic activity.

Industrial biocatalysis clearly would be driven by the isolation of new enzymes, and microbiology, which had provided natural products in the pharmaceutical industry, was now pressed into service to find new enzymatic activities. Companies such as Novozymes and Genencor have become successful producers of industrial enzymes.

But a problem in the search for new enzymatic activities from microbial sources was “culturing the unculturable.” Microbiologists had realized for many years that simply taking an environmental sample (e.g., a spoonful of dirt) and placing it in an environment rich in nutrients did not produce a population that included members of all the flora present in the original sample. Many organisms simply resisted the standard techniques of culturing. This was especially true for samples brought back

from extreme environments, such as deep-sea hydrothermal vents, where no life had been thought to exist. Such “exotic” organisms were prime candidates to screen for novel, and presumably useful, enzymatic activities.

A now standard tool of biotechnology, the polymerase chain reaction (PCR), was invented in 1985. PCR allowed the amplification of any existing piece of DNA in a given physical sample. One no longer had to grow the organism in order to gain access to its genes (and the enzymatic activities encoded by these genes). Using PCR and related techniques directly on the environmental sample made it possible to assemble very large collections of genes isolated from both unculturable and culturable organisms, to express them in conventional biotechnology platforms, and to screen them for useful activities. Further, it was possible to generate and screen massive numbers of mutants of these genes by the same techniques. The best known commercial enterprise in this endeavor is Diversa Corporation.

The ability to build and manipulate genes allowed the development of other techniques that fostered metabolic engineering. One is the group of shuffling techniques for the generation of mutants in an adaptive and evolutionary manner. This provided access to mutant enzymatic activities, and provided a mechanism by which the desired catalytic property actually drove the iterative mutation of the given enzyme until a desired outcome was reached. The commercial utility of this particular technology was manifested by the establishment of Maxygen, and the application of the technology to the chemical industry rather than the pharmaceutical industry. However, this was still a one-enzyme/one-reaction endeavor, not the construction of a synthetic pathway that would lead to a given molecule by a series of enzymatic reactions contained entirely within a single cell.

The application of shuffling to a group of enzymes, or even the entire genome of an organism, is a form of metabolic pathway engineering. This could theoretically create a novel pathway, but it is intended only to improve an organism’s existing capabilities. Codexis has a very useful example on their website illustrating how their technology is used to rapidly improve the production of doramectin.

The technologies described above illustrate the commercial applications of molecular biology that makes metabolic engineering practical commercially. In addition to the creation of powerful tools, the pursuit of basic cellular physiology and genetics has allowed the establishment of metabolic pathway databases that show the chemical reactions, the enzyme and biological source, and the gene sequence.

### **b) Metabolic flux analysis**

The simplest form of metabolic engineering is to block existing metabolic pathways so that certain intermediates accumulate in the cell, or to block the branching of a given pathway so that metabolic products are confined to one. This includes the overexpression of enzymes already present in existing metabolic pathways to remove bottlenecks in the flow of molecules through the pathway.

The biorefinery industry is already manipulating the metabolism of both bacteria and yeast to enhance ethanol production. It is also producing succinic acid, a commodity chemical itself and a replacement for maleic anhydride in multiple industrial processes. Of additional interest today is the work by Professor John Frost to produce shikimic acid, a starting material for the antiviral drug TamiFlu™. In this last example, the existing pathway from glucose to the aromatic amino acids is blocked to force the accumulation of shikimic acid (Frost and Knop).

The central challenge in the field of metabolic engineering is to use the tools of molecular biology to assemble a series of chemical reactions to produce a molecule that is not naturally occurring. New metabolic pathways that do not exist naturally are now able to be constructed thanks to the various techniques summarized previously. Several examples show the history and breadth of this field.

A useful, novel metabolic pathway can be constructed by the insertion of a single heterologous gene, the activity of which allows an existing metabolic pathway to be diverted. In 1982, Amgen filed a patent for the production of indigo by *E.coli* that involved inserting the gene for naphthalene dioxygenase (Ensley). In the resulting construct, the indole produced in the naturally occurring pathway for the degradation of tryptophan is oxidized by the naphthalene dioxygenase to produce indigo. In 2002, Genencor published work showing that this pathway could be extended by the addition of a second gene, isatin hydrolase. This allows an intermediate on the indigo pathway to be rerouted to another product, isatic acid (Chotani et al.).

An early example of the construction of a multi-enzyme pathway can be found in the production of therapeutic steroids. As steroids were of tremendous commercial value to the pharmaceutical industry in the 1950s, the cellular physiology surrounding them was well studied and the metabolic pathways were deduced over the next two decades. The central target in steroid synthesis is hydrocortisone. Decades of work by the pharmaceutical industry, as well as academic labs, produced elegant chemical syntheses. Eventually none could compete commercially with the isolation of steroid precursors coupled with the single biologically catalyzed hydroxylation at the 11 position on the steroid skeleton - a single, essential biological step in a multistep chemical synthesis.

The commercial value of cortico-steroids remains high and even today extraction of plant materials as a starting point for commercial production is practiced. In 1989, Gist-Brocades filed a patent application in which a novel steroid pathway had been constructed by inserting multiple genes, known to catalyze certain steroid reactions, into a single organism. The result was a microorganism (*Saccharomyces*, *Kluyveromyces*, and *Bacillus* are generally claimed in the patent) that was able to transform cholesterol into hydrocortisone. Five enzymes not normally present in the selected microorganism were assembled and inserted by classical molecular biology. As the chemistry of these multiple transformations involves redox reaction at each step, the attendant proteins for electron transport were also part of the

metabolic pathway construction. Taking this a step further, in 2003 Aventis published an improved version of this construct, in which cholesterol (which had to be fed to the organism) is replaced by pulling ergosterol out of the microorganism's own pathways (ergosterol is synthesized as part of the cell's membrane requirements). The overall result of this work was a *Saccharomyces cerevisiae* that produced hydrocortisone from glucose (Szczepara et al.).

Manipulating the shikimic acid pathway work mentioned earlier, Frost blocked the added genes that diverted the carbon flow from shikimic acid toward protocatechuic acid and then to catechol, a commodity chemical currently produced by the chemical oxidation of phenol (Frost and Draths, 1997). Adding a third gene, a dioxygenase, Frost was further able to transform the catechol to cis, cis-muconic acid which can be hydrogenated chemically to give adipic acid, one of the two components in Nylon™ 6,6 (Frost and Draths, 1996).

Likely the best known industrial example of metabolic engineering for the production of commodity chemicals from glucose is DuPont's process for the synthesis of 1,3-propanediol (1,3-PDO). This is one of two components for the polyester Sorona™, and DuPont has announced the construction of a fermentation facility in Loudon, TN, that will produce 100 million pounds per year of 1,3-PDO. Formally, only two enzymes are needed to transform glycerol to 1,3-PDO: glycerol dehydratase and 1,3-propanediol dehydrogenase. Practically, however, the engineering is more complicated. A reactivation factor is required to make the dehydratase useful, and since *E. coli* does not produce glycerol metabolically from glucose, two additional genes have to be inserted, and three potential pathway branch points blocked. The resulting *E. coli* construct is reported to be capable of producing 120 g/L 1,3-PDO in the final fermentation broth in 36-40 hours, using only glucose as the carbon source (Emptage et al.).

## D. Thermochemical Conversion

While ethanol and biodiesel production processes are established technologies, another approach to biofuels production is the use of thermochemical conversion of biomass to liquid fuels such as di-methyl ether, diesel, methanol, and hydrogen. This envisions the modification of existing gas-to-liquids (GTL) processes (Fischer-Tropsch) to create a biomass-to-liquids (BTL) technology. It is expected that these processes will produce a very clean fuel that is essentially sulfur free and rich in hydrogen for use in fuel cell applications. This approach is being pursued in Europe by companies such as Choren Industries, Daimler-Chrysler, and Volkswagen (Informa Economics et al., Biobased Multi-Client Study, March 2006).

The existing gasification industry produces more than 45,000 megawatts thermal (MW<sub>th</sub>) of syngas each year. There are some 117 gasification plants operating in 24 countries. The Africa/Middle East region accounts for over a third of the total output. Coal accounts for 49 percent of the synthetic gas (syngas) produced, and petroleum 37 percent. The remaining syngas is produced from natural gas, petcoke, and

biomass/waste. Biomass feedstock accounts for 2 percent of current syngas production. Approximately 37 percent of the syngas is used to produce chemicals, 36 percent for Fischer Tropsch fuels, 19 percent for power, and 8 percent for gaseous fuels (USDOE, 2004a).

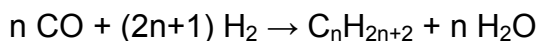
Thermochemical conversion uses elevated temperatures to convert biomass. Pyrolysis (absence of oxygen), gasification and hydrothermal processing are thermochemical conversion technologies with the potential for conversion of biomass to direct replacements for petroleum based fuels and chemicals. The difference between pyrolysis and gasification is primarily in the temperature at which each process operates. Pyrolysis takes place at temperatures of 400 - 650°C and results in the formation of a liquid (pyrolysis oil), while gasification involves temperatures of 650 - 900°C and results in the formation of the permanent gases (H<sub>2</sub>, CO, CO<sub>2</sub>, and CH<sub>4</sub>). Hydrothermal processing uses organic solvents or water at temperatures of 300 - 350° C and pressure ( $P_a = 2,300$  psi) to produce hydrocarbon liquids (aliphatic chains, carboxylic acid groups, ether linkages). Wet gasification is a form of hydrothermal processing that uses a catalyst, such as Ni-Ru, to produce methane or hydrogen.

Biomass gasification is a potential source of heat and electrical production in a biorefinery. Waste streams from other processes can be used as feedstock for thermochemical conversion to improve power efficiencies. Another advantage of thermochemical conversion is that all major components of biomass, including lignin, can be converted to intermediate compounds. Lignin can represent as much as 30 percent of biomass, and is recalcitrant to biological conversion. Once the gaseous products of thermochemical conversion have been cleaned, they can be used directly in existing petrochemical facilities to produce fuels and chemicals.

From a technical perspective, the conversion of biomass syngas is similar to the process currently used for conversion of coal to syngas. Biomass thermochemical conversion will compete directly with coal-syngas as well as products derived from natural gas. Biomass presents unique problems in handling and feeding when compared with petroleum based materials (i.e., coal). While the processes are similar for both biomass- and petroleum based thermochemical conversion, current processing facilities are too large to be economically feasible for biomass conversion. Other barriers include the geographic distribution of biobased feedstocks versus fossil fuel feedstocks, and the higher content of particulates and tars in biomass-derived syngas. For thermochemical conversion to reach economic feasibility, the technology must be integrated into a larger biorefinery. To date, finding a cost-effective all-thermochemical process has proven difficult (Badger). Pending development of integrated biorefineries, transition scenarios include the possibility of integrating some level of biomass thermochemical conversion into existing petroleum refineries.

### The Fischer-Tropsch Technology

The Fischer-Tropsch (FT) technology is a process capable of producing liquid hydrocarbon fuels from a gas mixture of carbon monoxide (CO) and hydrogen (H<sub>2</sub>). The length of the hydrocarbon chain produced is determined by the H<sub>2</sub>/CO ratio in the syngas, the catalyst selectivity and the reaction condition (temperature, pressure, reactor type). A wide range of products from gasoline to diesel to candle wax can be produced. The process was initially used by Germany during World War II. The main mechanism of the FT reaction is as follows:



The mixture of carbon monoxide and hydrogen is known as synthesis gas or “syngas”. Gasification is the process by which this syngas is obtained from coal, natural gas or low-value biomass (wood chips, grass and municipal solid waste). It consists of two main steps, pyrolysis, where the feedstock is decomposed into gases, liquids and solids (char), and the combustion step where the syngas is generated. The chemical reactions in the gasification process take place at high temperatures (approximately 500 - 1400°C). Pressures can be atmospheric or higher. The oxidizing agent can be air, oxygen, steam or a mixture of them.

The technology can produce diesel with extremely low sulfur, aromatics, and toxics compounds.

FT synthesis is an established technology, and several companies have already applied it on commercial scale. Thus, Sasol and Shell are engaged in the production of synthetic fuels from low-grade coal in South Africa, and natural gas in Malaysia, respectively.

The conversion of syngas to synthetic fuels has historically only been economic when inexpensive natural gas is available. Commercial synthetic fuel production in South Africa, based on coal derived syngas, was initially driven by the oil embargo on South Africa in response to the apartheid.

Biomass gasification is technically more challenging due to the presence of impurities (especially tar) in the syngas. Choren Industries has recently opened in Germany (Freiberg) the world’s first commercial facility (15,000 metric tons a year, or approximately 4.7 million gallons) to convert biomass into high-quality synthetic bio-fuel, marketed as SunDiesel.



## E. Biomass Feedstocks

Biomass is a broad term used to describe material of recent biological origin that can be used either as a source of energy or for its chemical components. It is derived from numerous sources, including trees, crops, algae, and other plants, as well as agricultural and forest residues. Wastes like food and drink manufacturing effluents, sludges, manures, industrial (organic) byproducts, and municipal solid waste are also considered biomass.

### 1. Glucose

Glucose can be considered the universal feedstock source for microbial conversion to industrial products. Almost all microorganisms are capable of utilizing this simple six-carbon sugar as a carbon source. Glucose is produced commercially via the enzymatic hydrolysis of starch. Many crops can be used as the source of starch. Corn, rice, wheat, potato, cassava, arrowroot, and sago are all used in various parts of the world. In the United States corn starch is used almost exclusively.

This enzymatic process has two stages. Over the course of 1 to 2 hours near 100°C, these enzymes hydrolyze starch into smaller carbohydrates containing on average 5 to 10 glucose units each. Some variations on this process briefly heat the starch mixture to 130°C or hotter one or more times. This heat treatment improves the solubility of starch in water, but deactivates the enzyme, and fresh enzyme must be added to the mixture after each heating.

In the second step, saccharification, the partially hydrolyzed starch is completely hydrolyzed to glucose using the glucoamylase enzyme from the fungus *Aspergillus niger*. Typical reaction conditions are pH 4.0 - 4.5, 60°C, and a carbohydrate concentration of 30 - 35 percent by weight. Under these conditions, starch can be converted to glucose at 96 percent yield after 1 to 4 days. Still higher yields can be obtained using more dilute solutions, but this approach requires larger reactors and processing a greater volume of water, and is not generally economical. The resulting glucose solution is then purified by filtration and concentrated in a multiple-effect evaporator. Solid D-glucose is then produced by repeated crystallizations.

### 2. Starch

Starch is a combination of two polymeric carbohydrates (polysaccharides) called amylose and amylopectin. Amylose is constituted by glucose monomer units joined to one another head-to-tail via alpha-1,4 linkages. Amylopectin differs from amylose in that branching occurs, with an alpha-1,6 linkage every 24 - 30 glucose monomer units. The overall structure of amylopectin is not that of a linear polysaccharide chain since two glucose units frequently form a branch point, so the result is the coiled molecule most suitable for storage in starch grains. Both amylopectin and amylose are polymers of glucose, and a typical starch polymer chain consists of around 2,500 glucose molecules in their varied forms of polymerization. In general,

starches have the formula  $(C_6H_{10}O_5)_n$ , where "n" denotes the total number of glucose monomer units.

Structurally, the starch forms clusters of linked linear polymers, where the alpha-1,4 linked chains form columns of glucose units that branch regularly at the alpha-1,6 links. The relative content of amylose and amylopectin varies between species, and between different cultivars of the same species. For example, high-amylose corn (maize) has starch consisting of about 85 percent amylose, which is the linear constituent of starch, while waxy corn starch is more than 99 percent amylopectin, or branched starch. The primary function of starch in plants is energy storage.

Starches are insoluble in water. They can be digested by hydrolysis, catalyzed by enzymes called amylases, which can break the glycosidic bonds in the alpha-1,4 linkages of the starch polysaccharide. Hydrolysis of starches consists of cleaving the starch molecules back into their constituent simple sugar units by the action of the amylases. A second enzyme, glucoamylase, catalyzes the hydrolysis of the 1,6-linkages.

### **3. Cellulose: Definition and Availability**

Cellulose is a common material in plant cell walls and was first noted as such in 1838. It occurs naturally in almost pure form only in cotton fiber. In combination with lignin and hemicellulose, it is found in all plant material. Cellulose is the most abundant form of biomass (Crawford). Some animals, particularly ruminants and termites, can digest cellulose with the help of symbiotic microorganisms. Cellulose is processed to make cellophane and rayon, and more recently Modal, a textile derived from beechwood cellulose. It is also the major constituent of paper.

Cellulose monomers (beta-glucose) are linked together through  $\beta$ -1,4 glycosidic bonds by condensation. Cellulose is a straight chain (no coiling occurs). In microfibrils, the multiple hydroxide groups hydrogen bond with each other, holding the chains firmly together and contributing to their high tensile strength. This strength is important in cell walls, where they are meshed into a carbohydrate matrix, helping keep plants rigid.

The primary components of most plant materials are commonly described as lignocellulosic biomass: cellulose, hemicellulose, and lignin. In the plant cell wall, the cellulose molecules are interlinked by another molecule, hemicellulose. The hemicellulose is a branched polymer, substituted with arabinose, xylose, galactose, fucose, or glucuronic acid. Unlike cellulose, which is crystalline, strong, and resistant to hydrolysis, hemicellulose has an amorphous structure with little physical strength. Lignin is also present in significant amounts and gives the plant its structural strength. Lignin is essentially a three-dimensional phenylpropane, with units held together by ether and carbon-carbon bonds. The composition of different lignocellulosic biomass is both species and tissue specific, so plant selection for feedstock requires prior knowledge of the composition (Table 45).

**Table 45: Composition of Lignocellulosic Biomass Based on Dry Weight**

Biomass	Cellulose percent	Hemicellulose percent	Lignin percent
Corn stover	37.5	22.4	17.6
Corn fiber	14.3	16.8	8.4
Pine wood	46.4	8.8	29.4
Poplar	49.9	17.4	18.1
Wheat straw	38.2	21.2	23.4
Switchgrass	31.0	20.4	17.6
Bagasse *	34.6	19.4	20.0

Source: Mosier et al.

Every year, approximately 100 billion tons of new plant biomass is produced worldwide (Graboski and Bain). This amount of renewable biomass has an energy content roughly 10 times the energy value of all petroleum used worldwide. Feedstock costs are absolutely critical to the economy of commodity chemicals and fuels. Biomass feedstocks are less expensive than petroleum on both mass and energy bases. Therefore, with efficient and economically viable technologies to convert biomass to fuels, chemicals, and other products, there is ample reason to believe that biomass can compete with petroleum-derived technologies.

The three major markets envisioned for biomass-derived technologies are fuels, organic chemicals and materials, and electricity. The most promising route to these markets is a biobased industrial biorefinery. The biorefinery concept is similar to conventional petroleum refineries, which produce multiple fuels and products from petroleum.

USDOE and USDA jointly conducted research to determine if U.S. land resources are sufficient to support a biorefinery industry capable of replacing a significant portion U.S. petroleum consumption (USDOE and USDA, 2005). Target dates were set at the mid-21<sup>st</sup> century when large-scale biorefinery industries are likely to exist. This work showed that combined U.S. forest and agricultural land resources are capable of sustainably replacing more than a third of the Nation's current petroleum consumption. Forest resources include logging residues, fuel treatment thinning, and fuel wood extracted from forestland. Agricultural resources include grains used for biofuel, animal manures and residues, and crop residues derived primarily from corn and small grains such as wheat straw. Residues from sugarcane, rice, fruits, and nuts can also be used.

The USDOE and USDA study estimates that agricultural lands can provide nearly 1 billion dry tons of sustainably collectable biomass, while continuing to meet food, feed, and export demands. This estimate includes timber and forest residues, crop residues, perennial crops, grains used for biofuels, animal manures, process residues, and other residues generated in the consumption food products. The study predicts that this will require increasing yields of corn, wheat, and other small

grains by 50 percent, developing much more efficient residue harvesting equipment, growing perennial crops primarily dedicated to bioenergy, and using a larger portion of other secondary and tertiary residues for bioenergy. The study estimates that this level of biomass production can be achieved by the year 2050.

## **F. Pretreatments**

### **1. The Need for Pretreatment**

The complex structure of lignocellulosic biomass, the crystalline structure of cellulose, and the physical protection provided by hemicellulose and lignin prevent efficient hydrolysis and subsequent release of fermentable sugars by hydrolytic enzymes. Therefore, pretreatment is required to alter the structure of cellulosic biomass. In general, an effective pretreatment enhances the susceptibility of biomass to enzymatic hydrolysis by disrupting or removing barriers such as lignin and hemicellulose so that more surface area is available for the enzyme, and/or by decreasing the crystallinity of the cellulose structure.

Lignocellulosic biomass treatment can be classified as physical, chemical, or physiochemical (which incorporates both physical and chemical effects (McMillan, Hsu). The most common physical treatment is comminution or pulverization, which provides a dramatic increase in hydrolysis rate but demands extensive energy, a major drawback for these treatments. Chemical treatments with strong acid or base effectively increase the hydrolysis of cellulose. These chemicals are generally quite corrosive and expensive and are often toxic or inhibitory to microorganisms, requiring the removal of any residue prior to further processing. These treatments, while effective, are often expensive. Physicochemical treatments have the advantage of physical treatment without the expense of high energy use.

### **2. Examples of Pretreatment and their Applicability**

Several pretreatment technologies were evaluated by the Biomass Refining Consortium for Applied Fundamentals and Innovation (CAFI) group. A team of researchers from Auburn University, Dartmouth College, Michigan State University, the National Renewable Energy Laboratory (NREL), Purdue University, and Texas A&M University coordinated this project to develop comparative information on the performance of leading pretreatment techniques. This work was performed by using a single feedstock (corn stover), common analytical methods, and a consistent approach to data interpretation. This evaluation showed that all of the evaluated pretreatment methods have potential as cost-effective technologies (Wyman et al.). The evaluated pretreatments were dilute sulfuric acid cocurrent, flowthrough pretreatment, pH-controlled water treatment, ammonia fiber explosion (AFEX), ammonia recycle percolation (ARP), and lime treatment. Table 46 and Table 47 summarize the favorable processing conditions and the hydrolysis yields of each process, while Table 48 summarizes the major chemical and physical effects of the different biomass pretreatments.

### **a) Steam Explosion**

Steam explosion was not included in the CAFI study, however a great deal of research has been conducted on this treatment (McMillan; Hsu) and it is used commercially in the Masonite process for the manufacture of fiberboard and other products (DeLong). No chemical is involved in this treatment. Biomass is rapidly heated with high pressure steam for a specific amount of time followed by quick release of the pressure. Removing hemicellulose is one of the major effects of this process. This makes the cellulosic portion of biomass more available which subsequently increases the digestibility of the biomass. It has been suggested that acetic acid and other acids released during the pretreatment may be the major cause for hemicellulose removal. Terminating the process with rapid release of pressure disrupts and opens up the cell wall structure of the biomass and increases the accessible surface area, enhancing the digestibility. Due to the high temperature (~235°C), some of the biomass is degraded during the process.

### **b) Flowthrough Hot Water Treatment**

Flowthrough technologies pass hot water at 180 - 220°C and elevated pressure ( $P_g = 350 - 400$  psi) for 12 to 24 minutes over a stationary bed of biomass. In this process, there is no need for additional chemicals or neutralization. A significant portion of lignin is removed and the solid left behind is highly digestible. Up to 96 percent overall sugar yield is achievable, but the process suffers from low concentration of sugars (due to dilution) and requires significant energy for product recovery (Mosier et al.).

### **c) Acid Pretreatment**

Dilute sulfuric acid is used commercially to produce furfural from cellulosic materials (Zeitsch). USDOE has spent much of the last two decades developing the dilute acid technology as a pretreatment for lignocellulosic biomass, and is now funding major efforts to position this technology in emerging biorefineries. In this process a mixture of biomass and acid is heated indirectly through the reactor vessel walls or by direct steam injection. The dilute acid is percolated through a bed and sprayed onto the biomass, after which it is agitated and/or heated in a reactor. Acid pretreatment with dilute sulfuric acid (0.5 - 3 percent) at temperatures of 130 - 200°C effectively removes hemicellulose, which results in high digestibility of the cellulose in the residual solids. In this process, lignin is not dissolved; however, data suggest that lignin is disrupted, increasing cellulose susceptibility to enzyme. With this treatment, up to 90 percent hemicellulose yields are achieved and enzymatic hydrolysis yields of glucose can be over 90 percent (Hsu). Dilute acid treatment has some limitations, including costly materials of construction, high pressure, neutralization, formation of degradation products, and release of fermentation inhibitors.

**Table 46: Favorable Processing Conditions for Biomass Pretreatments**

<b>Pretreatment</b>	<b>Chemical used</b>	<b>Temperature, °C</b>	<b>Pressure, atm absolute</b>	<b>Reaction time, minutes</b>	<b>Concentration of solid, weight percent</b>
Dilute sulfuric acid cocurrent	0.5-3 percent sulfuric acid	130-200	3-15	2-30	10-40
Flowthrough pretreatment	0.0-0.1 percent sulfuric acid	190-200	20-24	12-24	2-4
pH-controlled water pretreatment	water or stillage	160-190	6-14	10-30	5-30
AFEX	100 percent(1:1) anhydrous ammonia	70-90	15-20	<5	60-90
ARP	10-15 wt percent ammonia	150-170	9-17	10-20	15-30
Lime	0.05-0.15g Ca(OH) <sub>2</sub> /g biomass	70-130	1-6	1-6h	5-20
Lime + air	0.05-0.15g Ca(OH) <sub>2</sub> /g biomass	25-60	1	2 weeks-2months	10-20

Source: Wyman et al.

**Table 47: Sugar Yields for Each Pretreatment Followed by Enzyme Hydrolysis with 15 FPU/ g Glucan in the Original Corn Stover**

Pretreatment	Xylose yield (percent)			Glucose yield (percent)			Total sugar (percent)		
	Stage 1	Stage 2	Total yields	Stage 1	Stage 2	Total yields	Stage 1	Stage2	Combined (Glucose + xylose) sugars
Dilute acid	32.1/31.2	3.2	35.3/34.4	3.9	53.2	57.1	36.0/35.1	56.4	92.4/91.5
Flowthrough	36.3/1.7	0.6/0.5	36.9/2.2	4.5/4.4	55.2	59.7/59.6	40.8/6.1	55.8/55.7	96.6/61.8
pH controlled	21.8/0.9	9	30.8/9.9	3.5/0.2	52.9	56.4/53.1	25.3/1.1	61.9	87.2/63.0
AFEX		34.6/29.3	34.6/29.3		59.8	59.8		94.4/89.1	94.4/89.1
ARP	17.8/0	15.5	33.3/15.5	0	56.1	56.1	17.8/0	71.6	89.4/71.6
Lime	9.2/0.3	19.6	28.8/19.9	1.0/0.3	57	58.0/57.3	10.2/0.6	76.6	86.8/77.2

Note: Stage 1 refers to pretreatment and stage 2 to the enzymatic hydrolysis of solids generated after each pretreatment. The first value in each column represents total sugars released into solution and the second is for the monomers. A single value indicates release of only monomers. Yields are defined based on the maximum potential sugars released from the corn stover used of 64.4 g per 100g of dry solids with maximum potential xylose being 37.7 percent and the maximum potential yield of glucose being 62.3 percent on this basis. FPU = Filter Paper Units.

Source: Wyman et al.

**Table 48: Chemical and Physical Effects of Alternative Biomass Pretreatments on the Biomass Structure**

Pretreatment	Increase Surface area	Cellulose crystallinity	Removes hemicellulose	Removes lignin	Alter lignin structure
Steam explosion	++	Increases	++		+
Dilute acid	++	Increases	++		++
Flowthrough acid	++	ND	++	+	++
Flowthrough hot water	++	ND	++	+	+
pH controlled	++	ND	++		ND
AFEX	++	Decreases	+		++
ARP	++	Decreases	+	++	++
Lime	++	ND	+	++	++

Note: ++: Major effect, +: Minor effect, ND: Not determined

Source: Mosier et al.



#### **d) Flowthrough Acid Pretreatment**

The addition of very dilute sulfuric acid (about 0.07 - 0.1 percent versus the 0.5 - 3 percent typical dilute acid technology) in a flow-through reactor is very effective in pretreatment of biomass. This technique achieves high hemicellulose sugar yields and highly digestible cellulose, but generated products are very dilute. The large amount of water used in this process results in high energy requirements for pretreatment and product recovery.

#### **e) Controlled pH Pretreatment**

Controlled pH pretreatment using potassium hydroxide (KOH) is based on the properties of water under pressure and elevated temperature (160 - 190°C). Temperature affects the  $pK_a$  of water; the pH of pure water at 200°C is almost 5.0 (Weil et al.). Water with high dielectric constant is able to dissociate ionic substances such as hemicellulose and lignin. One-half to two-thirds of lignin dissolves from most biomass treated at 220°C for 2 minutes. In this process, water under pressure (6 - 14 atm) penetrates the cell structure of biomass, hydrates cellulose, and removes hemicellulose so that the treated biomass is highly reactive. In this pretreatment, KOH is not used as a catalyst but to maintain the pH between 5 and 7 and prevent the hydrolysis of monosaccharides.

#### **f) Lime Pretreatment**

In lime pretreatment, biomass materials are sprayed with a slurry of lime (calcium hydroxide) and water (typical loading of 0.05% - 0.15g  $Ca(OH)_2$ /g biomass) and stored in a pile for a period of days to weeks at temperatures of 25 - 60°C. Addition of air/oxygen to the reaction mixture (oxidative lime treatment) improves the delignification of the biomass. Removal of lignin (typically 33 percent), acetyl, and various uranic acid substitutions from hemicellulose are the major effects of lime pretreatment, and results in a very reactive biomass. Due to the low process temperature, there is no need for a pressure vessel, reducing the capital cost of this process (Eggeman and Elander). The logistics of handling and storing large amounts of biomass is a major drawback.

#### **g) Ammonia Treatments**

In ammonia fiber explosion (AFEX), biomass is treated with liquid anhydrous ammonia at moderate temperatures (60 - 100°C) and a pressure of 250 - 300 psi for 5 minutes. The pressure is then rapidly released. In this process, the combined chemical and physical effects of modifying or altering hemicellulose and lignin structure, cellulose decrystallization, and increased surface area enables near-complete enzymatic conversion of cellulose and hemicellulose to fermentable sugars (Teymouri et al.). AFEX can be performed in lower cost vessels (compared with acid pretreatment, the hydrolysate is compatible with fermentation organisms without conditioning), ammonia can be recovered and reused, and any residual ammonia serves as a nitrogen source

for microbial production of products from this feedstock. Efficient ammonia recovery is critical to the economics of this pretreatment. With the use of moderate temperatures and high pH, the formation of sugar degradation products is minimal while the sugar yield is high.

Another ammonia process is ammonia-recycled percolation (ARP). In this process, aqueous ammonia (10 - 15 percent by weight) at elevated temperature (150 - 170°C) passes through the biomass and then is then recovered for recycling (Kim et al.). ARP is highly effective in delignifying biomass and increasing the enzymatic digestibility. The ARP process removes about 70 to 85 percent of lignin. The crystalline structure of cellulose is not altered by the ARP process. This process also suffers from a high energy requirement for pretreatment and product recovery due to the large amount of water used.

## VI. Integrated Biobased Production: The Biorefinery Concept

The biorefinery model is not new. The conceptual framework is consistent with the traditional petroleum based refinery where crude oil is fractionated into various coproducts, such as gasoline, kerosene and asphalt. As biorefineries built on ethanol and biodiesel fuel platforms continue to expand, the growth in new biobased coproducts will similarly increase. Significant growth in terms of larger volumes and greater varieties of biobased products is expected to occur as the development of new technologies and the emergence of new chemical models emerge over the next two decades.

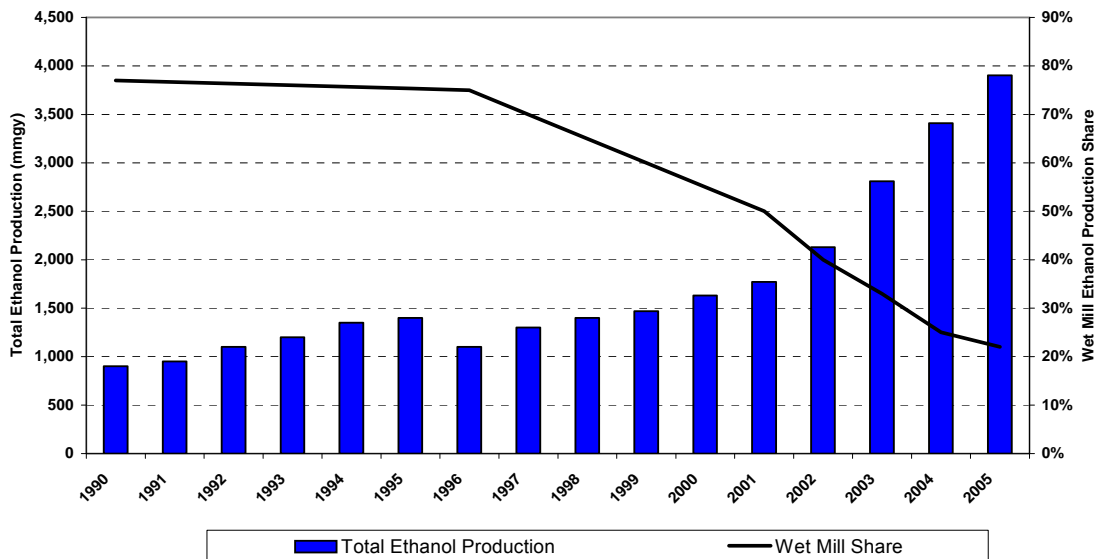
### A. Existing Biorefinery Technologies

There are two basic technologies currently being used in the United States to produce ethanol from corn. The most widely used (78 percent of U.S. ethanol production capacity) is the dry-mill process (also called dry-grind process), which uses the entire kernel to produce ethanol. Wet-mill technology uses the concentrated starch fraction of the kernel.

#### 1. Production History

When the Clean Air Act Amendments of 1990 were passed, most ethanol was produced in wet mills. These plants are generally large, some with capacities over 100 million gallons a year (mgy). This technology's ethanol production share remained relatively flat through 1996 (Figure 54).

**Figure 54: U.S. Ethanol Production and Wet Mill Production Share 1990 - 2004**



Source: Informa Economics et al., Biobased Multi-Client Study, March 2006.

After 1996, virtually all new plants built were dry-mill facilities due to lower capital costs and slightly higher ethanol yields. Until recently, dry-mill plants were small, with maximum capacities around 50 mgy, but a few newly constructed and proposed dry mills have capacities above 100 mgy.

## 2. Dry Mill Ethanol Process

Dry milling is an eight-step process (Figure 55):

1. Milling.
2. Liquefaction.
3. Saccharification.
4. Fermentation.
5. Distillation.
6. Dehydration.
7. Denaturation.
8. Coproduct Processing.

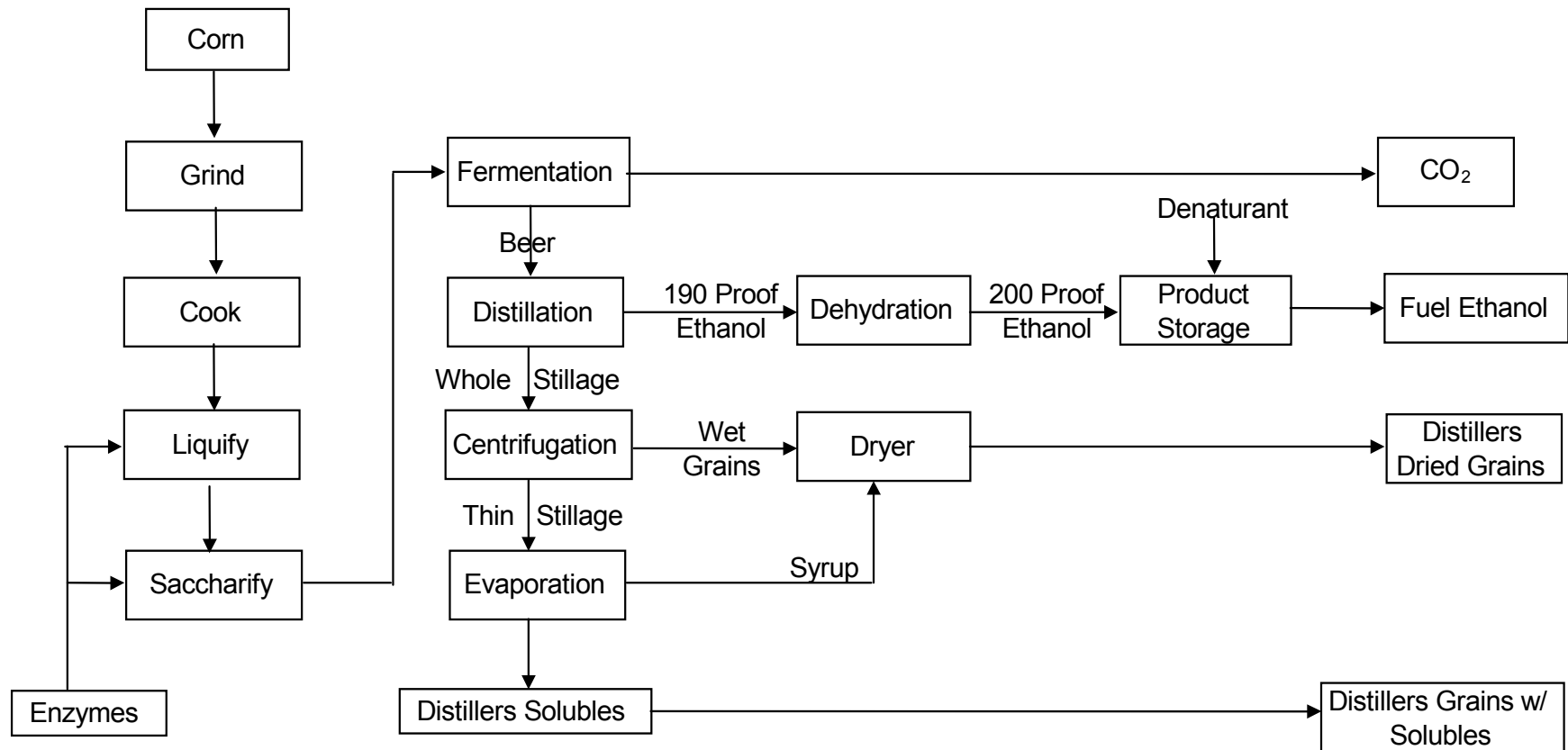
In milling, the entire corn kernel (or other grain feedstock) is ground into flour called “meal” using a hammer mill without first separating the component parts of the grain. In the liquefaction step, enzymes (alpha amylase) and water are added to the meal to form mash. The enzymes begin to break the cornstarch into simple sugars. To complete liquefaction, the mash is heated to between 250 and 300 degrees to reduce the level of bacteria in the mixture. In the saccharification step, another enzyme (gluco-amylase) is added to the mash to complete the breakdown of the starch into dextrose.

To begin the fermentation process, the mash is cooled and yeast is added to break the dextrose down into ethanol and carbon dioxide. The mash generally remains in the fermentation tank for 40 - 50 hours, at which point it is called beer. The beer consists not only of ethanol, but also the solids from the original corn feedstock that are not fermented. After fermentation, the beer is transferred to distillation columns where the ethanol is separated from the rest of the beer. At this point, the ethanol is 96 percent pure ethanol (190 proof). It can then be dehydrated to 200 proof using a molecular sieve. The ethanol is then blended with 2 - 5 percent denaturant (conventional gasoline), which renders the product undrinkable.

After distillation of the ethanol, the remaining portion of the beer is called stillage. The stillage is centrifuged to separate the coarse grain from the liquid. The liquid contains soluble material and is dried to approximately 70 percent moisture by evaporation. The resulting product is called condensed distillers solubles (CDS). The CDS is usually added back to the coarse grains, although it can be sold separately. This product is called wet distillers grains with solubles (WDGS), which can be shipped to local livestock feeding operations (primarily cattle). WDGS, however, cannot be transported long distances due to problems with rancidity, as

well as the prohibitive economics of transporting material that is approximately 65 percent water. WDGS can be dried further to produce distillers dried grains with solubles (DDGS), which can be shipped locally via truck or further distances via rail. DDGS is a middle-protein feed with a minimum crude protein content of approximately 30 percent (for older facilities, the crude protein content is roughly 27 percent), fat content of 11 percent, and fiber content of 4 percent. The remaining coproduct of the fermentation process, carbon dioxide, can be used in beverage manufacture, dry ice production, or in flash freezing. In locations where there is a surplus of carbon dioxide, the economics might not support capturing carbon dioxide output. In those cases the release of carbon dioxide would add to green house gas emissions.

Figure 55: Corn Dry Milling Process



Source: Informa Economics et al., Biobased Multi-Client Study, March 2006.

### 3. Wet Mill Ethanol Process

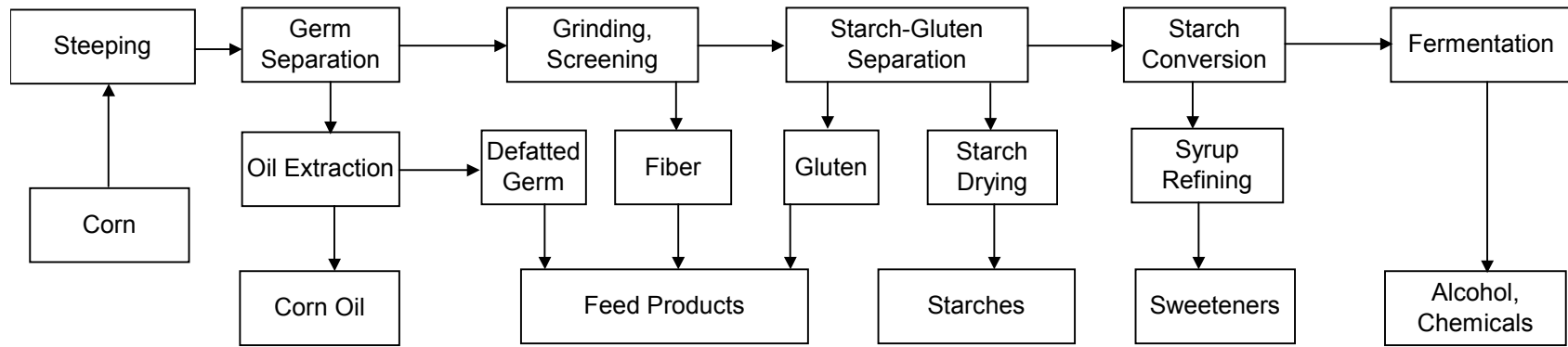
Whereas the dry-mill process is relatively straightforward and has been focused on one primary product (ethanol), the wet-mill process is a step closer to the biorefinery concept, separating the corn kernel into several valuable components (Figure 56). The entire corn kernel is first steeped in a weak solution of sulfur dioxide for 24 - 48 hours at around 125°F to prepare it to be broken into its component parts. After steeping, the corn kernel is ground to recover the germ, which is further processed to remove the corn oil. The remaining portion of the germ is called corn germ meal and is either sold as a feed ingredient or included in corn gluten feed (at wet mills that have captive oil extraction units). Corn germ meal is typically 20 percent protein, 2 percent fat, and 9.5 percent fiber. When sold separately, it is used primarily in swine and poultry rations.

The rest of the corn kernel is screened to remove the bran (fiber), which is mixed with the steep water and then sold in wet form as wet corn gluten feed (WCGF) or dried to produce corn gluten feed (CGF). CGF is approximately 21 percent protein, 2.5 percent fat, and 8 percent fiber, and is used primarily in cattle rations.

The remaining unprocessed portion of the corn kernel is centrifuged to separate the gluten, which is concentrated and dried to produce corn gluten meal (60 percent protein, 2.5 percent fat, 1 percent fiber), from the starch, which can be processed into a number of products. Corn gluten meal is primarily used as broiler (chicken) feed, but is also used in pet foods. Corn gluten meal can also be sold to further processors for the manufacture of concentrated vegetable proteins, which are used in applications such as meat replacers and extenders.

The starch resulting from the wet milling process can be sold or further processed into other value-added products. Fermentation into ethanol is similar to the process for dry milling (excluding the initial treatment). Starch can also be dried and sold, or processed into starches tailored to specific food and industrial applications. The starch can be converted into high-fructose corn syrup (mainly used in soft drinks) or glucose, which is standard corn syrup. In the past, some wet mills with the requisite equipment would shift from ethanol production in the winter months to high-fructose corn syrup in the summer months, when soft drink consumption increased.

**Figure 56: Corn Wet Milling Process**



Source: Informa Economics et al., Biobased Multi-Client Study, March 2006.



## **B. Emerging Biorefinery Technologies**

### **1. Corn Fractionation in Dry Mills**

The current petrochemical industry is predicated on multiple products extracted from crude petroleum in a refinery. This multiplies revenue streams and reduces waste streams from petroleum processing. Corn wet mills producing ethanol also produce multiple products, such as corn oil, gluten feed, and high-fructose corn syrup. To be competitive in the absence of government subsidies, dry-mill ethanol producers must adopt the same strategy and develop value-added products to enhance their profitability and sustainability. To do this, new technologies are needed for integration into corn dry milling.

Corn wet mills have a major advantage over dry mills in producing high-value coproducts, as noted above, but are capital intensive. Corn dry mills, though less costly, suffer from low coproduct value in distillers dried grains with solubles (DDGS) and carbon dioxide. To compensate, a number of technological advances have been made to reduce processing costs and increase the value of coproducts.

#### **a) Raw Starch Hydrolysis Technology**

The cooking step necessary to liquefy starch in the dry-grind ethanol process is energy intensive and has some undesirable side effects. For example, the Maillard reaction (which limits the availability of sugar and protein) can result in yeasts with more wasteful product, such as glycerol (the high humectancy of glycerol limits the drying process of DDGS).

The cooking step can be substituted by a raw starch hydrolysis method, also referred to as cold hydrolysis, where enzymes are used to hydrolyze starch that has not been cooked into fermentable sugar. Compared with traditional dry mills, the dry-grind process using raw starch hydrolysis results in DDGS of higher quality and increased protein content, and lower energy cost during drying. The modified DDGS can be sold at a premium based on its exact protein content.

Broin Companies, with “Broin Project X” (BPX), and Genencor International Inc., with Stargem™, have both recently commercialized raw starch hydrolysis technology. The method is still in its infancy, but is promising. Nine plants are currently using BPX (Williams).

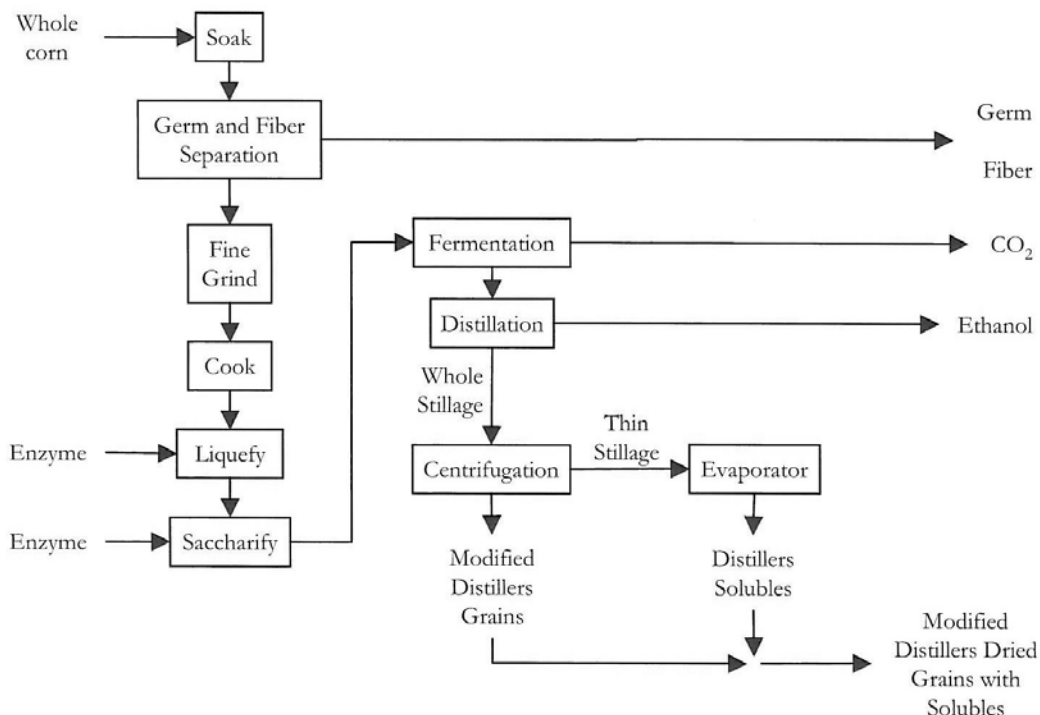
#### **b) Modified Dry Grind Ethanol Process**

The modified dry-grind ethanol process was developed in the 1990s to increase the value and quantity of coproducts made from traditional corn dry mills (Figure 57). In this process, the germ and fiber from the corn are separated at the front end, before the commencement of fermentation. The endosperm is fermented to produce

ethanol, while the residual is converted into value-added coproducts. Thus, this biorefining technology separates the corn into fiber, germ, and endosperm.

Because much of the germ and fiber are not fermentable into ethanol, efficiency is improved over conventional dry mills. In addition, removing the nonfermentable components at the front end enables DDGS of better quality and higher protein content.

**Figure 57: Modified Dry Grind Ethanol Process with Germ and Fiber Recovery**



Source: Singh et al. July 2001.

The modified dry-grind ethanol process is becoming increasingly popular. Cargill and Badger State Ethanol LLC (Monroe, WI) both plan to implement it. Broin has two operations (and another under construction) using this process.

Several dry-grind ethanol processes have been modified whereby fermentation rates, yields, and coproduct composition vary. These processes can be grouped into two families: the first uses a dry milling process<sup>21</sup> and the second a wet fractionation technology.<sup>22</sup> These two processes differ in the quality of coproducts and capital costs. With the former, germ recovered has a lower oil content and fiber a lower quality, whereas the latter requires higher capital costs. Various coproduct uses exist for the germ, fiber, and DDGS from the dry-grind process.

<sup>21</sup> The whole corn is soaked in water and then ground.

<sup>22</sup> The whole corn is soaked in water before conventional wet milling degermination, and germ and fiber recovery.

### Fiber

Corn fibers recovered through the modified dry-grind ethanol process are of good quality. The type of recovery process used, however, determines the use of the fibers. Wet fractionation enables the recovery of very high-quality fibers, allowing their subsequent use as dietary fibers.

### Dietary Fiber

The most widely accepted definition of dietary fiber is that put forth by the American Association of Cereal Chemists (AACC): "Dietary fiber is the edible parts of plants or analogous carbohydrates that are resistant to digestion and absorption in the human small intestine with complete or partial fermentation in the large intestine. Dietary fiber includes polysaccharides, oligosaccharides, lignin and associated plant substances. Dietary fibers promote beneficial physiological effects including laxation, and/or blood cholesterol attenuation, and/or blood glucose attenuation."

The demand for dietary fibers has been especially high in countries with high consumer awareness of food-related health: North America, Europe, and Japan. Demand is growing an estimated 12 percent a year, making dietary fibers a very attractive market. However, because the market is relatively new, the actual supply and demand of fiber products in the United States is uncertain.

Dietary fibers are a highly specialized and heterogeneous product not traded or quoted on any commodity exchange. Due to tight supplies and large demand, food-grade corn fibers are currently expensive. The price of dietary corn fibers can range from 20 to 70 cents a pound, depending on the type of fibers (for instance, soluble or insoluble). Very few, if any, U.S. plants currently produce dietary corn fibers. However, a number of other corn products rich in fibers, such as corn grits, are marketed as food-grade fibers.

### Feed Products

Fibers can be used in a number of pet food applications. Broylax Companies, for example has trademarked a feed product made of bran and corn-condensed distillers solubles, Dakota Bran™ Cake.

Corn germ can be sold either as a high-energy feed product or as a source of corn oil. Corn oil usually trades at a premium (of \$0.02 to \$0.025 a pound) to soybean oil due to better flavor and other attributes. Germ recovered using a dry milling process has much lower oil content than with wet fractionation, and so is more suitable as feed.

The concentration of proteins in distillers dried grains (DDG) is increased as fiber is diverted. This enhances its potential for use in nonruminant livestock diets. In the modified dry-grind ethanol process, less mass is fermented than in a dry mill, resulting in DDG with higher (40 - 48 percent) protein content. The protein feed market is well defined, with price patterns for different products based on protein concentration. Ultimately, the price of soybean meal (SBM) dictates the pricing for

all major protein feeds. Modified DDG is typically traded at the same level as high-protein SBM.

### Combined Technologies

The modified dry-grind ethanol process can now be coupled with raw starch hydrolysis, which should decrease processing costs and may increase DDG quality. Raw starch hydrolysis allows for the saccharification of corn starch without higher temperature hydrolysis, thereby saving energy and reducing process time (the hydrolysis and fermentation are performed at similar temperature and pH). This process requires the corn to be milled to a smaller particle size and is especially adaptable to plants using corn endosperm feedstock. Broin Companies has filed patents for such a process (BPX) and the use of enabling enzymes. Broin Companies has teamed with Novozymes to introduce this technology into their ethanol plants.

### **c) Corn Oil Extraction**

Corn oil of food-grade quality can be extracted from corn germ produced by corn fractionation. Both solvent extraction and expeller extraction can be used. Additional technology is being marketed to extract corn oil from dry millers' fermentation residues, usually from thin stillage extracted by centrifugation. The resulting corn oil has an increased level of free fatty acids, making it an unlikely candidate for food-grade corn oil and a likely source of oil for biodiesel production. New technologies being investigated for oil extraction include enzymatic extraction and cellulase hydrolysis (Moreau). Currently, most oil is extracted using hexane. Using enzymes would eliminate the hexane, a chemical with health and safety issues for food production.

## **2. Lignocellulose Based Biorefineries**

As with grains, processing cellulosic biomass is directed toward extracting fermentable sugars from the feedstock. The sugars in cellulose and hemicellulose are locked in complex carbohydrates called polysaccharides (long chains of monosaccharides or simple sugars). Two processing options are used. Acid hydrolysis breaks down the complex carbohydrates into simple sugars. Enzymatic hydrolysis uses pretreatment to reduce the size of the feedstock prior to hydrolysis, conducted by enzymes. The final step involves microbial fermentation, yielding ethanol and carbon dioxide.

Grain based ethanol uses fossil fuels to produce heat during the conversion process, generating substantial greenhouse gas emissions. Cellulosic ethanol production can substitute biomass for fossil fuels, changing the emissions balance.

The Department of Energy (USDOE) biofuels program has identified the high cost of cellulose enzymes as the key barrier to economic production of cellulosic ethanol. Two enzyme producers, Genencor International and Novozymes Biotech, have

received research funding from USDOE to engineer significant cost reductions and efficiency improvements in cellulose enzymes.

Another major thrust of Research and Development efforts is improving pretreatment technologies. Pretreatment technologies use dilute acid, steam explosion, ammonia fiber explosion (AFEX), organic solvents, or other processes to disrupt the hemicellulose/lignin sheath that surrounds the cellulose in plant material. Each technology has advantages and disadvantages in terms of costs, yields, material degradation, downstream processing, and generation of process wastes. One of the most promising technologies, AFEX, uses liquid ammonia under moderate heat and pressure to separate biomass components. A detailed description of these pretreatment technologies is presented in the previous section.

The economics of biorefineries require coproducts such as power, protein, chemicals, and polymers to offset processing costs and improve profit margins. Generation of coproducts also results in greater biomass and land use efficiencies, along with a more effective use of invested capital. Lignin and protein, two important coproducts, can significantly improve the economics of biorefineries. Lignin, a nonfermentable residue from hydrolysis, has energy content similar to coal and can be used to power the biorefinery, thereby reducing production costs. Iogen is operating a facility in Ottawa, Canada, utilizing proprietary enzyme hydrolysis and fermentation techniques to produce 260,000 gallons a year of ethanol from wheat straw.

Two companies are exploring the integration of cellulosic biomass in existing corn ethanol and wet grain milling facilities. Broin Companies has received a \$5.4 million grant from USDOE to investigate using fiber and corn stover in the production of ethanol. A \$17.7 million grant from USDOE is funding Abengoa's research on processes to pretreat a blend of distillers' grain and corn stover to produce ethanol. The project calls for the building of a pilot-scale facility in York, Nebraska.

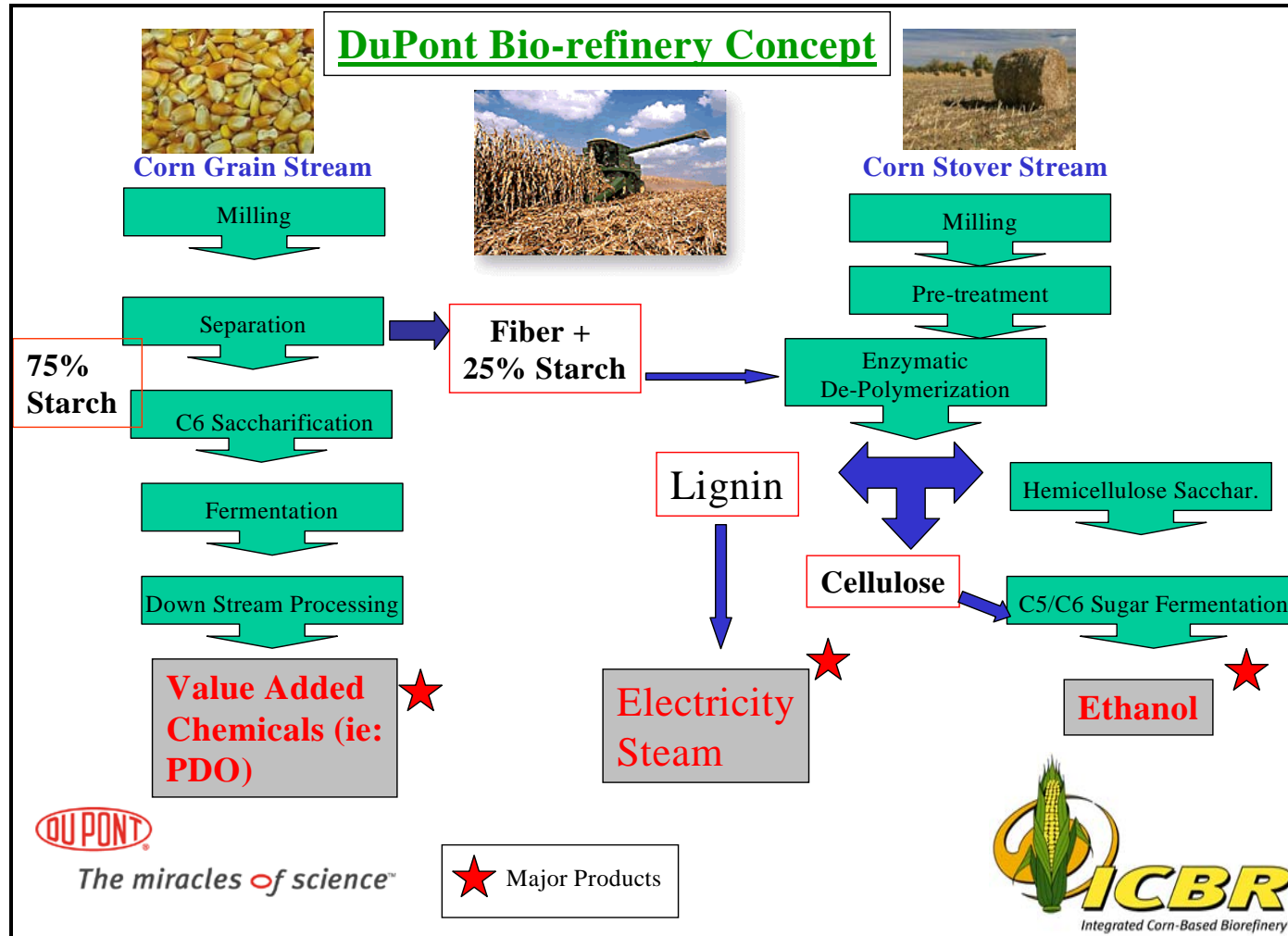
BC International is applying a proprietary acid hydrolysis technology to agricultural residues and forest thinning feedstocks to produce ethanol. The company is developing facilities in Louisiana, California, and Asia, and claims their process lowers the cost of ethanol.

An emerging body of thought among industry participants and observers is that the initial breakthrough in cellulosic conversion to ethanol will be the transformation of corn kernel cellulose in dry-mill ethanol plants (Tiffany and Eidman). The benefits of this process would be substantial. The plants would have an immediate yield increase of 5 - 10 percent, with minor variable cost increases. In addition, the volume of DDGS would be substantially reduced. The profitable sale of DDGS has emerged as an important economic consideration for the fuel ethanol industry.

If successful, the logistics of converting corn kernel fiber to ethanol are expected to be applicable to other cellulosic raw materials like corn stover (Figure 58).

Using existing biorefineries, specifically pulp and paper mills, as test sites for ethanol is another option to accelerate commercialization. Many of these facilities in North America are underutilized and possess infrastructure that may allow their economic conversion to grain based ethanol production (initially) and ethanol from cellulosic raw material (potentially).

Figure 58: DuPont's Corn-Based Biorefinery Concept



Source: Informa Economics et al., Biobased Multi-Client Study, March 2006.

## VII. Biomass Feedstocks: Supply and Spatial Distribution of Raw Materials

Industrial biobased products in the United States use an estimated 12 billion pounds of biomass/year (Energetics, Inc., 2003). Based on the feedstocks used the biobased products fall into four main categories:

- Cellulose derivatives, fibers, and plastics:
  - Primarily derived from wood pulp and cotton linters; products include cellulose acetate, cellulose nitrate, and regenerated cellulose.
  - Major producers include Dow Chemical, Celanese, DuPont.
- Oil and lipid based products:
  - Primarily derived from soybean and oilseeds; products include oils, fatty acids, and glycerine.
  - Major producers include Cambrex, Vertec BioSolvents AG, Environmental Products LLC, West Central Soy, and Lonza.
- Sugar and starch products:
  - Primarily derived from corn, sugar cane, sugar beets, wheat, rice, potatoes, barley, sorghum grain, and wood; products include alcohols, starch, acids, xanthan gum, industrial enzymes used in laundry detergents, textile sizing, alcohols, and oils.
  - Major producers include Archer Daniels Midland (ADM), Arkenol, Cargill, Minnesota Corn Processors, DuPont, Grain Processing Corporation, Tate & Lyle, Williams Bio-Energy, Genencor, and Novozymes.
- Gum and wood chemicals:
  - Primarily derived from trees; products include resins, tall oil, pitch, fatty acids, and turpentine.
  - Major producers include Westvaco, Hercules, Norit America, Arizona Chemical, Georgia Pacific, and Akzo Nobel Resins.

A summary assessment of key North American biobased feedstocks based on Informa Economics et al., Biobased Multi-Client Study (March 2006) is presented in Table 49. Within the set of traditional crop outputs (primary feedstocks), corn, soybeans, and canola are expected to continue to dominate. A new biorefinery industry is contingent on raw material from substantial, stable, and well-established sources. Within the new generation of raw materials (residual feedstocks), corn stover, wheat straw, and timber waste appear to be most likely. The efficient handling and assembly systems in place for these biomass resources offer advantages.

It is not likely that any commercial cropland will convert from traditional crops to dedicated biomass such as switchgrass, unless these energy crops and dedicated biomass can compete with traditional crops. However, the use of biomass from cropland in the Conservation Reserve Program (CRP) [Map 10] would be a potential source of raw material supply if wildlife, conservation, and environmental interests



were maintained, appropriate financial terms set, and associated WTO trade issues resolved. Systems are already in place for harvesting hay from CRP acreage, historically on an emergency basis and more recently under more lenient circumstances. Several analyses indicate that grass species in place are generally suitable for biorefinery use and capable of significantly greater biomass yields if intensive cultural practices are applied.

As with the corn based ethanol industry, a biorefinery based on biomass - whether agricultural residue, CRP resources, or woody biomass - will locate near the raw material. Map 11 to Map 22 indicate where the primary feedstocks and residues are cropped in the U.S. and Canada. Animal waste streams from dairies and feedlots (and their likely use in methane conversion) are another potential source of biomass (Map 23 and Map 24). Canada is included in the mapping analysis because of the economic integration of feedstock resources. For example, the production of canola in Canadian prairies is very important in the development of the U.S. biodiesel industry. A number of biodiesel facilities proposed or under construction in North Dakota are expecting to import significant volumes of canola from Canada in order to crush the seed and use the oil in the manufacturing of biodiesel. Currently substantial amounts of canola are imported from Canada for use by U.S. food manufacturers. There are also close ties regarding research and corporate initiatives/ventures, such as the investment of \$30 million in 2006 by the Wall Street firm Goldman Sachs in the Canadian firm Iogen to help develop cellulose to ethanol technologies.

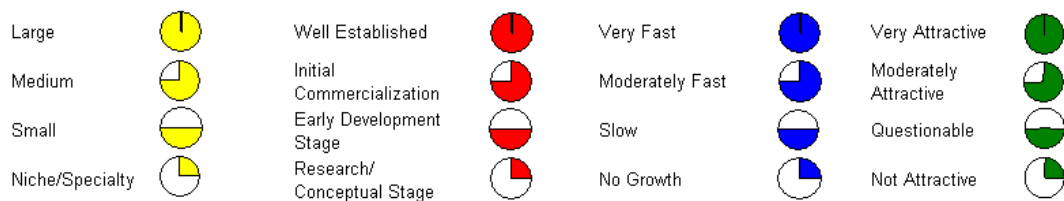
Given the low energy density of biomass as a raw material, transportation logistics will be a critical consideration. Many industry observers believe that a system of terminals, analogous to the grain elevator system will be required. At such terminals, bulk could be reduced physically or pretreated chemically to increase energy density before transport to the biorefinery.

Some industry participants contend that straw, wheat, small grains, and rice will be the initial raw material of choice over the more abundant corn stover. The thinking is that handling systems are already in place for these crops and could collect the biomass now. In the case of rice straw there is a need to remove the residue from the field anyway. Others argue corn stover can be gathered with machinery and techniques nearly identical to straw handling and agribusiness can respond quickly to market needs (for additional machinery).

Nonetheless, substantial management issues regarding storage and handling of biomass remain to be resolved.

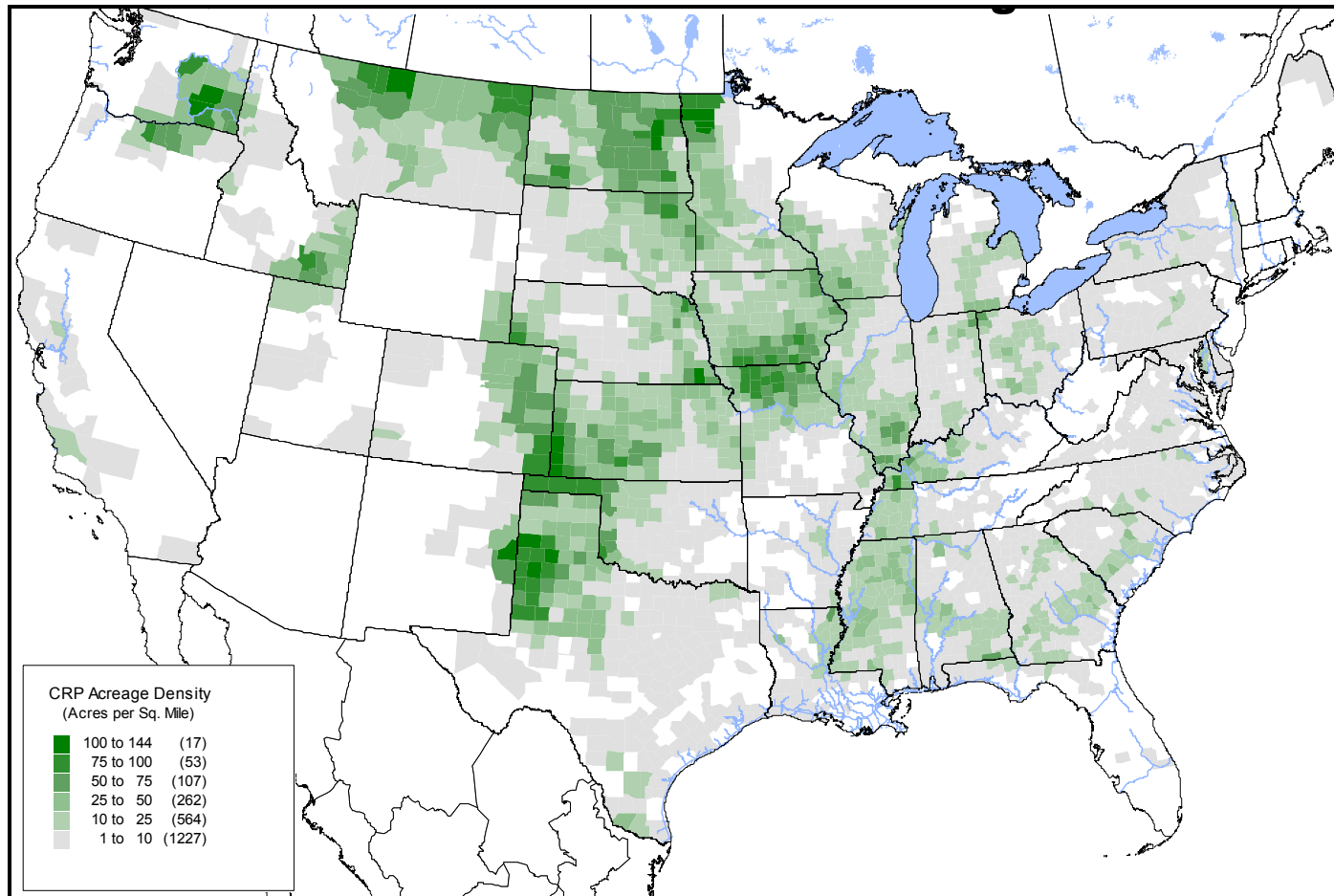
**Table 49: Summary Assessment of U.S. and Canadian Biobased Crop Feedstocks**

Feedstocks	Current Scale of Resource Base	Complexity of Assembling	Stage of Development in BioEconomy	Potential Market Growth	Overall Attractiveness
<b>Primary Feedstocks:</b>					
Canola					
Corn					
Wheat					
Sorghum					
Soybeans/Soybean Oil					
Switchgrass/Conservation Reserve					
Grasses (other sources)					
Cultivated Trees (willows/poplars)					
Manged Timber Tracts					
<b>Residual Feedstocks:</b>					
Corn Stover					
Corn Fiber					
Wheat Straw					
Barley					
Oats					
Rice Straw					
Rye					
Timber Waste					



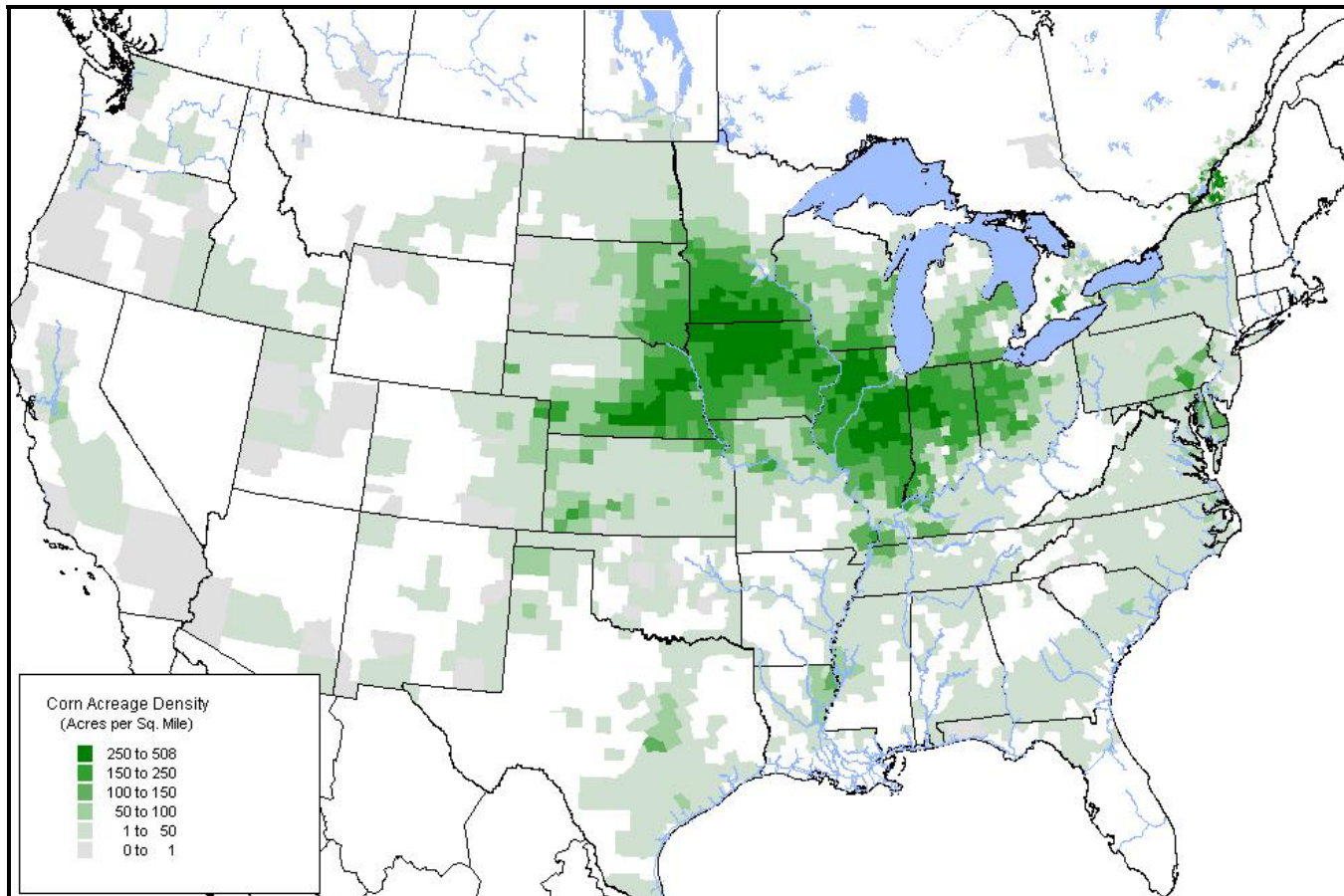
Source: Informa Economics et al., Biobased Multi-Client Study, March 2006.

Map 10: Land in the U.S. Conservation Reserve Program, 2002



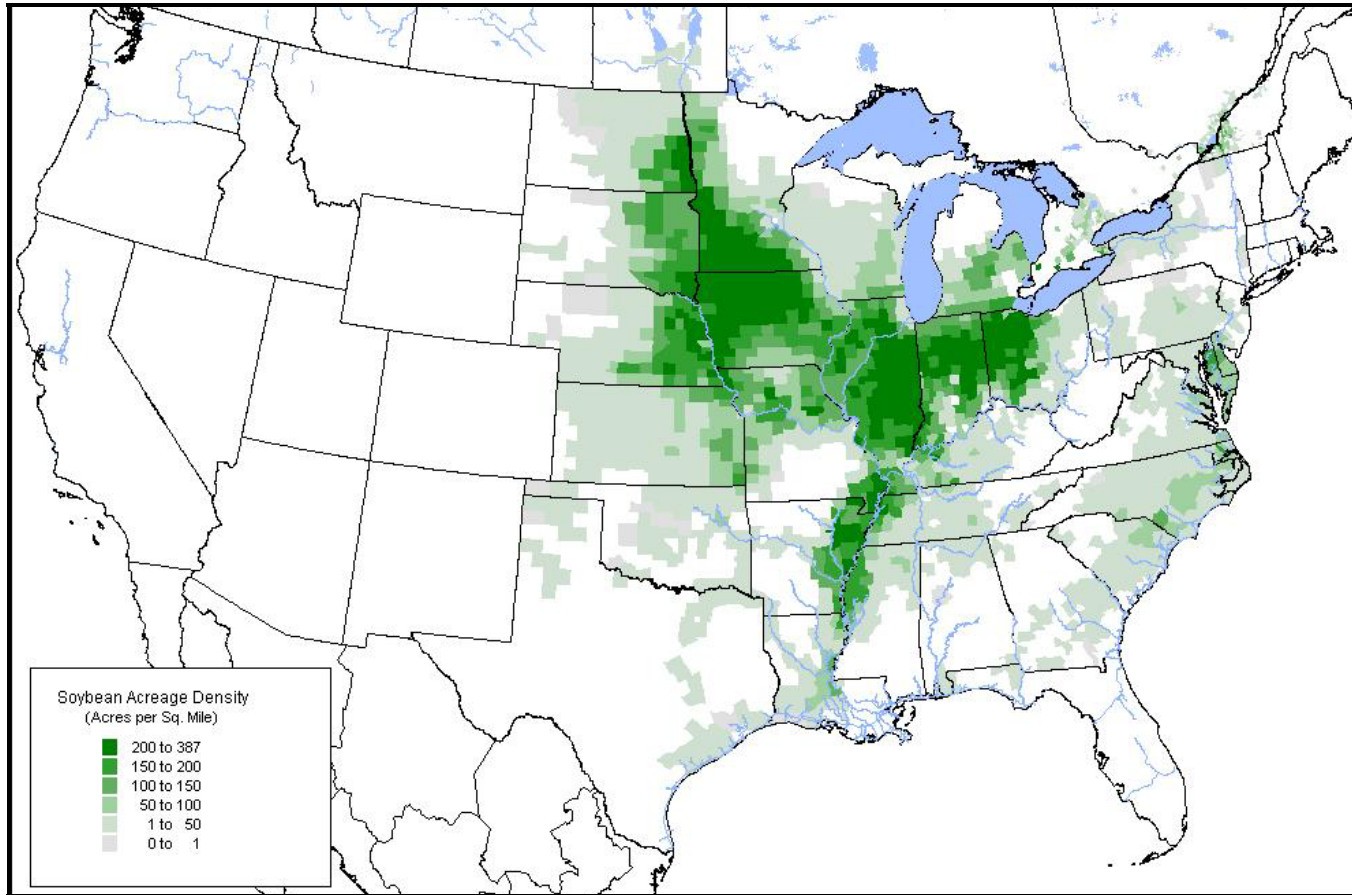
Sources: Data - U.S. Department of Agriculture, National Agricultural Statistics Service, and Mapping – Informa Economics.

**Map 11: U.S. Corn Acreage, 2002 - 2005**



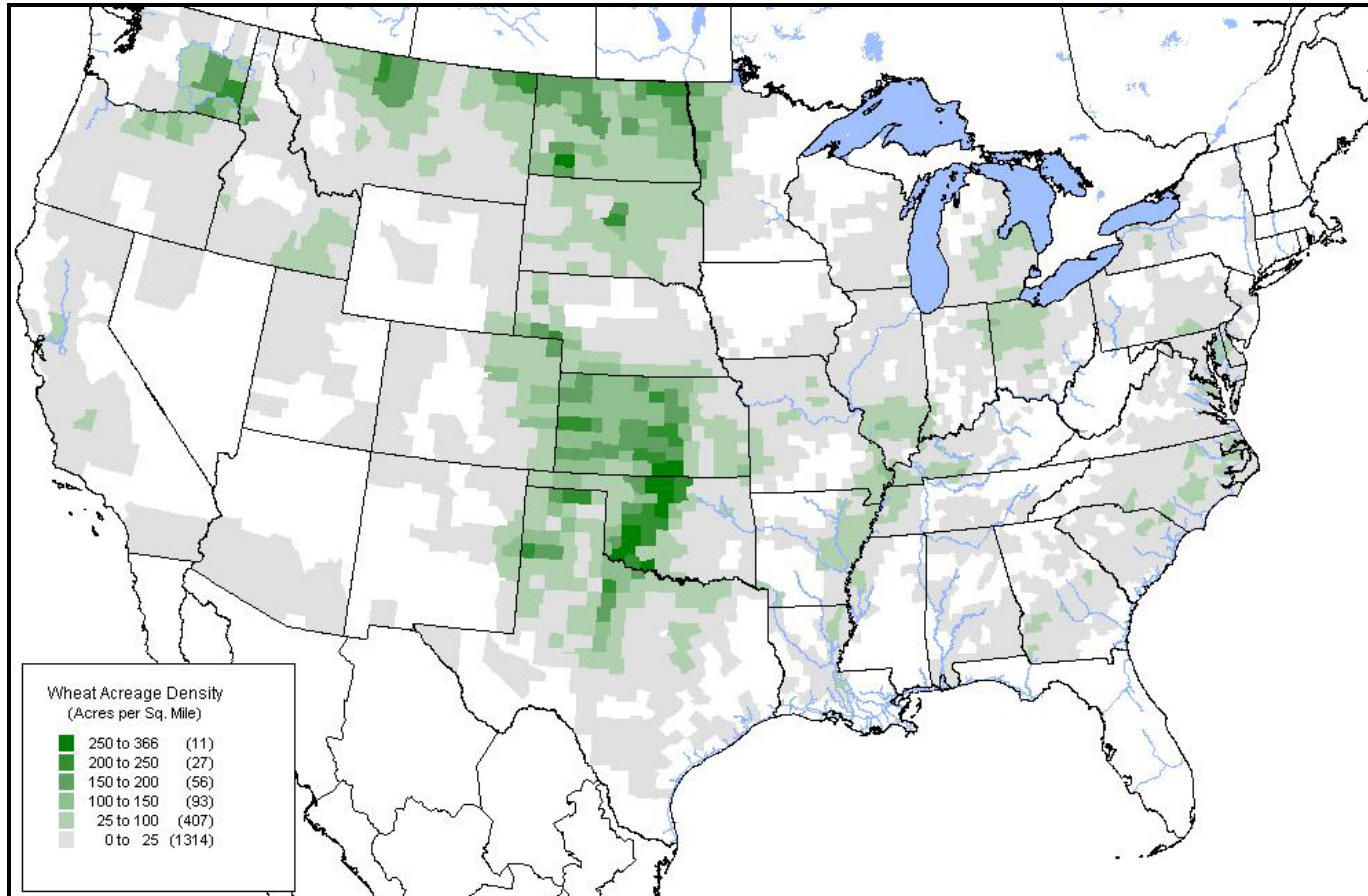
Sources: Data - U.S. Department of Agriculture, National Agricultural Statistics Service, and Mapping – Informa Economics.

Map 12: U.S. Soybean Acreage, 2002 - 2005



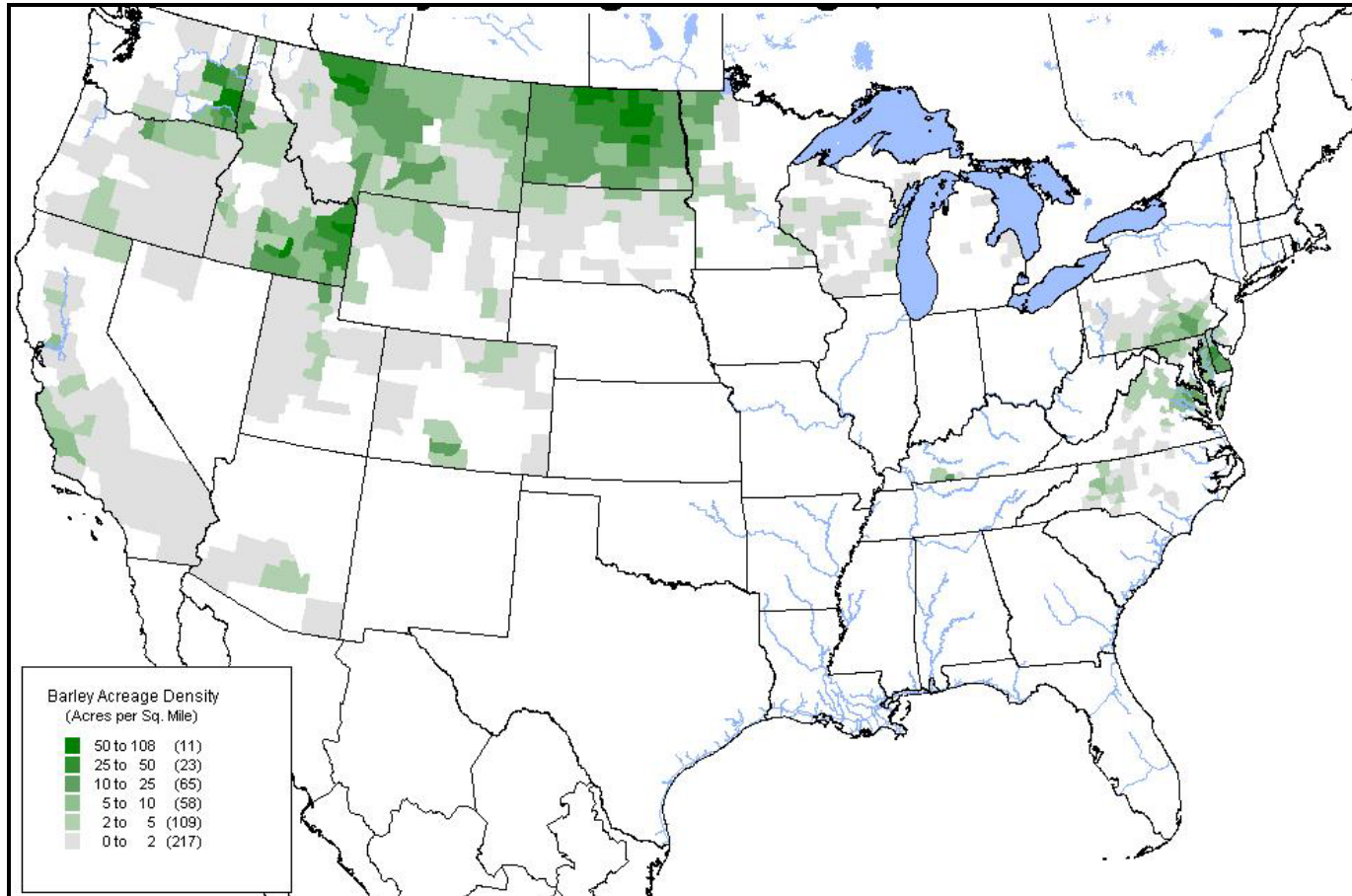
Sources: Data - U.S. Department of Agriculture, National Agricultural Statistics Service, and Mapping – Informa Economics.

Map 13: U.S. Wheat Average Acreage, 2002 - 2005



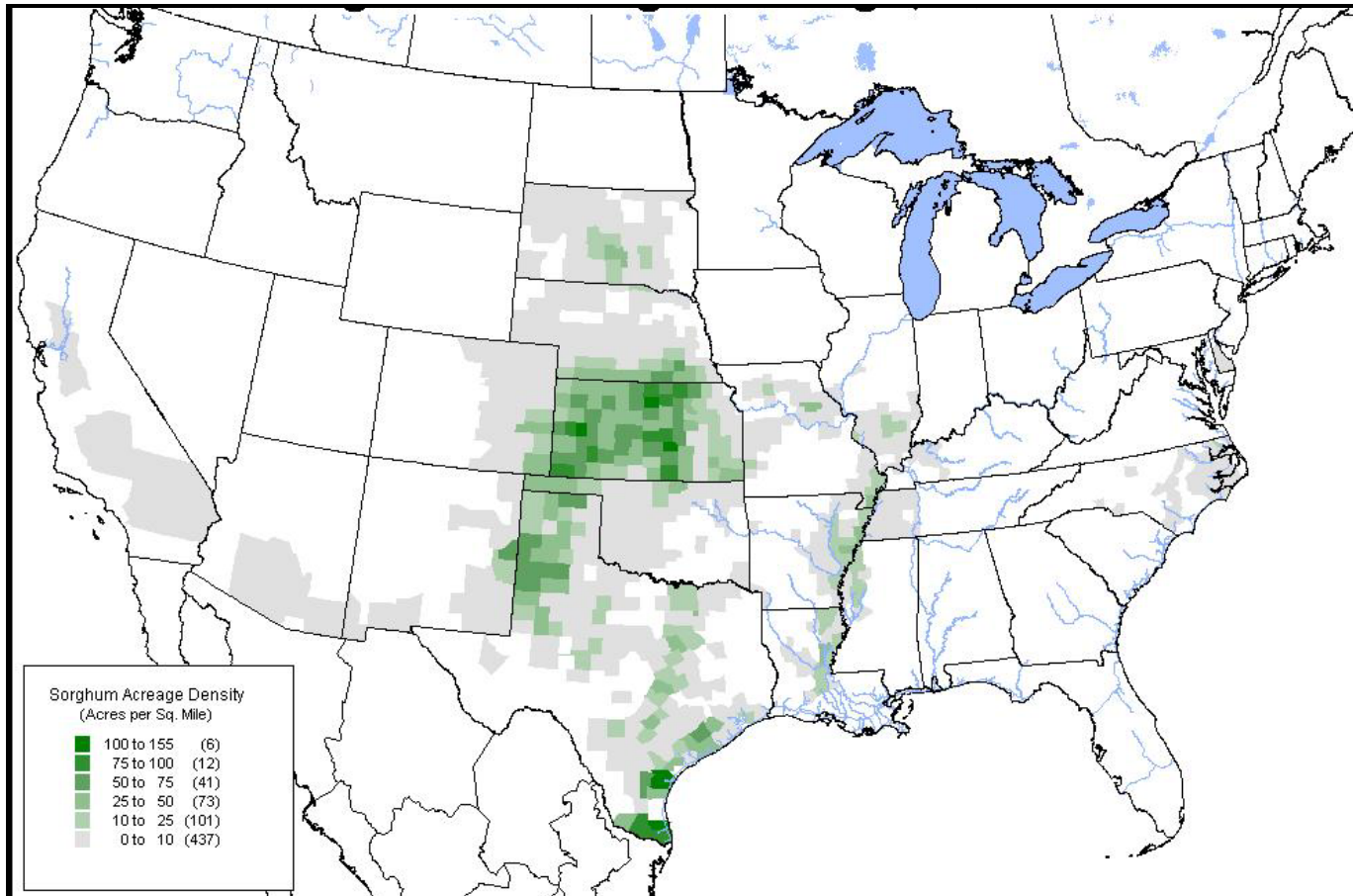
Sources: Data - U.S. Department of Agriculture, National Agricultural Statistics Service, and Mapping – Informa Economics.

Map 14: U.S. Barley Average Acreage, 2002 - 2005



Sources: Data - U.S. Department of Agriculture, National Agricultural Statistics Service, and Mapping – Informa Economics.

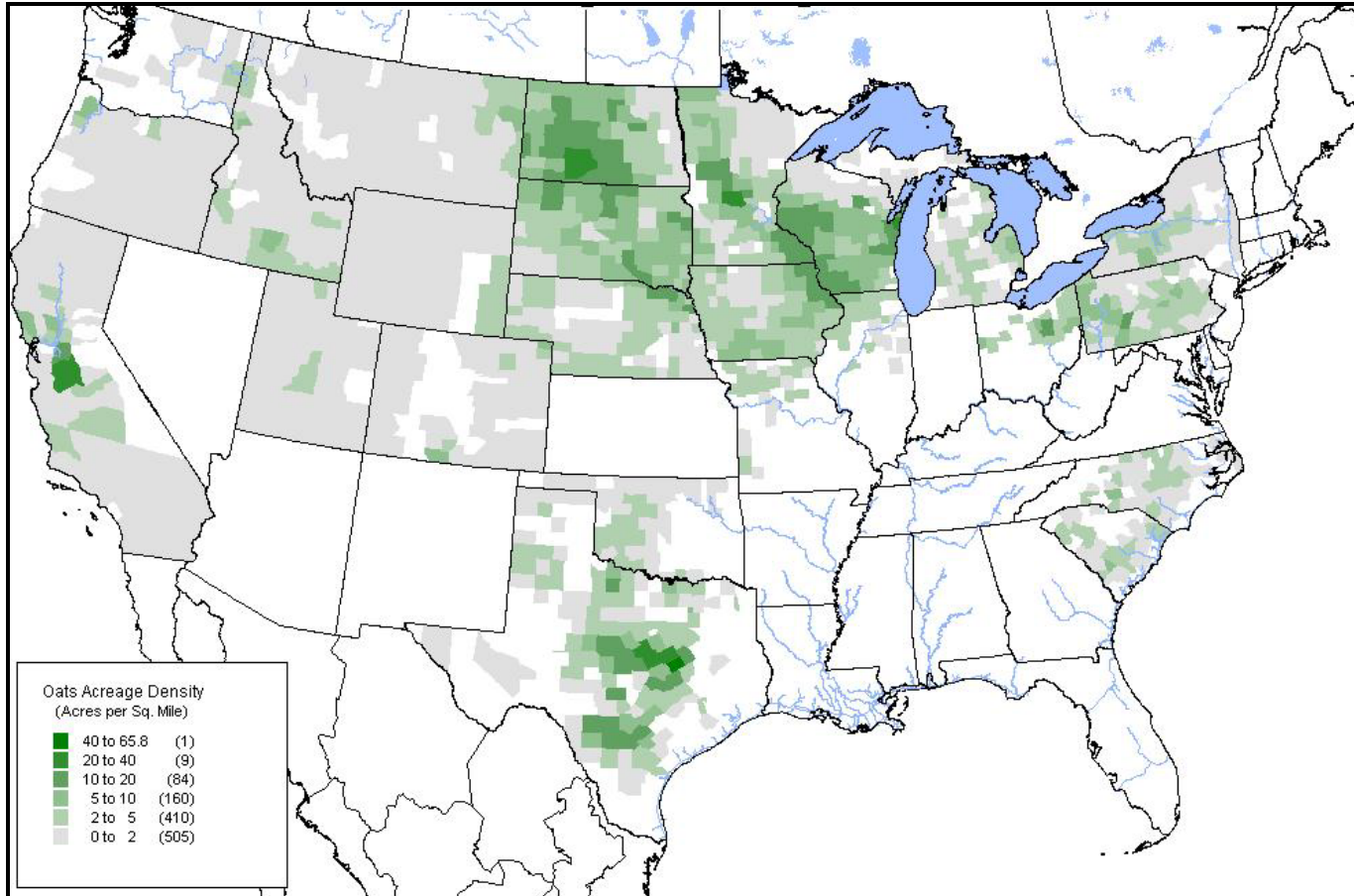
Map 15: U.S. Sorghum Average Acreage, 2002 - 2005



Sources: Data - U.S. Department of Agriculture, National Agricultural Statistics Service, and Mapping – Informa Economics.



Map 16: U.S. Oats Average Acreage, 2002 - 2005



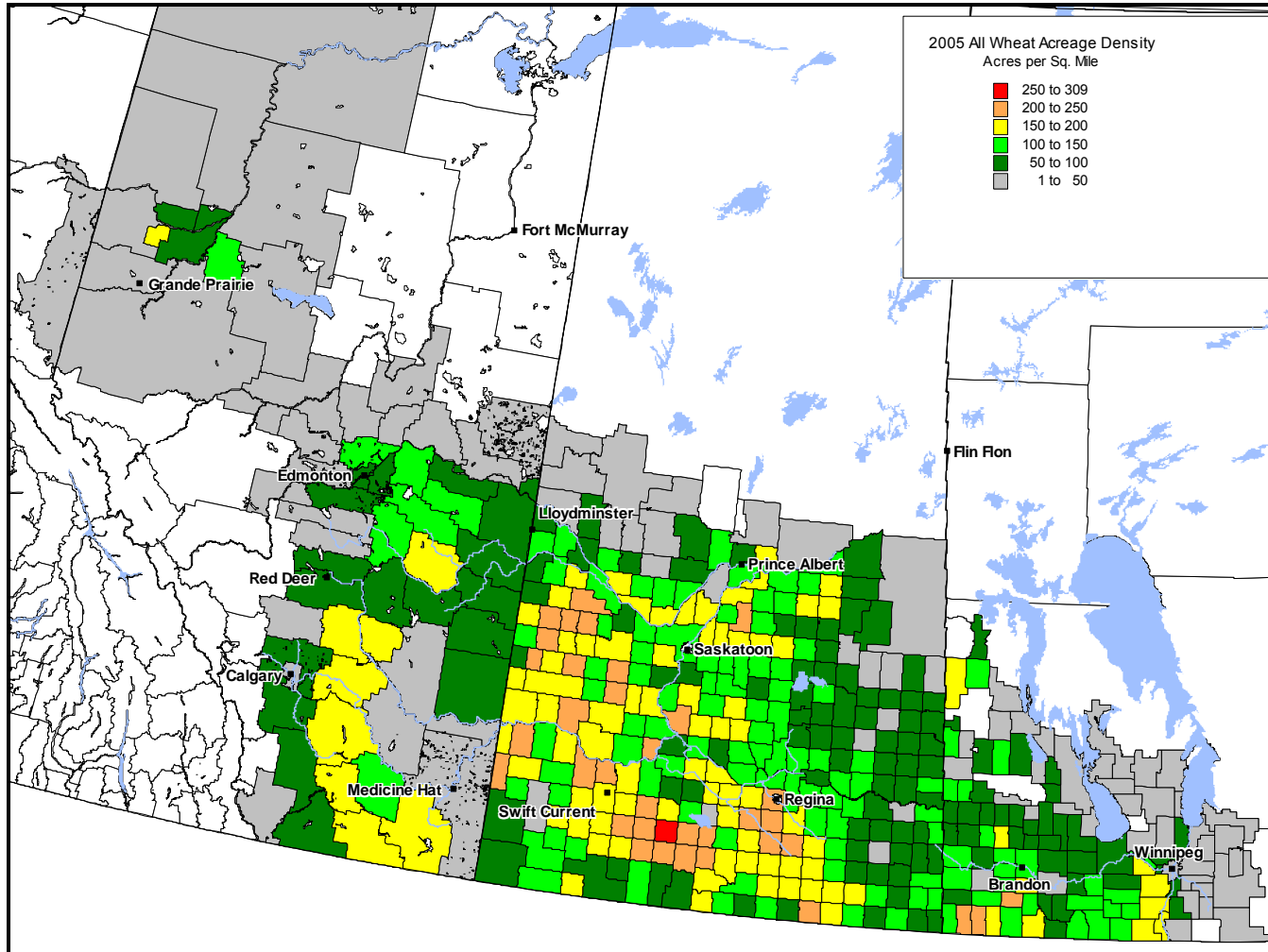
Sources: Data - U.S. Department of Agriculture, National Agricultural Statistics Service, and Mapping – Informa Economics.

**Map 17: U.S. Rice Average Acreage, 2002 - 2005**



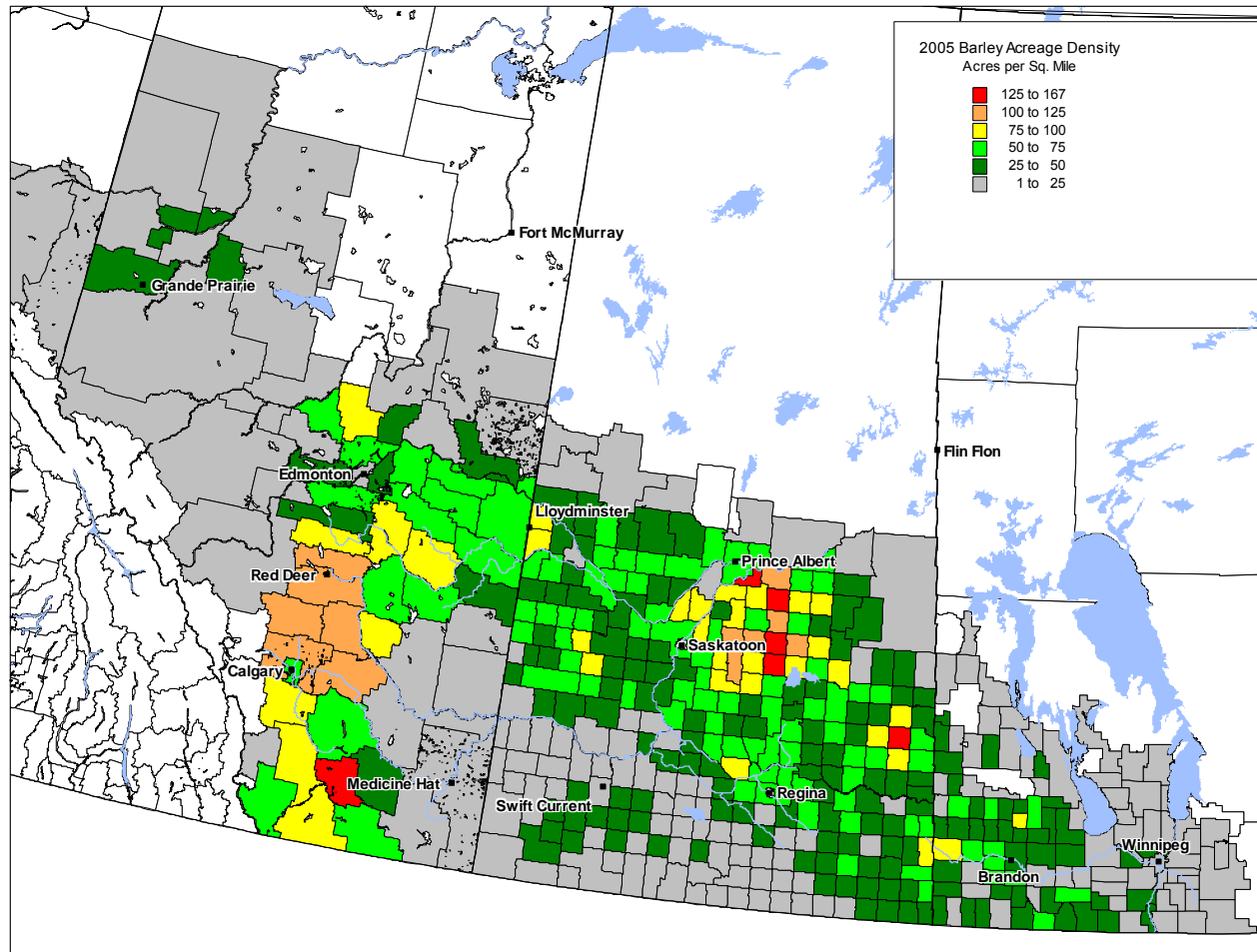
Sources: Data - U.S. Department of Agriculture, National Agricultural Statistics Service, and Mapping – Informa Economics.

Map 18: Canadian, Wheat Production, 2005



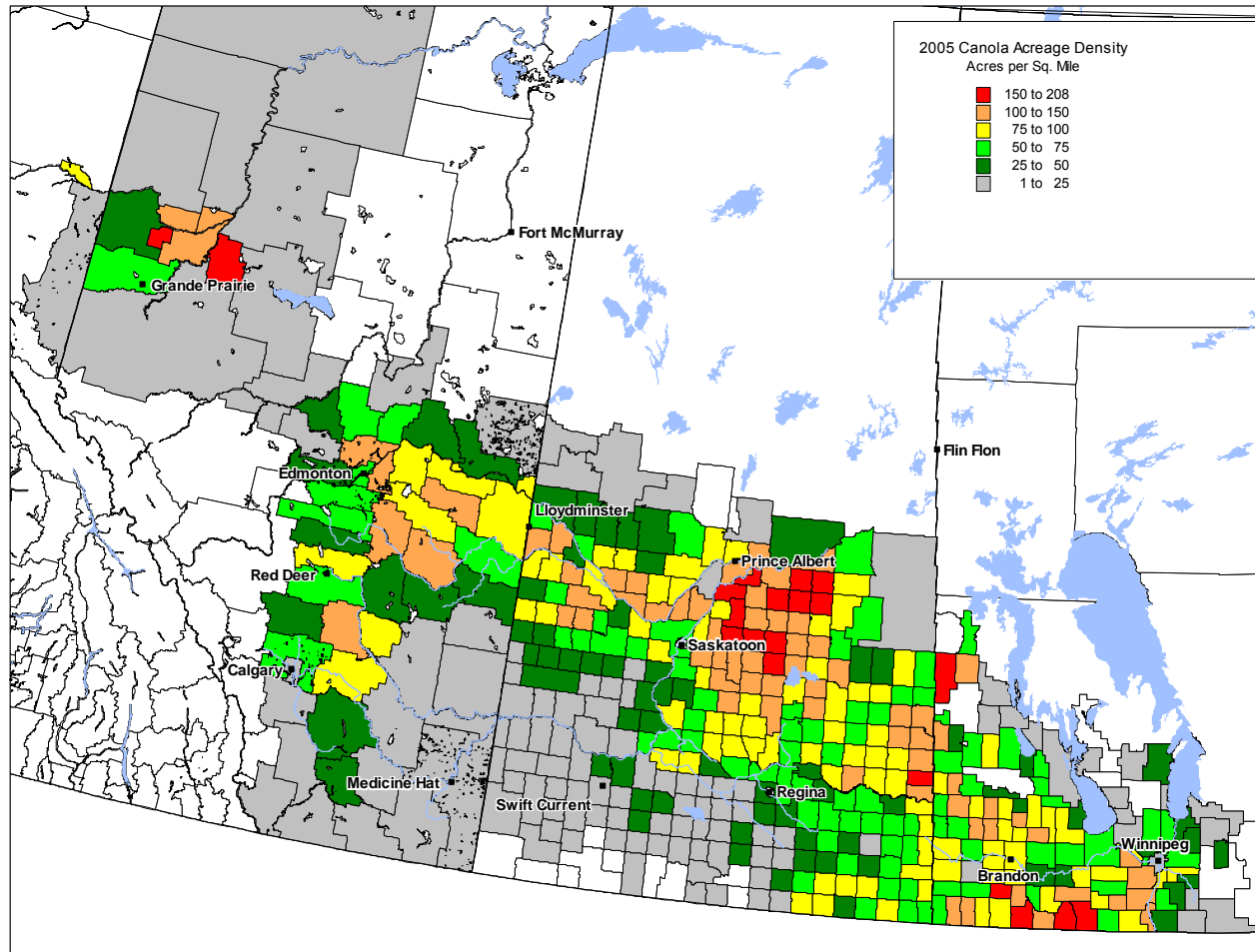
Source: Informa Economics et al., Biobased Multi-Client Study, March 2006.

Map 19: Canadian, Barley Production, 2005



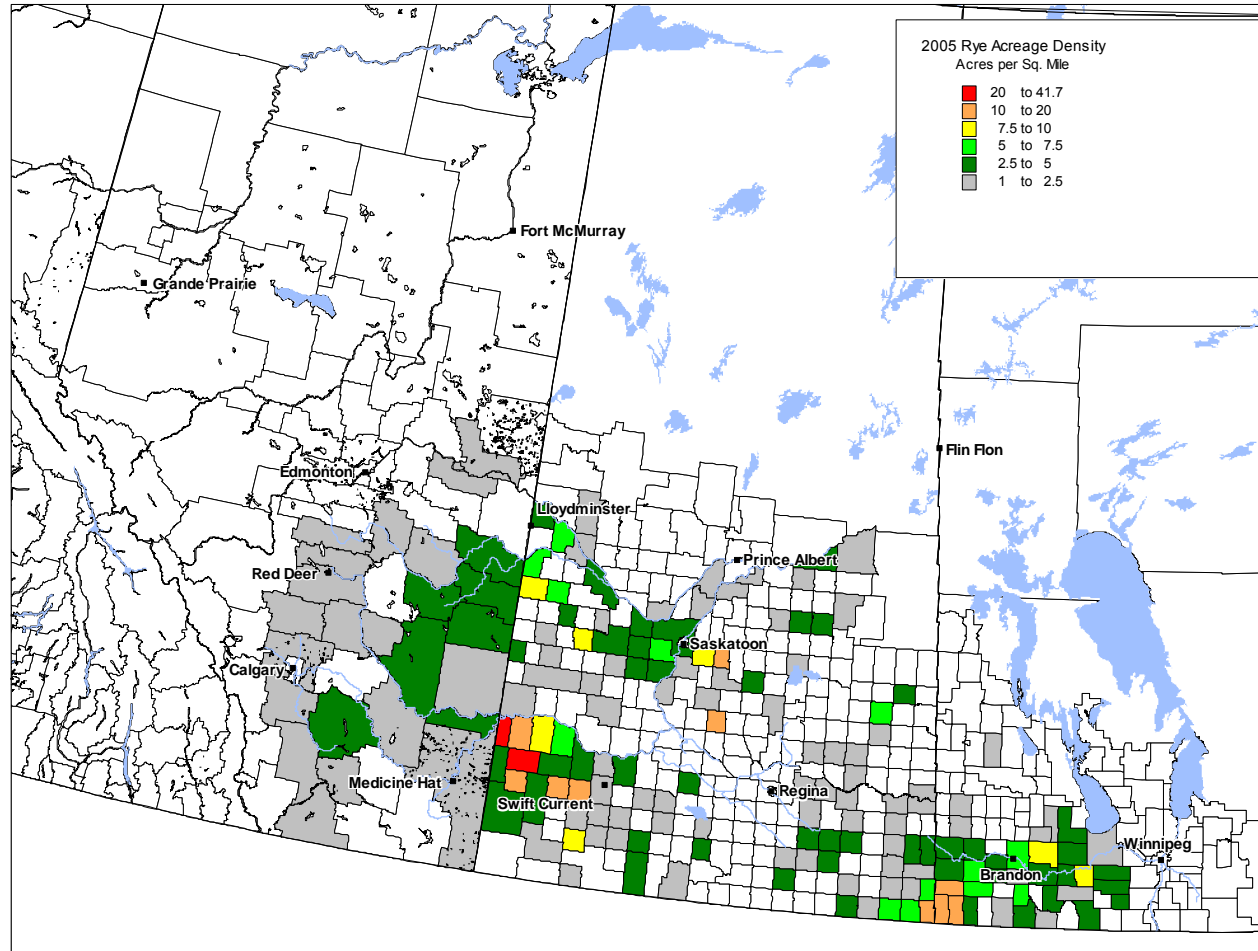
Source: Informa Economics et al., Biobased Multi-Client Study, March 2006.

Map 20: Canadian, Canola Production, 2005



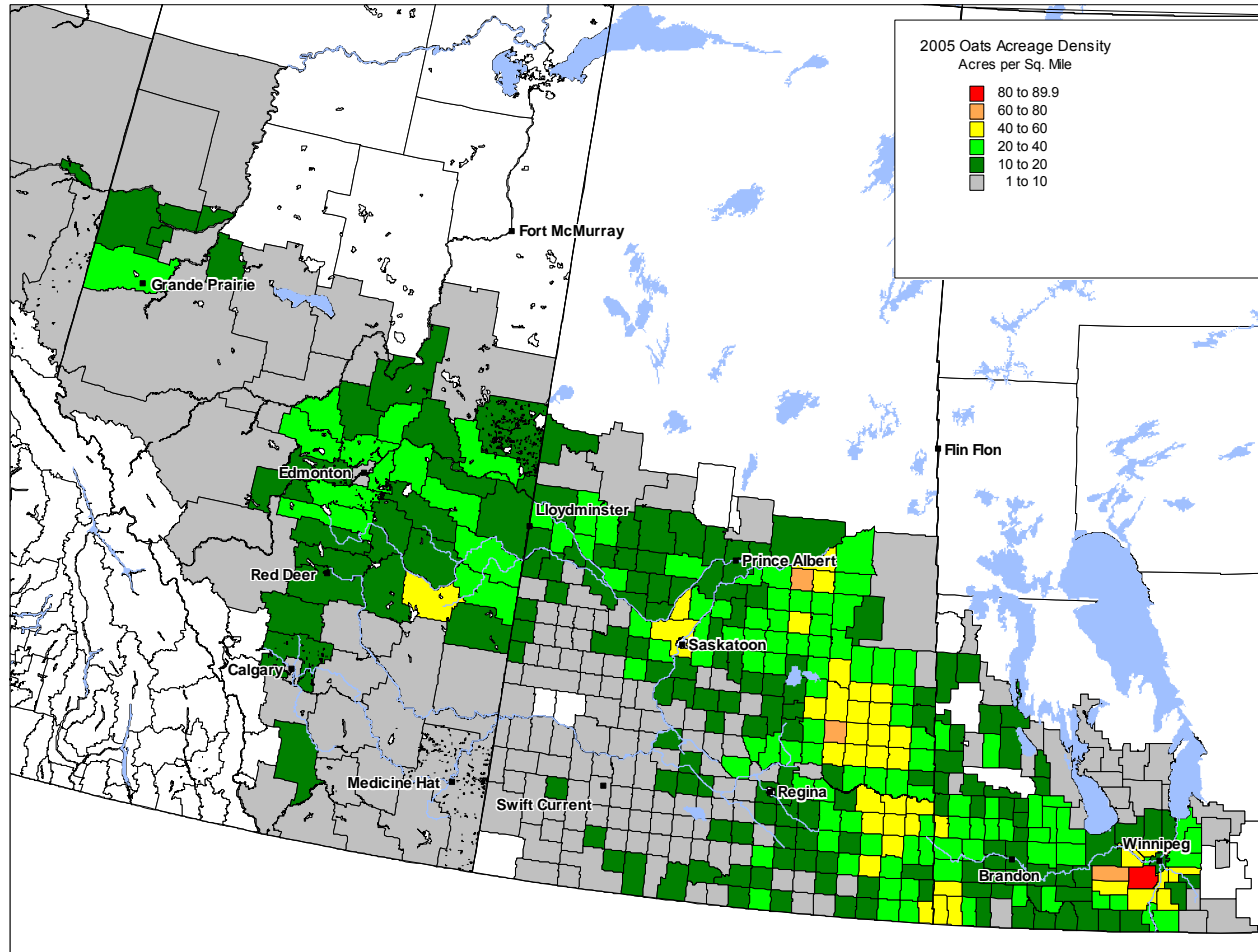
Source: Informa Economics et al., Biobased Multi-Client Study, March 2006.

Map 21: Canadian, Rye Production, 2005



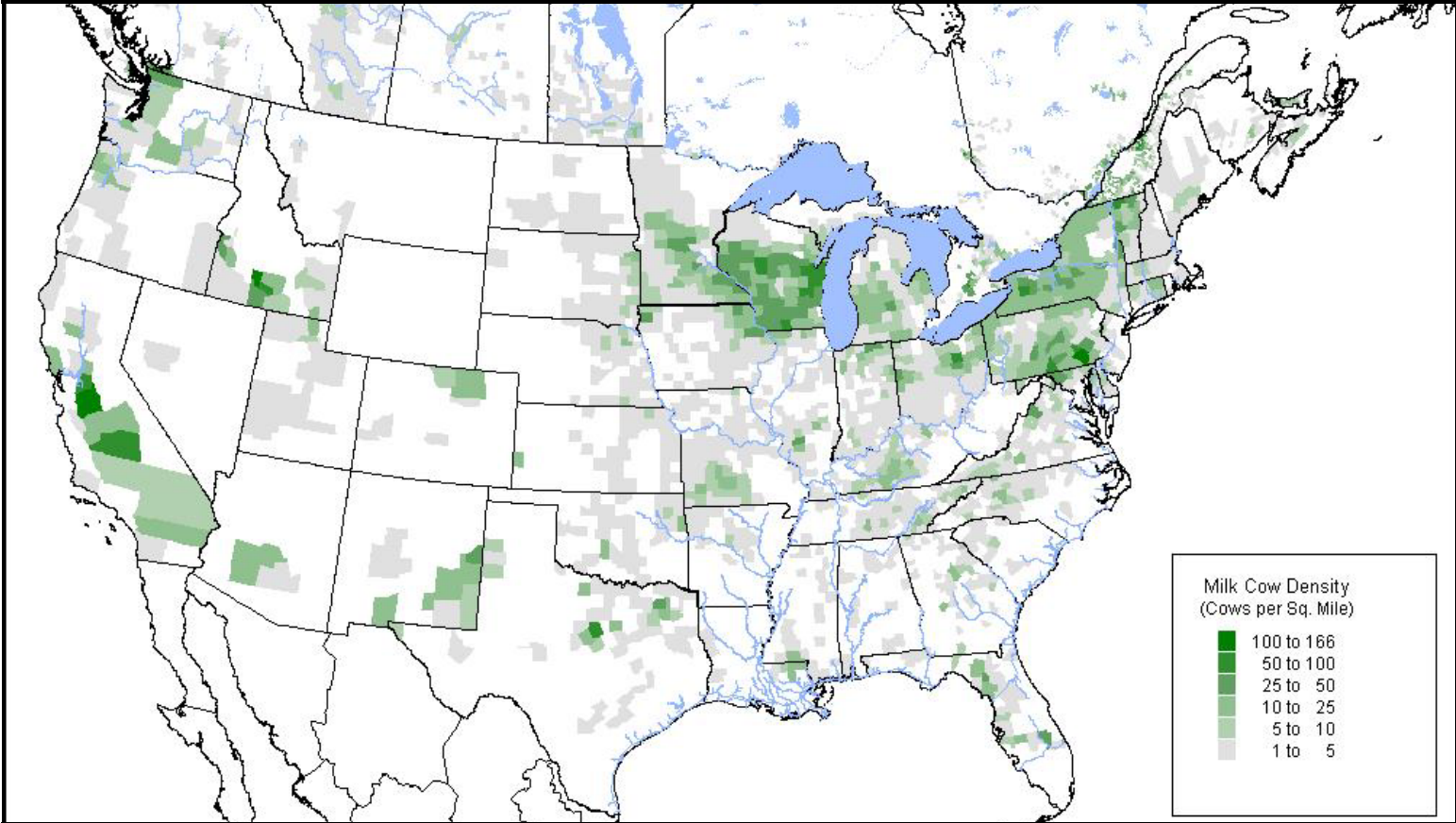
Source: Informa Economics et al., Biobased Multi-Client Study, March 2006.

Map 22: Canadian, Oats Production, 2005



Source: Informa Economics et al., Biobased Multi-Client Study, March 2006.

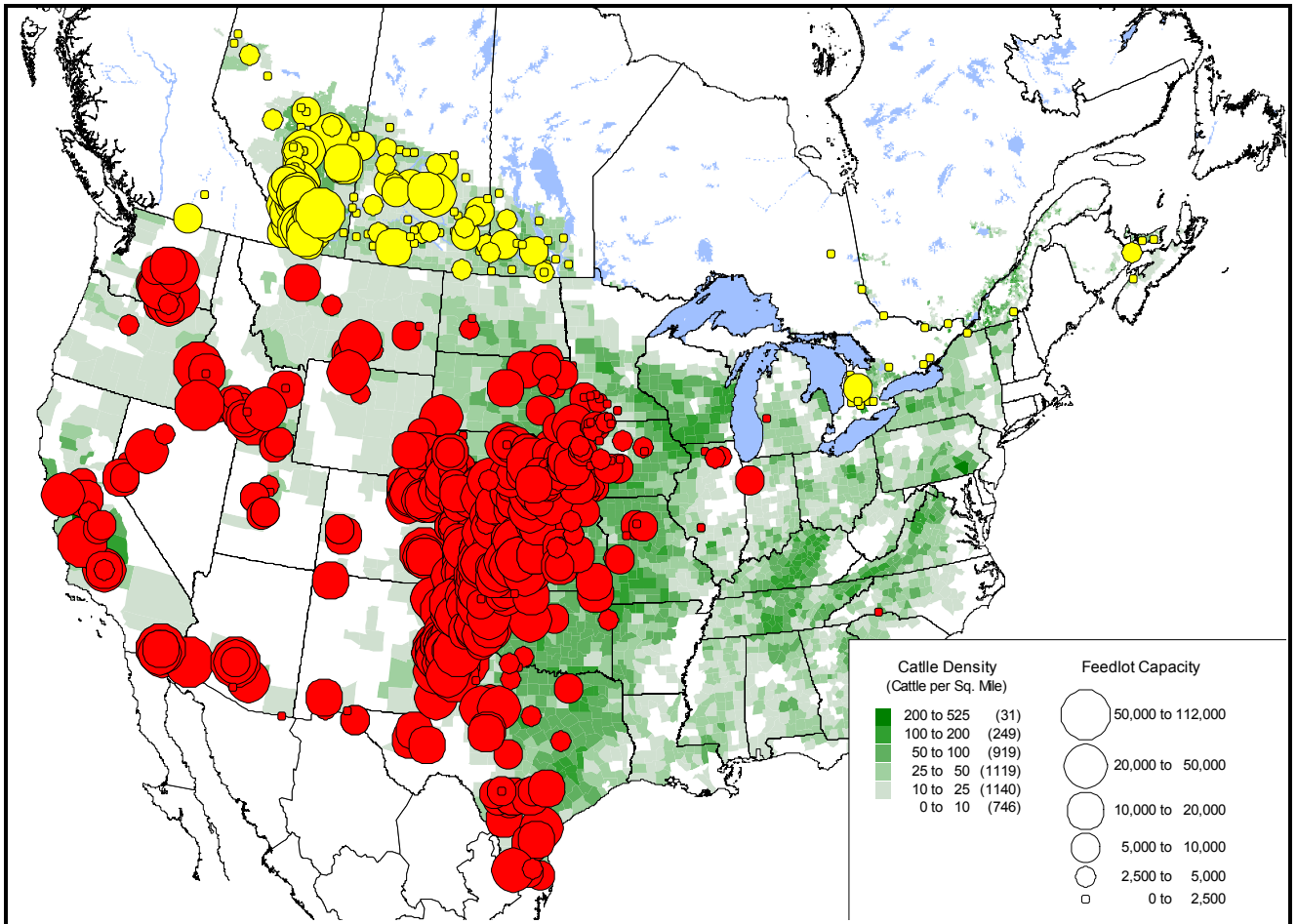
Map 23: U.S. Milk Cow Density, 2002



Sources: Data - U.S. Department of Agriculture, National Agricultural Statistics Service, and Mapping – Informa Economics.



Map 24: U.S. Feedlot Capacity, 2004



Source: Informa Economic et al., Biobased Multi-Client Study, March 2006.

Another area of potential feedstock promise for biobased products is in the form of forest biomass. In 2005, a study by the USDOE and the USDA examined whether total land resources in the United States are sufficient to sustain production of over 1 billion dry tons of biomass annually (Perlack et al. 2005).<sup>23</sup> It was estimated that total U.S. land area is approximately 2 billion acres, with 33 percent in forest lands, 26 percent in agricultural lands, and 20 percent in grasslands or pasture. The study showed that forest resources could contribute an annual volume of 368 million dry tons of feedstock.

<sup>23</sup> It is estimated that this volume of dry biomass could displace 30 percent or more of the nation's current consumption of liquid transportation fuels.

Forest biomass can be broken down into five different categories:

- Forest products industry residue (this includes tree bark, woodchips, shavings, sawdust miscellaneous scrap wood, and black liquor, a by-product of pulp and paper processing).
- Logging and site-clearing residues (this includes unmarketable tree tops and small branches that are left onsite or burned).
- Forest thinning (this includes removing excess woody materials to reduce fire hazards and improve forest health).
- Fuel wood (this includes roundwood or logs burned for space heating or other energy sources).
- Urban wood residues (this includes municipal solid waste and construction and demolition debris).

These wood based feedstocks would involve and probably stimulate the following economic activities; (1) wood growing, procurement, chipping and chemical processing by the pulp and paper industry, (2) willow biomass growing, harvesting, burning by farmers and the wood fuel industry and (3) fermentation of sugars into primary products such as ethanol and other coproducts.

Critical to the success of this industry will be the development and adoption of technology able to unlock (fractionate) the woody cellulosic biomass into a feedstock stream that can be fermented into biofuels at a commercially profitable level. Once the cellulosic conversion gap is bridged, the economic benefits and impacts on the U.S. forestry industry could be enormous.

Several studies have addressed the availability of biomass feedstock on a national scale. Walsh et al. estimated biomass quantities available at prices from \$20 to \$50 per dry ton, delivered, in each of the 48 states. Perlack et al. (2005) evaluated whether U.S. land resources could provide a sustainable supply of 1 billion dry tons of biomass a year, the amount needed to displace 30 percent of current U.S. petroleum consumption. Gallagher et al. (2003) conducted a nationwide assessment of the potential supply of agricultural residues, while De La Torre Ugarte et al. examined the implications of large-scale production of bioenergy crops.

Walsh et al. classifies biomass feedstocks into five categories:

- Forest residues - marketable wood that could be harvested for energy;
- Primary mill wastes.
- Agricultural residues - corn stalks and wheat straw.
- Dedicated energy crops - switchgrass, hybrid poplar, and hybrid willow.
- Urban wood wastes - yard trimmings, construction wastes, etc., commonly disposed of in municipal solid waste (MSW) and construction/demolition (C/D) landfills.

Quantities available, by type, were estimated at prices of \$30, \$40, and \$50/dry ton. Nationwide, total quantities ranged from 105 million tons (at \$30 or less/dry ton) to 511 million tons (at \$50 or less). Costs for biomass harvest, transport, etc., in this study are based on 1995 prices, and would be considerably higher using current energy costs.

- At \$30 or less/ton, wood wastes dominate national feedstock. Dedicated energy crops are not competitive at these price levels, and only minimal amounts of agricultural residues are estimated to be available (3.2 million tons, all from Oklahoma).
- At costs between \$30 and \$40, agricultural residues become more available (135 million tons) and dedicated energy crops begin to enter the picture (66 million tons).
- At costs between \$40 and \$50, the volumes of biomass provided by dedicated energy crops are estimated to almost triple, to 188 million tons. Primary mill wastes and agricultural residues increase by lesser amounts.

The leading states in biomass availability are all in the Midwest/Northern Great Plains. Illinois and Iowa are the top two states, followed by Nebraska, Kansas, Minnesota, and North Dakota (all with 21 - 22 million tons at \$50 or less). In Illinois and Iowa, agricultural residues dominate the biomass supply at prices between \$30 and \$40/dry ton. These residues are mostly corn stover (94 percent in Illinois and 99 percent in Iowa). As prices rise to \$50, energy crops assume a growing importance in both states. Nebraska shows a similar pattern. In Kansas, agricultural residues increase to 8.57 million tons at \$40 and then stabilize, while energy crops rise to 2.9 million tons at \$40 and grow to 11.4 million tons at \$50. In Minnesota, too, agricultural residues dominate the biomass supply at \$40, while energy crops account for most of the growth from \$40 to \$50.

The principal biomass potential for the North Dakota and South Dakota lies in energy crops (i.e., switchgrass) (Walsh et al.). In South Dakota, as biomass prices rise from \$30 to \$40, agricultural residues increase from zero to 3.7 million tons while energy crops climb from zero to 5.6 million tons. As biomass prices rise to \$50/ton, energy crops increase to 12.8 million tons while agricultural residues drop

to 2.9 million tons (apparently, marginal cropland is converted to energy crops, thus reducing the supply of agricultural residues). In North Dakota, agricultural residues supplied are minimal at prices below \$40, increasing to 3.7 million tons at \$50, while energy crops rise from 1.9 million tons at \$40 to 16.7 million tons at \$50. Substantial Conservation Reserve Program (CRP) acreage in the state (much of which is assumed to be available for energy crops) is likely behind the large expansion of energy crops.

Energy crop alternatives are switchgrass, hybrid poplar, and willow. De La Torre Ugarte et al. used the POLYSIS agricultural policy simulation model to determine (1) the farmgate price needed to make energy crops competitive with other cropland uses, (2) the regional distribution of bioenergy crop production, (3) the impact of bioenergy crops on prices and production of 'conventional' crops, and (4) effect on farm incomes. Of 29.8 million acres of CRP land in the analysis baseline (as of 1998), 16.9 million acres were made available for energy crop production (De La Torre Ugarte et al). Most cropland was assumed to be available for conversion. Farmers were allowed to use CRP acres for energy crops while retaining 75 percent of their CRP payment.

Results indicate that switchgrass is usually the best energy crop alternative. One scenario featured a farmgate price of \$30 per dry ton for switchgrass and required wildlife management practices for CRP land (less fertilizer and chemicals, could harvest only alternating halves of a field each year). The other scenario used a price of \$40/dry ton while seeking maximum bioenergy production (standard fertilizer and chemicals, harvest entire field each year).

Under the wildlife management scenario, 19.4 million acres are planted to bioenergy crops (12.3 million acres to switchgrass and 7.1 million acres to poplar). Under the production scenario, 41.9 million acres are planted to bioenergy crops (all switchgrass), with 23.4 million acres coming from land previously planted to major crops and 12.9 million acres from CRP. In North Dakota, 1.9 million dry tons of switchgrass are produced under the wildlife scenario, versus 16.8 million tons under the production scenario. Nationwide, under the production scenario, 188 million dry tons of biomass is produced annually, entirely from switchgrass.

Gallagher et al. (2003) estimate biomass supplies from crop residues, likely the lowest cost form of biomass. Supply functions are estimated for major agricultural production regions (Corn Belt, Great Plains, West Coast, Delta), considering harvest costs, livestock feed demand, and other values of residues (erosion control, nutrients). Key findings include:

- Wheat straw in the Northern Great Plains can be an economical source of biomass with estimated delivered cost of \$21/ton. Cost estimates are based on 1997 prices and do not include a return for the landowner. Biomass feedstock values are reflected in the cost estimates in some cases.

- Livestock demand is less a factor for wheat straw than for most other forms of biomass, as the feed value is estimated to be only \$21.21/ton (versus \$41.90/ton for corn stover).
- The Corn Belt and Great Plains account for over 90 percent of crop residue supply.

Perlack et al. (2005) investigated whether U.S. land resources could provide a sustainable supply of 1 billion dry tons of biomass a year, the amount needed to displace 30 percent of current U.S. petroleum consumption. U.S. agricultural and forest lands were estimated to provide over 1.3 billion (dry) tons a year by 2050 (assuming a variety of technology/yield improvements and land-use changes). Of the total, about 933 million tons (72 percent) would come from agricultural lands: 425 million tons of annual crop residues, 377 million tons of perennial crops, 56 million tons of grains used for biofuels, and 75 million tons of animal manures, process residues, and other miscellaneous feedstocks. Among the assumptions key to these estimates are (1) increased yields, (2) harvest technologies capable of recovering up to 75 percent of crop residues, (3) exclusive use of no-till practices, and (4) 55 million acres of CRP and other cropland dedicated to perennial bioenergy crops.

Sustainable residue removal rates, in this report, approximate the percentage of crop residues that can be removed while maintaining soil carbon and controlling erosion. For wheat (nationwide), sustainable removal rates were an estimated 14 percent for conventional tillage and 48 percent for no till. Corn stover and wheat straw are the residues with most potential as a feedstock, while switchgrass is the energy crop most likely to provide competition.

### **a) Corn Stover**

In a life-cycle model for the production of ethanol from corn stover in Iowa, corn stover is harvested as round bales and transported to the plant with a 17 bale wagon (Sheehan et al.). The cost to the plant includes (1) direct cost of baling and transport, (2) farmer profit of \$10/dry metric ton (mt), and (3) fertilizer (nutrient) replacement cost of \$7/dry mt. The base cost for delivered feedstock is \$46/dry mt (\$41.62/ton), rising as more plants are built that require longer hauls.

These cost estimates appear similar to North Dakota costs for wheat straw. However, costs do not reflect current (2006) energy costs. Adjusting for higher costs of transportation and fertilizer replacement would raise these Iowa costs by several dollars per ton. One advantage of wheat straw over corn stover is one or two fewer harvest operations (by baling straw direct from the combine windrow).

Sokhansanj et al. (2002) examined published data on collecting corn stover using field machinery to estimate collection efficiency and costs. Main collection operations for stover include cutting and shredding, windrowing, baling, and transport to a storage site. The shredding and windrowing operations can be

combined, but at the risk of inadequate drying of the stover. The stover harvest season is shorter than the corn (grain) harvest season. In central Indiana, losses of stover become excessive (more than 50 percent) after November 10 (a date at which the grain harvest is only 57 percent completed in an average year). Thus, stover available for harvest is estimated to be 45 percent of total stover produced. For an assumed stover yield of 1.27 tons/acre, the estimated cost for baling and delivery to a storage site 5 miles away would be \$19.70/dry ton.

Perlack and Turhollow (2003) evaluated costs for collecting, handling, and transporting corn stover to an ethanol conversion facility. Costs are evaluated for plant sizes requiring 500 - 4,000 dry tons/day (i.e., 175,000 - 1.4 million dry tons per year). Conventional baling and transportation equipment is assumed. Producers are compensated at \$10/dry ton to cover nutrient value plus profit. The resulting delivered costs range from \$43.10 to \$51.60/dry ton. Adjustment to reflect 2006 fuel and fertilizer costs would raise stover costs to \$51.72 - \$61.92.

### **b) Switchgrass**

Hallam et al. compared production costs of various crops for use as biomass feedstocks, based on trials conducted in central Iowa (near Ames) and southern Iowa (near Chariton). Energy crops studied include switchgrass, reed canarygrass, big bluestem, and alfalfa (all perennials), as well as sweet sorghum, forage sorghum, and maize (annuals). Intercropping of sorghum with reed canarygrass and alfalfa was also considered.

Costs of production included transportation to a plant 30 miles away (est. cost = \$3.82/ton). Breakeven prices (i.e., price to cover full production and transportation cost) were calculated for each crop. Switchgrass was the least costly perennial crop at \$35.36/ton in southern Iowa and \$43.32 in central Iowa. Sweet sorghum was the least costly annual, with a breakeven price of \$29.44/ton in southern Iowa and \$34.67/ton in central Iowa. However, estimated soil loss associated with sorghum cultivation is 5 mt/ha (hectare) at Ames and 35 mt/ha at Chariton, versus less than 2 mt/ha for the perennial grasses or alfalfa.

Perrin et al. studied switchgrass production in Nebraska, North Dakota, and South Dakota. Experimental plots indicate that yields of 2.5 to 4.5 tons/acre may be achievable by the second year after establishment. Production costs are estimated to be about \$30/ton, while land charges would add another \$10/ton (for nontillable land) to \$30/ton (for marginal row crop land). Thus, the farmgate price is an estimated \$40 - \$60/ton. A transportation cost of \$10/ton gives a delivered cost for switchgrass of \$50/ton or more.

Duffy and Nanhou present production costs for switchgrass identifying seven different scenarios for establishing stands on cropland and grassland in southern Iowa. Scenarios are defined based on: (1) time of year the switchgrass is planted, (2) type of land used (cropland or grassland), and (3) type of machinery used for

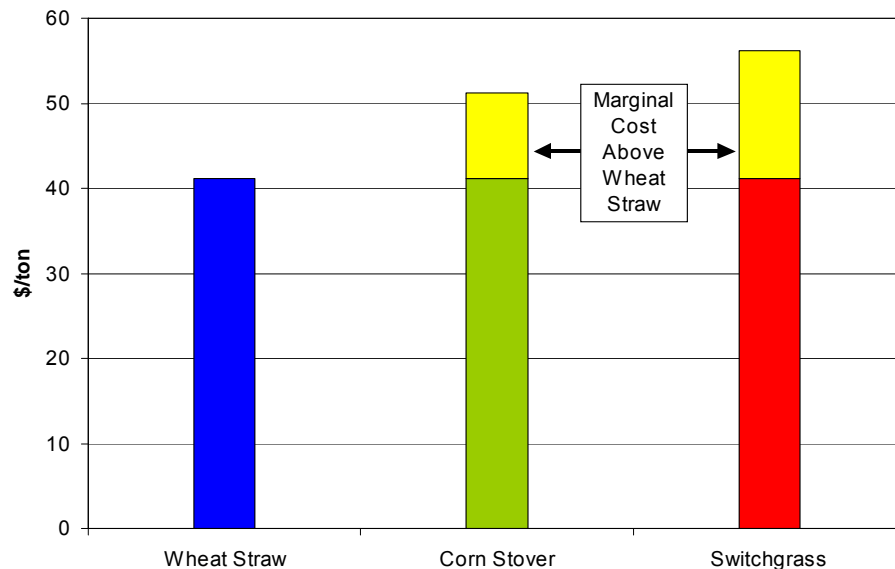
planting. Costs are farmgate costs (i.e., do not include transportation to the plant). Transportation costs are estimated at \$0.10/dry ton per mile (distances less than 50 miles). Costs are calculated for different yields, and range from \$70.32 - \$80.94 at a yield of 3 tons/acre to \$48.53 - \$53.84/ton at a yield of 6 tons/acre.

If yields fell to 1.5 tons/acre, costs would exceed \$116/ton for all scenarios. Higher land charges (\$75/acre for cropland and \$50/acre for grassland) are one explanation for estimated production costs that substantially exceed those of the Perrin study.

**c) Wheat Straw**

Leistriz, et al, estimate that wheat straw can be delivered to a biorefinery plant (within 50 miles of feedstock) at a cost of \$41.20/dry ton, after paying harvest, nutrient replacement, and transportation costs and providing the producer with a \$10/ton net return. This compares favorably with corn stover; wheat straw appears to have a \$5 - \$10/ton cost advantage, after adjustment for recent increases in energy costs, and switchgrass, a cost advantage of \$10 - \$15/ton or more (Figure 59).

**Figure 59: Estimate of Net Cost of Feedstock Delivered to Plant**



Source: Informa Economics et al., Biobased Multi-Client Study, March 2006.

## VIII. Growth of the Biobased Economy: Projections and Impacts

The future direction of the biobased economy depends on many issues. For a simplified view, Informa developed two matrices to better understand these issues and their ramifications for the direction of the U.S. biobased economy. One matrix addresses the short-run (1 to 3 years) horizon and the second the intermediate timeframe (until 2015). The potential course of the biobased economy varies significantly as the time horizon lengthens. For example, the longer oil prices remain high, the greater the prospect of continued capital investments in the renewable energy sector. Conversely, if oil prices were to dramatically retreat for a sustained period of time, capital flows into the biobased economy would begin to dramatically slow. Overarching the discussion of the biobased economy is the evolutionary direction of the biofuels sector. If the biofuels sector continues to grow, the advancement of biorefineries will intensify, creating new and expanded developments and opportunities in the area of biobased products. However, if there is a retrenchment of energy prices to lower levels, it would be difficult for biobased products to grow appreciably based purely on economic/market signals.

### A. Potential for Industry Growth

The two forces that will likely have the greatest impact on the future growth trajectory for biobased products are oil prices and levels of government support in the United States and other countries. Unquestionably the directions of both industries are heavily dependent on energy prices and the cost of inputs (corn for ethanol and soybean oil for soy diesel); however, the future path of the biodiesel industry is more uncertain. As noted in the biodiesel section of this report, if the government tax credit of \$1.00 a gallon were removed and the price of crude soybean oil was approximately 23.5 cents per pound, the price of crude oil would have to trade above \$70 to \$75 per barrel for a 30 million-gallon-a-year biodiesel plant to break even.<sup>24</sup> Given the fact that the tax credit is slated for sunset in 2008, capital investment into the sector has remained cautious to date. If the tax credit program were extended for a meaningful length of time, such as 5 to 10 years, it is highly probable that the rate of growth in the industry would be significant.

Informa in each matrix compares the price of oil at three different levels relative to three different levels of Federal and state support. The matrices were given to numerous economists to draw upon their expert opinion on the matrix scenarios. The results are qualitative in nature and yield a general view of the potential impact on the biobased products' economy; the findings are summarized in Table 50 and Table 51.

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<sup>24</sup> Note: Biodiesel plants of smaller scale, such as 5 to 15 million gallons a year, would require even higher crude oil prices to remain profitable.



The Matrix Assumptions Are As Follows:

Three levels of crude oil are considered:

- \$25 per barrel - the level where oil traded for much of the 1980s and 1990s.
- \$45 per barrel - the level that many economic organizations are using as a benchmark price for crude oil over the next 10 years.
- \$105 per barrel - an extremely bullish outlook, anticipating possible “super spikes.” The investment firm Goldman Sachs has analyzed the potential for such a scenario.

Government support and incentives are benchmarked based on current levels:

- Low (below current Federal and state levels of assistance).
- Medium (at current levels).
- High (above current levels).

The highlights of the short-term analysis are:

- Below \$25 per barrel, the ethanol industry begins to consolidate as margins tighten.
- If oil stays at \$45 per barrel and government support remains constant or grows, downstream product development within the public and private sector will advance.
- With oil at \$45 per barrel coupled with low government support, biodiesel economics would be unfavorable.
- If oil moves to \$105 per barrel, private research and capital investment in biorefining expands significantly. Corn acreage increases swiftly to meet the demand for more ethanol.

The highlights of the intermediate-term analysis are:

- With oil at \$25 per barrel and medium government support, the growth of the ethanol industry slows and production settles at about 8 billion gallons annually.
- At \$45 per barrel and medium government support, a permanent shift toward corn production at the expense of soybeans is possible.
- At \$45 per barrel and high government support, breakthroughs in biomass conversion technology accelerate.
- At \$105 per barrel and (even with) low government support, the ethanol and biodiesel industries move into high gear and demand for corn and soybean oil as feedstock skyrockets.

**Table 50: Short-run (1 - 3 Year) Impact of Oil Prices and Government Support on Biomass and U.S. Agriculture**

	<b>Petroleum at \$25/Barrel</b>	<b>Petroleum at \$45/Barrel</b>	<b>Petroleum at \$105/Barrel</b>
<b><u>Low</u> Government Support and Incentives (below current level)</b>	<ul style="list-style-type: none"> <li>• Minimal negative revenue impact</li> <li>• The ethanol industry begins to feel margin pressure</li> <li>• The biodiesel industry slows to a crawl</li> <li>• Good price risk managers will benefit</li> <li>• Ethanol industry will consolidate rapidly with low-cost producer surviving</li> </ul>	<ul style="list-style-type: none"> <li>• Positive revenue impact (\$0-2 bil.)</li> <li>• Ethanol industry consolidates at a deliberate pace</li> <li>• Biodiesel economics are unfavorable</li> </ul>	<ul style="list-style-type: none"> <li>• Positive revenue impact (\$4-6 bil.)</li> <li>• Biodiesel industry grows much slower relative to the ethanol industry</li> <li>• Corn acreage expands</li> <li>• Distribution of ethanol/biodiesel will be critical</li> </ul>
<b><u>Medium</u> Government Support and Incentives (current level)</b>	<ul style="list-style-type: none"> <li>• Minimal revenue impact</li> <li>• The ethanol industry will consolidate</li> <li>• Large-scale firms will develop downstream products</li> <li>• Biodiesel follows a slow growth trajectory</li> </ul>	<ul style="list-style-type: none"> <li>• Positive revenue impact (\$2-4 bil.)</li> <li>• Move toward more U.S. corn acreage for ethanol, yields will influence how much</li> <li>• Reduction in soybean acreage</li> <li>• Strong returns to ethanol producers</li> <li>• Biodiesel economics improve</li> </ul>	<ul style="list-style-type: none"> <li>• Positive revenue impact (\$4-6 bil.)</li> <li>• Biodiesel industry sees a large inflow of private capital</li> <li>• Corn acreage expands rapidly</li> <li>• Distribution of ethanol/biodiesel will be critical</li> </ul>
<b><u>High</u> Government Support and Incentives (above current level)</b>	<ul style="list-style-type: none"> <li>• Slightly positive revenue impact</li> <li>• Low-cost ethanol producers remain profitable</li> <li>• Seeds are planted for future technological breakthroughs in biomass</li> <li>• Import more oilseeds</li> <li>• Biodiesel grows at a modest pace</li> </ul>	<ul style="list-style-type: none"> <li>• Positive revenue (\$2-4 bil.)</li> <li>• Development of downstream products will accelerate</li> <li>• Biodiesel grows rapidly</li> <li>• Seeds are planted for future technological breakthroughs in biomass as the private sector is willing to take risks</li> <li>• Ethanol industry continues to grow at a rapid pace, but at a slower rate than in 2006.</li> </ul>	<ul style="list-style-type: none"> <li>• Positive revenue impact (\$5-7 bil.)</li> <li>• Biodiesel and ethanol industries see a massive inflow of private capital</li> <li>• Corn acreage expands very rapidly</li> <li>• Significant research and development push by private sector</li> </ul>

Source: Informa Economics et al., Biobased Multi-Client Study, March 2006.

**Table 51: Intermediate (2015) Impact of Oil Prices and Government Support on Biomass and U.S. Agriculture**

	<b>Petroleum at \$25/Barrel</b>	<b>Petroleum at \$45/Barrel</b>	<b>Petroleum at \$105/Barrel</b>
<b>Low Government Support and Incentives (below current level)</b>	<ul style="list-style-type: none"> <li>Negative revenue impact</li> <li>Private sector biomass investments dry up</li> <li>Ethanol industry consolidates rapidly – margins squeezed</li> <li>High cost ethanol plants exit industry</li> <li>Biodiesel industry shuts down</li> </ul>	<ul style="list-style-type: none"> <li>Positive revenue impact (\$4-6 bil.)</li> <li>Ethanol industry becomes more concentrated</li> <li>Industry is driven purely by petroleum/fuel prices/economics</li> <li>Chemical companies pursue niche biobased products</li> <li>Biodiesel industry struggles</li> </ul>	<ul style="list-style-type: none"> <li>Significant positive revenue impact (\$7-10 bil.)</li> <li>Fuel driven industry</li> <li>Ethanol industry maintains rapid growth</li> <li>Biodiesel becomes more prominent</li> <li>Private research and development accelerates dramatically in biobased products</li> </ul>
<b>Medium Government Support and Incentives (current level)</b>	<ul style="list-style-type: none"> <li>Negative revenue impact</li> <li>Private sector biomass investments dry up</li> <li>Ethanol industry consolidates</li> <li>An 8 billion-gallon ethanol industry</li> <li>Biodiesel industry contracts, investment hard to come by</li> </ul>	<ul style="list-style-type: none"> <li>Significant positive revenue impact (\$5-7 bil.)</li> <li>Potential for long run shift to U.S. corn production from soybean production</li> <li>Industry is fuel driven with modest downstream product development</li> <li>A 12-billion-gallon ethanol industry</li> <li>Chemical companies pursue niche biobased products</li> <li>Biodiesel gains momentum</li> </ul>	<ul style="list-style-type: none"> <li>Major positive revenue impact (\$10-15 bil.)</li> <li>Exceptional returns to ethanol producers</li> <li>Fuel-driven industry with rapid breakthroughs in biomass technology (e.g., cellulose to ethanol)</li> <li>Private research and development accelerates dramatically</li> <li>An 18-billion-gallon ethanol industry</li> <li>Further expansion of the biodiesel industry requires the importation of oil feedstocks</li> </ul>
<b>High Government Support and Incentives (above current level)</b>	<ul style="list-style-type: none"> <li>Positive revenue impact (\$4-6 bil.)</li> <li>Biomass investments are negligible from the private sector</li> <li>Technology breakthroughs in biomass slow</li> <li>Biodiesel is very uneconomical</li> </ul>	<ul style="list-style-type: none"> <li>Significant positive revenue impact (\$7-10 bil.)</li> <li>U.S. exports of soybeans slow in order to meet biodiesel demand</li> <li>Industry is fuel driven with rapid downstream product development and new breakthroughs in conversion technologies</li> <li>Chemical companies pursue niche biobased products</li> <li>The biodiesel industry grows at a modest rate while the ethanol industry grows at a fast rate</li> </ul>	<ul style="list-style-type: none"> <li>Remarkable positive revenue impact (\$12-20 bil.)</li> <li>Fuel-driven industry with rapid breakthroughs in biomass technology (e.g., cellulose to ethanol)</li> <li>Potential for U.S. to import soybeans/soybean oil from Brazil</li> <li>Private research and development accelerates dramatically with rapid breakthroughs in biomass technology (e.g., cellulose to ethanol)</li> <li>The biodiesel and ethanol capacity increases dramatically</li> </ul>

Source: Informa Economics et al., Biobased Multi-Client Study, March 2006.

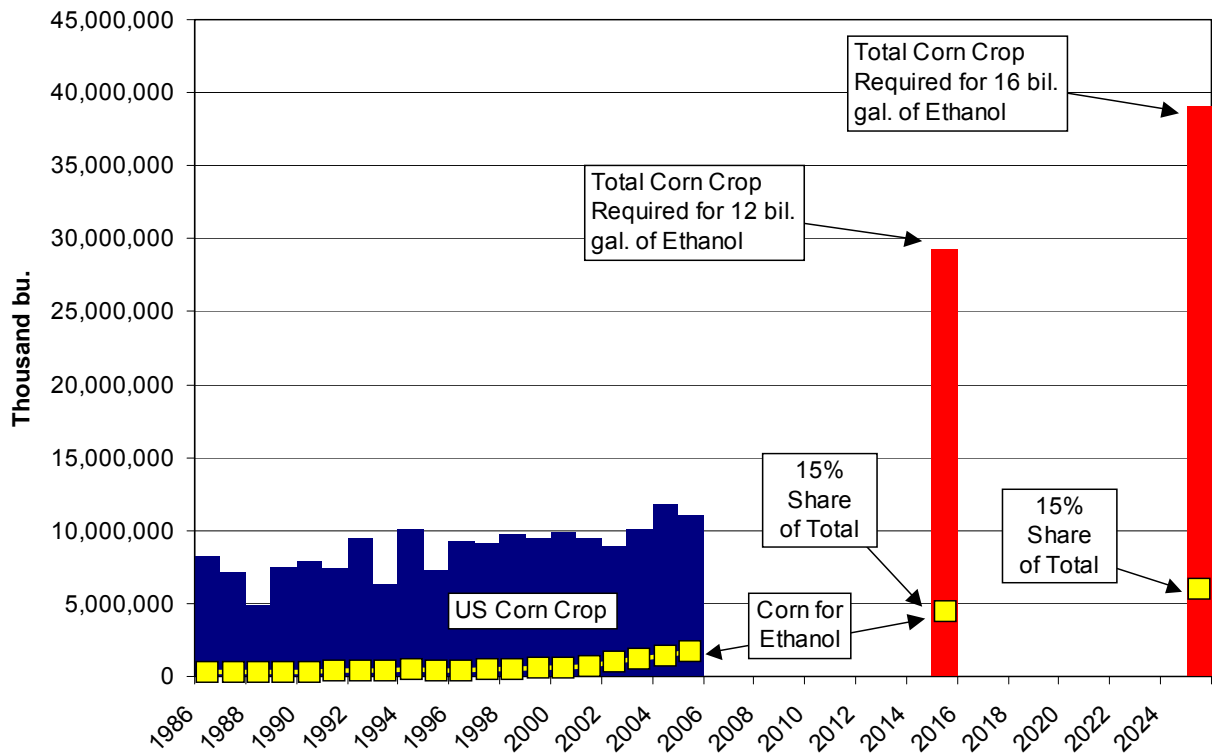
## B. U.S. Ethanol Potential Based on Corn as the Feedstock

This section is separate from the previous matrix section, and considers the question, how much biomass feedstock from corn can the U.S. agriculture system supply in order to meet the rapid expansion of the U.S. ethanol industry? Different scenarios are explored in this section highlighting how the growth of the ethanol industry could alter the landscape of the U.S. agricultural economy as the demand for corn grows. A combination of both fundamental supply/demand and technical analyses were utilized to explore the parameters of the feedstock capacity question based on Informa Economics' long term outlook for both the ethanol industry and the production of U.S. grains.

### Scenarios

- Under one scenario, approximately 15 percent of the U.S. corn crop will be used to make ethanol in the 2006 crop year. Given a baseline growth trajectory in which ethanol production reaches 12 billion gallons in 2015 and 16 billion gallons in 2025, the U.S. corn crop would have to be almost 30 billion bushels in 2015 and 39 billion bushels in 2025, while maintaining the 15 percent utilization rate, Figure 60.

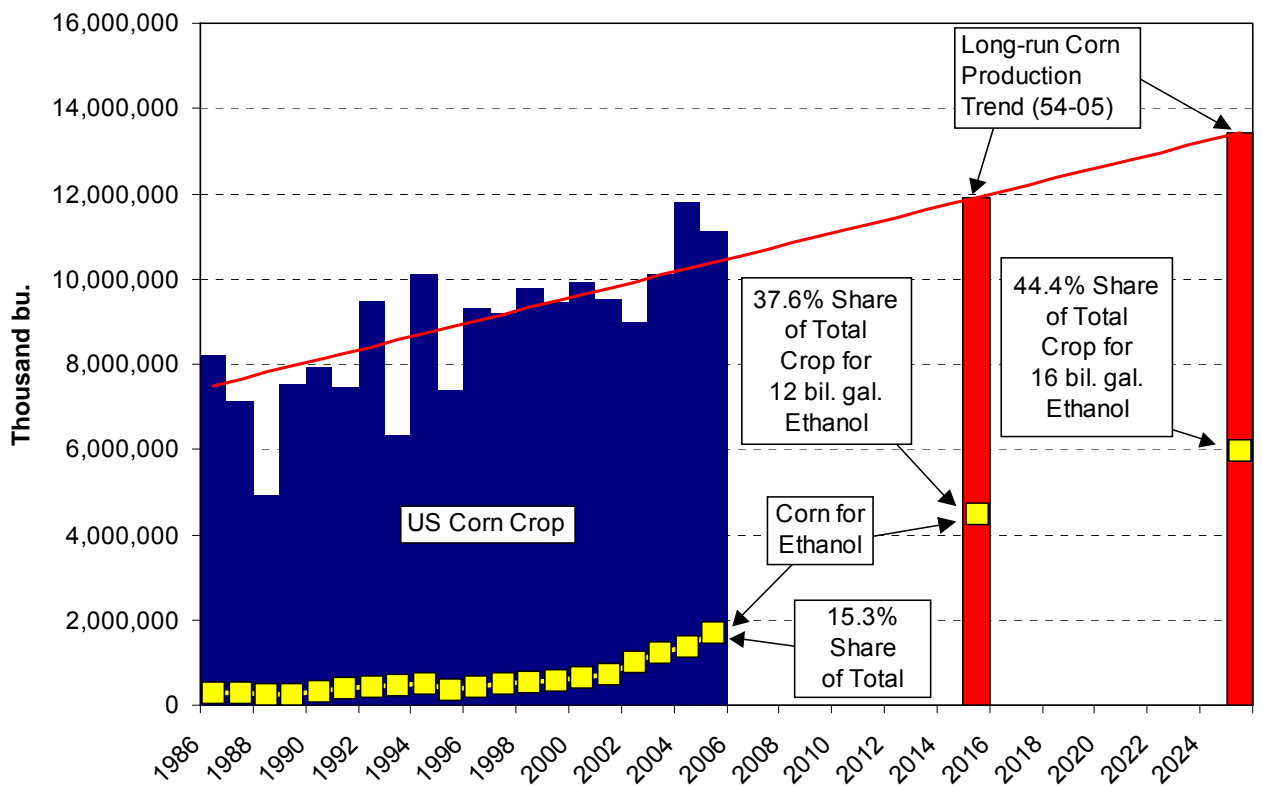
**Figure 60: Corn Production Required to Produce 12 and 16 Billion Gallons of Ethanol, Assuming 15 percent of Crop Allocated to Ethanol**



Source: U.S. Department of Agriculture, National Agricultural Statistics Service, Informa Economics (forecast).

- Another scenario assumes that corn yields will rise. An estimated 37.6 percent of the corn crop would be required to support the target level of 12 billion gallons in 2015, and 44.4 percent of the corn crop would be needed to support the ethanol target of 16 billion gallons by 2025 (Figure 61).

**Figure 61: Proportion of Corn Required to Produce 12 and 16 Billion Gallons of Ethanol Given Current Technology and Production Trends**



Source: U.S. Department of Agriculture, National Agricultural Statistics Service, Informa Economics (forecast).

Each of these scenarios is at the extreme of the continuum; however, they portray the likelihood that significant structural changes in U.S. agriculture could occur if ethanol production continues to grow rapidly and there are no major breakthroughs in conversion technologies (especially cellulose-to-ethanol conversion).

Additional ethanol yields are likely to be realized by fermenting the pericarp (coarse) and endosperm (fine) fiber fractions of the corn kernel. This could increase ethanol yield by 10 or 11 percent compared with the yield obtained by fermenting starch alone.

Assumptions Concerning a “Big” Corn Based Ethanol Industry by 2025:

- 12 billion gallons in 2015 (5.75 percent annual increase in 2011 - 2015).
- 30 billion gallons in 2025 (10.6 percent annual increase in 2015 - 2025).
- Assume 98.8 percent of ethanol comes from feed grains and corn supplies 98 percent of the total.
- The ethanol yield from corn improves over 2015 - 2025 at the same time rate derived for 2005 - 2015. The assumed yield per bushel of corn is 2.69 gallons in 2005/06, 2.82 gallons in 2014/15 and 2.95 gallons in 2025/26.
- Corn used to produce fuel ethanol is projected at 10,270 million bushels in 2025/26. This assumes 1.5 percent annual yield growth to 2015/16 and 1.9 percent growth to 2025/26.
- Feed and residual corn use is assumed to grow 1.4 percent annually from 2006/07 through 2025/26, adjusted for coproduct volume from corn used in fuel alcohol production. Coproducts equal to 33 percent of the corn volume used to produce ethanol are considered a corn substitute in the feed and residual estimate. Corn feed and residual use reaches 4.94 billion bushels in 2025/26 (Table 52).
- Corn exports are assumed to be 1,400 million bushels by 2025/26, lower than in recent years. Promise of steady U.S. ethanol expansion is expected to stimulate world grain production and result in smaller U.S. grain exports.
- The biodiesel assumption included in the ethanol scenario for 2025 allows for 6.53 billion pounds of soybean oil used in biodiesel in 2025/26.
- A 0.5 bushel annual yield increase in soybean production per acre is assumed in the base outlook to 2015/16. A 1.5 percent annual yield increase is assumed for 2016 - 2025 (the 1990 - 2005 average is 1.59 percent), and that implies a 53.8 bushel per acre yield for 2025.
- Soybean oil and whole soybean exports are projected to be 500 million pounds and 750 million bushels, respectively, in 2025 (Table 53).
- U.S. soybean planted area of 62.3 million acres is assumed to be sufficient to supply estimated domestic needs in 2025. This compares to a level of 72.1 million planted acres in 2005.
- Given this set of assumptions about supply and use, U.S. corn acreage is forecast at 94.5 million acres by 2025, while soybean and wheat acreage is forecast to decline (Table 54).

**Table 52: U.S. Corn Balance Sheet Projections to 2015 and 2025**

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2015	2025
Planted Area (mil. acres)	75.7	78.9	78.6	80.9	81.8	78.1	84.0	86.0	86.5	87.5	87.5	94.5
Harvested Area	68.8	69.3	70.9	73.6	75.1	71.0	77.0	79.0	79.5	80.5	80.5	87.5
Harvested Yield (bu/acre)	138.2	129.3	142.2	160.4	147.9	150.8	153.0	155.3	157.6	160.0	172.4	208.0
Beginning Stocks (mil. bu)	1,899	1,596	1,087	958	2,114	2,231	1,408	1,223	1,248	1,288	1,753	
Production	9,503	8,967	10,089	11,807	11,112	10,707	11,780	12,270	12,530	12,880	13,870	18,200
Imports	10	14	14	11	10	10	10	10	10	10	10	
Total Supply	11,412	10,578	11,189	12,776	13,236	12,948	13,198	13,503	13,788	14,178	15,633	
Feed Use/Residual	5,864	5,563	5,795	6,160	6,075	6,100	6,000	5,990	6,010	6,030	6,050	4,940
Food/Seed/Ind	2,046	2,340	2,537	2,688	2,980	3,490	4,050	4,330	4,530	4,730	5,990	11,850
(of which Fuel Alcohol)	706	995	1,167	1,323	1,600	2,100	2,650	2,920	3,110	3,300	4,510	10,270
Total Domestic Disappearance	7,911	7,903	8,332	8,848	9,055	9,590	10,050	10,320	10,540	10,760	12,040	16,790
Exports	1,905	1,588	1,900	1,814	1,950	1,950	1,925	1,935	1,960	1,970	2,060	1,400
Total Disappearance	9,816	9,491	10,232	10,662	11,005	11,540	11,975	12,255	12,500	12,730	14,100	18,190
Ending Stocks	1,596	1,087	958	2,114	2,231	1,408	1,223	1,248	1,288	1,448	1,533	

Note: Forecast begins in 2005

1/ Includes only that revenue associated with actual production. Direct, Counter Cyclical and similarly determined revenue is not included.

Source: U.S. Department of Agriculture, National Agricultural Statistics Service, Informa Economics (forecast).

**Table 53: U.S. Soybean Complex Balance Sheet Projections to 2015 and 2025**

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2015	2025
<b>SOYBEANS</b>												
Planted Area (mil. acres)	74.1	74.0	73.4	75.2	72.1	76.9	71.5	70.5	71.0	71.5	70.0	62.3
Harvested Area	73.0	72.5	72.5	74.0	71.4	76.0	70.5	69.5	70.0	70.5	69.0	61.3
Harvested Yield (bu/acre)	39.6	38.0	33.9	42.2	43.3	41.9	42.4	42.9	43.4	43.9	46.4	53.8
Beginning Stocks (mil bu)	248	208	178	112	256	635	999	881	604	504	675	
Production	2,891	2,756	2,454	3,124	3,086	3,181	2,990	2,980	3,040	3,090	3,200	3,300
Imports	2	4	6	6	3	5	4	4	4	4	4	
Total Supply	3,141	2,969	2,638	3,242	3,345	3,821	3,993	3,865	3,648	3,598	3,879	
Crush	1,700	1,615	1,530	1,696	1,695	1,725	1,870	1,920	1,950	1,980	2,080	2,390
Food/Seed/Residual	169	132	109	187	165	151	142	141	144	147	152	157
Total Domestic Disappearance	1,869	1,747	1,639	1,883	1,860	1,876	2,012	2,061	2,094	2,127	2,232	2,547
Exports	1,064	1,044	887	1,103	850	946	1,100	1,200	1,050	950	1,000	750
Total Disappearance	2,933	2,791	2,526	2,986	2,710	2,822	3,112	3,261	3,144	3,077	3,232	3,297
Ending Stocks	208	178	112	256	635	999	881	604	504	521	647	
<b>SOYBEAN MEAL (000 ton)</b>												
Beginning Stocks	383	240	220	211	172	187	220	220	250	250	250	
Production	40,292	38,194	36,324	40,717	40,015	40,983	44,420	45,610	46,320	47,030	49,410	56,770
Imports	148	173	285	147	200	200	150	150	150	150	150	
Total Supply	40,823	38,607	36,829	41,075	40,387	41,370	44,790	45,980	46,720	47,430	49,810	
Domestic Disappearance	32,568	32,073	31,529	33,563	33,400	34,400	34,920	35,440	35,970	36,510	39,330	45,660
Exports	8,015	6,314	5,089	7,340	6,800	6,750	9,650	10,290	10,500	10,670	10,230	11,110
Total Disappearance	40,583	38,387	36,618	40,903	40,200	41,150	44,570	45,730	46,470	47,180	49,560	56,770
Ending Stocks	240	220	211	172	187	220	220	250	250	250	250	
<b>SOYBEAN OIL (mil. lbs)</b>												
Beginning Stocks	2,767	2,359	1,491	1,076	1,699	2,769	2,669	2,639	2,634	2,594	2,499	
Production	18,898	18,438	17,080	19,360	19,785	19,600	20,940	21,500	21,840	22,180	23,300	26,770
Imports	46	46	336	23	35	50	50	50	50	50	50	
Total Supply	21,711	20,843	18,907	20,458	21,519	22,419	23,659	24,189	24,524	24,824	25,849	
Domestic Disappearance	16,833	17,091	16,896	17,435	17,650	18,500	19,920	20,605	21,080	21,495	22,870	26,240
of which Biodiesel	100	120	125	465	1,550	2,325	3,215	3,695	3,985	4,225	4,850	6,530
Exports	2,519	2,261	935	1,324	1,100	1,250	1,100	950	850	750	500	500
Total Disappearance	19,352	19,352	17,831	18,759	18,750	19,750	21,020	21,555	21,930	22,245	23,370	26,740
Ending Stocks	2,359	1,491	1,076	1,699	2,769	2,669	2,639	2,634	2,594	2,579	2,479	

Note: Forecast begins in 2005

1/ Includes only that revenue associated with actual production. Government Direct, Counter Cyclical and similarly determined revenue is not included.

Source: U.S. Department of Agriculture, National Agricultural Statistics Service, Informa Economics (forecast).



**Table 54: U.S. Planted Acreage to 2015 and 2025 (Thousand Acres)**

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2015	2025
Corn, All	75,702	78,894	78,603	80,930	81,759	78,102	84,000	86,000	86,500	87,500	87,500	94,500
Sorghum, All	10,248	9,589	9,420	7,486	6,454	6,483	6,800	6,950	7,000	7,100	7,100	7,650
Barley	4,951	5,008	5,348	4,527	3,875	3,667	3,800	3,750	3,750	3,700	3,600	3,350
Oats	4,401	4,995	4,597	4,085	4,246	4,324	4,270	4,220	4,170	4,120	3,870	3,000
All Wheat	59,432	60,318	62,141	59,674	57,229	57,128	57,500	57,000	56,500	55,000	54,500	52,000
Winter Wheat	40,943	41,766	45,384	43,350	40,433	41,404						
Other Spring Wheat	15,579	15,639	13,842	13,763	14,036	13,899						
Durum Wheat	2,910	2,913	2,915	2,561	2,760	1,825						
Rye	1,328	1,355	1,348	1,380	1,433	1,350	1,340	1,330	1,320	1,310	1,260	1,200
Rice	3,334	3,240	3,022	3,347	3,384	2,972	3,400	3,200	3,100	3,100	3,200	3,200
Soybeans	74,075	73,963	73,404	75,208	72,142	76,895	71,500	70,500	71,000	71,500	70,000	62,250
Peanuts	1,541	1,353	1,344	1,430	1,657	1,391	1,376	1,361	1,346	1,331	1,256	1,250
Sunflowers	2,633	2,581	2,344	1,873	2,709	2,196	2,196	2,196	2,196	2,196	2,196	2,250
Rapeseed/Canola	1,494	1,460	1,082	865	1,159	923	943	963	983	1,003	1,103	1,250
Flaxseed	585	784	595	523	983	890	700	700	700	700	700	700
Cotton, All	15,769	13,958	13,480	13,659	14,195	14,634	13,750	13,450	13,250	13,050	12,750	12,250
Cotton, Upland	15,499	13,714	13,301	13,409	13,925	14,300	13,500	13,200	13,000	12,800	12,500	12,000
Cotton, Am-Pima	270	244	179	250	270	334	250	250	250	250	250	250
Hay, All	63,516	63,942	63,383	61,966	61,649	61,478	62,000	62,000	62,000	62,000	62,000	62,000
Beans, Dry Edible	1,437	1,930	1,406	1,354	1,659	1,710	1,475	1,475	1,475	1,475	1,475	1,450
Tobacco	432	428	411	408	298	307	297	287	277	267	217	175
Sugar Beets	1,365	1,427	1,365	1,346	1,295	1,372	1,357	1,342	1,327	1,312	1,237	1,300
Double-Counted Acres:												
Soybeans Double-Cropped	4,102	4,179	4,138	4,481	2,926	3,644	3,600	3,600	3,600	3,600	3,600	3,500
Spring Reseeding	1,400	1,200	300	0	0	100	0	0	0	0	0	0
<b>Crop Total</b>	<b>316,742</b>	<b>319,847</b>	<b>318,855</b>	<b>315,580</b>	<b>313,201</b>	<b>312,078</b>	<b>313,104</b>	<b>313,124</b>	<b>313,294</b>	<b>313,064</b>	<b>310,364</b>	<b>306,275</b>
<b>Government Acres:</b>												
Conservation Reserve	33,560	33,890	34,087	34,860	34,861	34,955	33,926	34,176	34,176	34,176	34,176	35,000
<b>Total Government</b>	<b>33,560</b>	<b>33,890</b>	<b>34,087</b>	<b>34,860</b>	<b>34,861</b>	<b>34,955</b>	<b>33,926</b>	<b>34,176</b>	<b>34,176</b>	<b>34,176</b>	<b>34,176</b>	<b>35,000</b>
<b>Grand Total</b>	<b>350,302</b>	<b>353,737</b>	<b>352,942</b>	<b>350,440</b>	<b>348,061</b>	<b>347,033</b>	<b>347,029</b>	<b>347,299</b>	<b>347,469</b>	<b>347,239</b>	<b>344,539</b>	<b>341,275</b>

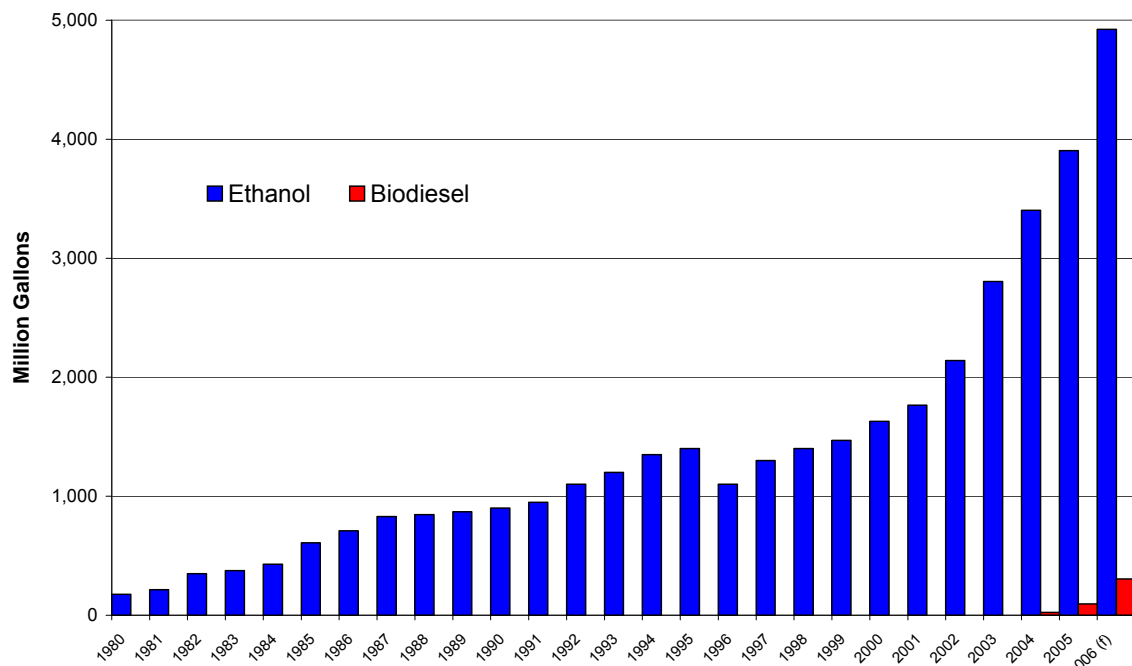
Note: Forecast begins in 2005

Source: U.S. Department of Agriculture, National Agricultural Statistics Service, Informa Economics (forecast).

## C. Long-Term Potential for Biodiesel

Biodiesel production (Figure 62) is expected to grow at a faster rate than ethanol because the U.S. biodiesel industry is being developed in an economic environment of 1) high energy prices which enhances the financial viability of biodiesel production, 2) high federal and state incentives that reduce the short and medium term risks of biodiesel investments, and 3) renewed interest of public and private institutions on energy independence and renewable fuels. While the rate of growth in biodiesel will fluctuate and likely slow from rates observed in recent years, biodiesel production is expected to reach the 1-billion gallon level before 2016.

**Figure 62: Ethanol versus Biodiesel Production History**



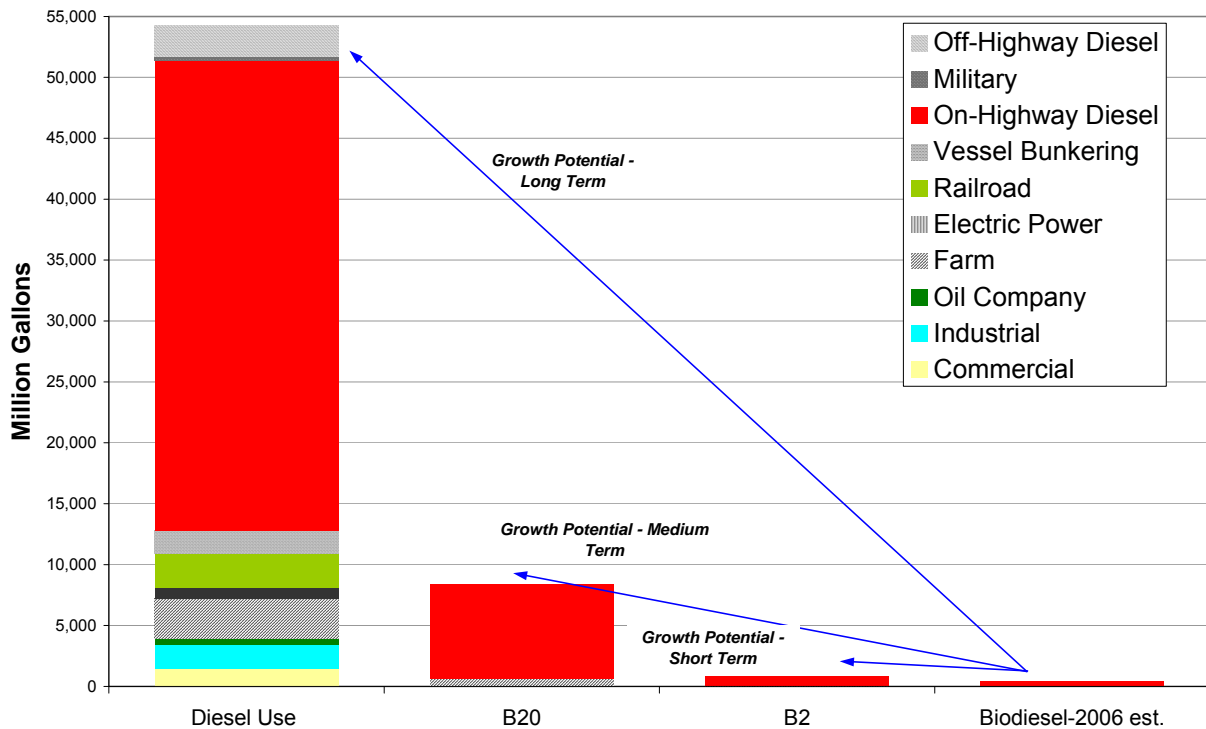
Source: Renewable Fuel News, National Biodiesel Board, Informa Economics (forecast)

The opportunity to expand biodiesel production is significant if one considers that the total U.S. diesel market, for all uses, is estimated to reach 55 billion gallons by the end of 2006. However, as noted earlier in this report, the biodiesel demand (i.e., biodiesel opportunity) in the short and medium term should be examined as a fraction of the total diesel market (due to technical constraints) and should include for the most part only the on-highway and farming market segments. The underlying assumption is that other market segments, such as off-highway or vessel bunkering, will be late adopters of biodiesel. In the short term (1 to 3 years), the effective biodiesel market is judged to be equivalent to a national 2 percent (B2) blend, which in 2006 will be approximately 837 million gallons (Figure 63). By the end of 2006, Informa Economics estimates that biodiesel production will reach 300 million gallons, a volume equivalent to 35 percent of the B2 effective market.

In the medium term (5 to 10 years), biodiesel blends will increase to what is considered to be a maximum market before any modifications need to be made to automobile or tractor engines or to the quality or chemical profile of biodiesel. This maximum blend has been estimated to be 20 percent (B20) by several institutions including the National Renewable Energy Laboratory. Hence, the biodiesel market potential in the medium term is estimated to be over 8.5 billion gallons (based on 2006 diesel consumption for on-highway and farm uses).

In the long term, the potential is significant, that is, over 55 billion gallons. However, economic, technical, political, and structural barriers will need to be overcome in order to realize this theoretical potential. A technological breakthrough will be needed to enable the use of multiple renewable feedstocks at a cost that is competitive with that of petroleum based diesel.

**Figure 63: Growth Opportunities for Biodiesel Production in the United States**



Source: U.S. Department of Energy, National Biodiesel Board, and Informa Economics.

A technology that has the potential to take biodiesel to the next generation of fuels is the Gasification Fisher Tropsch process to transform biomass to liquids. A significant amount of research has been and continues to be conducted in this area to bring this technology to an economically viable and commercially available state.

While biodiesel growth opportunities are significant, this market does have risks that need to be overcome and that can limit private investment. The main risks include the following:

- Biodiesel is highly dependent on the dollar a gallon federal tax credit. Given the economic conditions experienced during 2005 and 2006, the industry would not have been profitable without the tax incentive. Thus, future growth of the industry will depend crucially on continued supported by government.
- There is no link between input costs (e.g., vegetable oil) and biodiesel prices. This environment provides for a higher level of margin exposure and volatility, especially among producers who do not have experience using risk management systems or tools.
- Profitability is highly linked to the price of conventional diesel and hence to the volatility and uncertainty of the overall energy prices.
- New technologies or processes can change the economics of production and make some of the existing players, especially the small ones, uncompetitive.
- Domestic production of vegetable oil, the main feedstock, may not be able keep up with the rapid demand growth due to biodiesel. The main consequence would be high vegetable oil prices which in turn would reduce competitiveness of some firms and could drive small, out-of-position, players out of business.

#### **D. Employment Impacts**

The original seeds of development in the ethanol industry began over 20 years ago; however, the combination of supportive local, state, and Federal policies and record high energy prices has dramatically accelerated the expansion of the industry, especially over the last 5 years. A wave of economic impacts has followed, including the creation of new jobs to staff that operate plants; the emergence of consulting firms that specialize in ethanol feasibility studies; the need for rail (transportation) companies to learn the intricacies of moving DDGS and ethanol; and the involvement of engineering firms in the planning and construction of the facilities. All of these spin-off effects have helped the U.S. agricultural economy.<sup>25</sup>

The ethanol industry is expected to continue to grow robustly over 2007 - 09, as MTBE is phased out and oil prices remain high, and then expand at a more moderate pace through 2015. The industry will likely continue to grow as a result of technological breakthroughs such as cellulosic conversion of corn stover and new cost saving technologies such as better enzymes.

Many economic development groups and universities have prepared economic impact studies to help validate the construction of ethanol plants within their

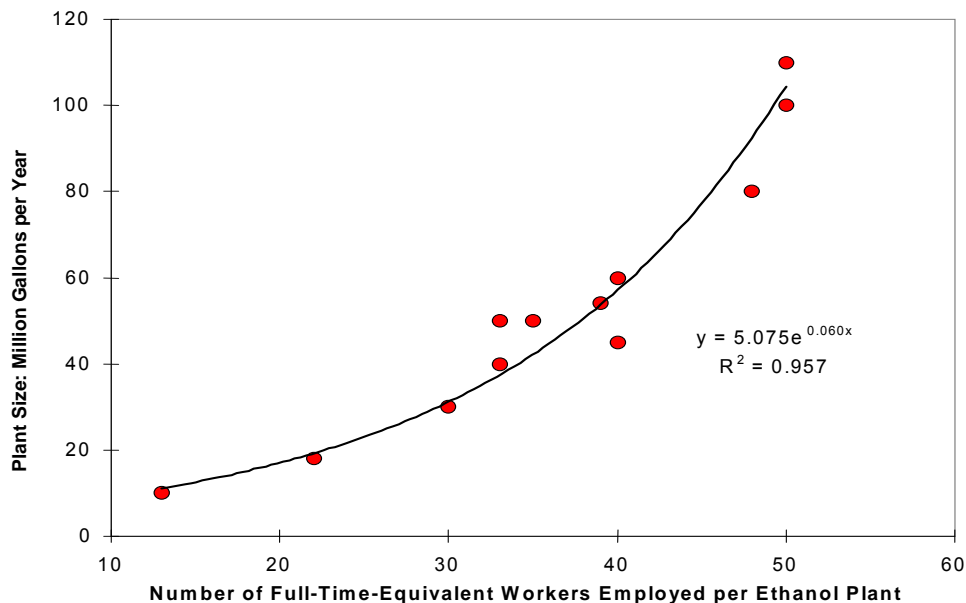
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<sup>25</sup> Numerous other benefits have accrued to the rural economies as a result of ethanol production, such as, increased tax bases and, in general, higher feedstock prices which translates into greater revenues for farmers.

respective regions.<sup>26</sup> Many of these reports have focused on the job creation. Job creation has been used successfully to help procure special financial treatment from state and local governments. But how much would “significant” capacity expansion benefit the overall economy? Estimates vary considerably regarding the number of jobs directly and indirectly related to the ethanol industry. Critical to the ethanol industry is the balance between capital and labor, which would seem to shift as plant capacity increases. A large ethanol plant would require more capital and relatively less labor while a smaller plant would have more labor and less capital.

Operational statistics for dry-mill plants were from numerous sources (such as press releases and academic reports) identifying plant capacity (representing capital) and the number of full-time-equivalent (FTE) workers for each plant. By fitting an exponential curve to the data, an R-squared of 0.96 was calculated (Figure 64). The exponential shape of the curve displays the industry’s adherence to the notion of “economies to scale.” This exercise forms the basis for estimating the employment impact of adding additional industry capacity by the year 2025.

**Figure 64: Estimate of the Capital/Labor Relationship for the U.S. Ethanol Industry**



Source: Informa Economics et al., Biobased Multi-Client Study, March 2006.

<sup>26</sup> Examples of such studies are Peterson et al., Stuefen, Petersan, and Gallagher and et al. (2001).

## **E. Calculating the Employment Impact of the U.S. Ethanol Industry in 2006 and 2025**

The Renewable Fuels Association estimates that as of March 2006 there were 97 U.S. ethanol plants producing 4,481 million gallons per year; 85 dry mills produce 77 percent of the ethanol, and 12 wet mills produce 23 percent.

The U.S. Census of Manufacturing estimated that the number of employees in the “wet corn milling” (which includes high-fructose corn syrup) sector as 8,776 FTE in 2004. Informa’s estimate is 8,672 FTE in 2006. An estimated 23 percent of the wet corn milling industry is dedicated to ethanol and the rest to high-fructose corn syrup production, so 1,995 FTE workers were employed making ethanol via wet corn milling in 2006. Dry-mill based ethanol production employed an estimated 2,940 FTE workers in 2006, for a total of 4,935 FTE workers.

To calculate anticipated employment by 2025, the following assumptions were made (1) ethanol production will grow to 30,000 mgy; (2) the labor/capital ratio will change; and (3) the majority of new capacity will be dry mill based. The labor/capital ratio is almost certain to change as new plants become larger. Using the labor/capital equation identified in Figure 64 and assuming an industry wide plant average of 100 mgy in 2025, ethanol output of 30,000 mgy would require an additional 13,270 FTE jobs, a total of 18,205. This estimate includes only jobs directly linked to ethanol production, and not the indirect and induced effects of the ethanol industry on employment.

The backward employment links to the ethanol economy play an important role. Figure 65 provides a detailed description of the linkages within the ethanol economy. For example, the farmers’ production of corn (the lifeblood of the ethanol process) depends on seed manufacturers, equipment dealers, and bankers, among others. And “ethanol wages” are spent in rural settings to buy groceries, gas, and other goods, supporting ancillary jobs (induced effect).

Estimates of employment multipliers in the ethanol industry can vary widely. One reason for the latitude is the structure and design of the input-output models used. There is no precise industry definition or classification for dry-mill ethanol platforms within the models. The popular input-output computer program IMPLAN, for example, has a classification for wet corn mills but none for dry mills. Since wet corn mills are more labor intensive, the use of wet mill multipliers for ethanol production would overstate any employment impact of the U.S. ethanol industry. Other research has used multipliers from IMPLAN categories such as “Other Basic Organic Chemical Manufacturing” (because “Ethyl Alcohol Manufacturing” is a subcategory), but ethyl alcohol manufacturing is deeply buried within the larger category and is a suspect starting point. As a result, this study blends multipliers to achieve an average of the previous studies and a better balance in impact estimation process. It should also be noted that the multiplier impacts discussed in this analysis include only those impacts that are related directly to ethanol

production and the impacts on those industries associated with ethanol production in the backward links. In order to determine the forward link impacts (e.g., ethanol transportation, retail sales) a more complex study would be required, beyond the scope of this report. By not including estimated forward employment impacts in this study the total employment impacts are very conservative.

**Highlights**

- The current ethanol industry has an estimated direct, indirect, and induced impact of 31,020 jobs (Table 55).
- If the current level of ethanol production were raised 25.5 billion gallons to 30 billion gallons in 2025, 83,411 new jobs would be created. Many of these jobs would be in rural regions that produce corn. These estimates are only for ongoing operational activities; one time construction impacts are not included.
- Employment impacts would be even higher if farming revenues increase. Any sustained increase in the price of corn translates into improved cash receipts for producers and would likely set off another round of positive employment impacts in those industries that provide inputs for the corn economy.

**Table 55: Projected Employment Impact of a 30 Billion Gallon Ethanol Industry in 2025**

Year	Direct Employment # FTE	Direct Effect FTE:	Indirect Effect**	Induced Effect***	Total Effect
<b>2006 (4.5 bil gal)</b>					
Current	4,935	4,935	18,330	7,755	<u>31,020</u>
<b>2025 (30 bil gal)</b>					
Current	4,935	13,270	49,289	20,852	<u>83,411</u>
+ Growth	<u>13,270</u>				
Total	18,205	18,205	67,619	28,607	<u>114,431</u>

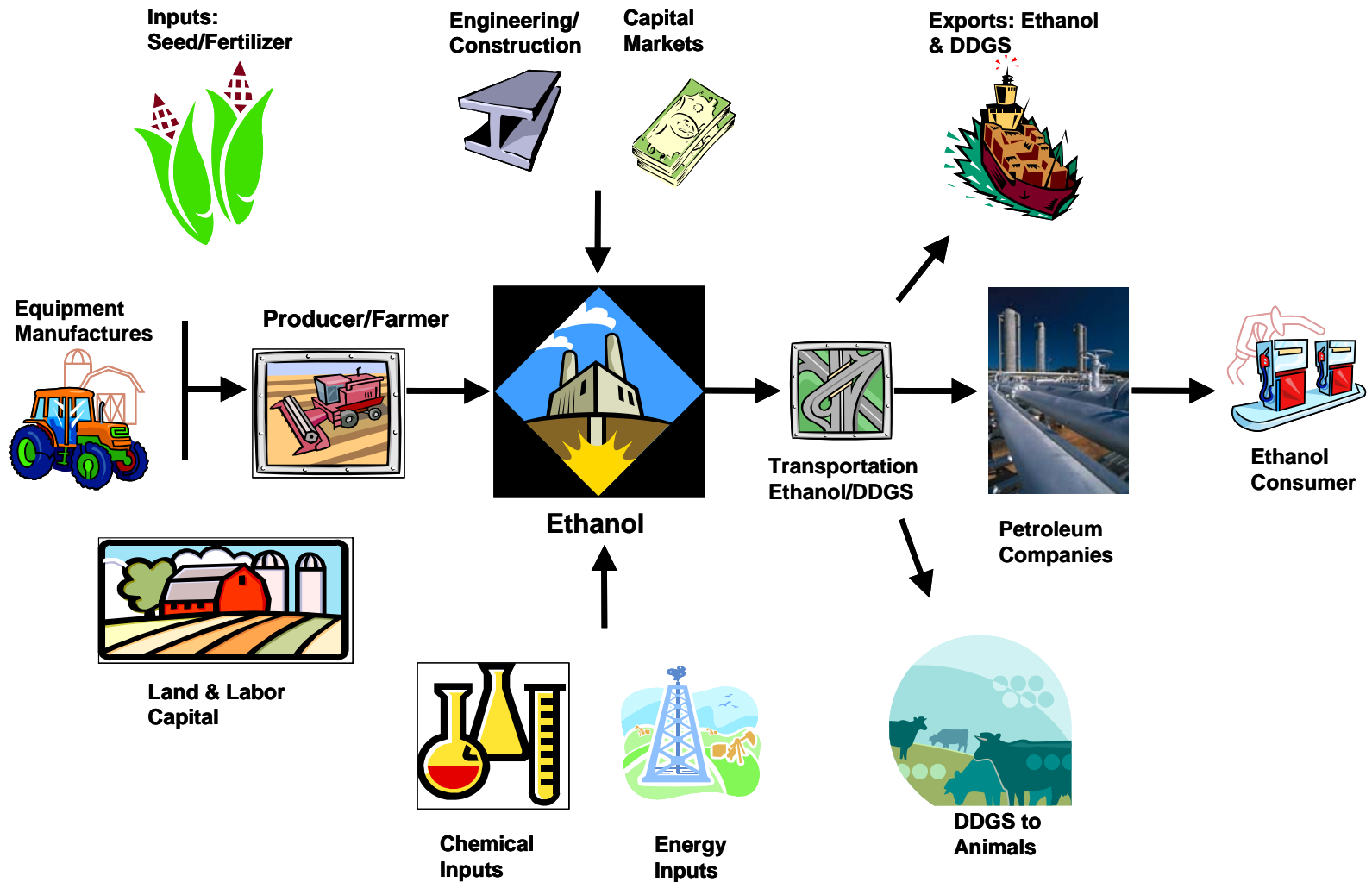
\* The economic impact estimated in this table is for ongoing operations only; one-time construction impacts are not included.

\*\* The indirect effect shows the number of jobs created in the supporting industries for each direct job created.

\*\*\* The induced effect reflects the number of jobs created by additional demand throughout the economy as ethanol-related wages, taxes, etc., are increased.

Source: Informa Economics et al., Biobased Multi-Client Study, March 2006.

Figure 65: Economic Linkages to the Production of Ethanol



Source: Informa Economics.



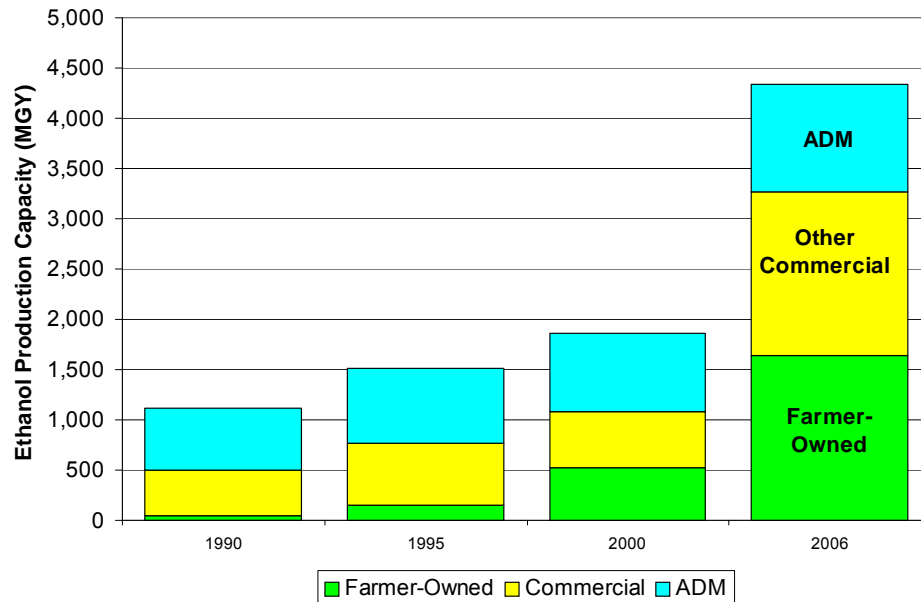
## F. Ownership Considerations

Ethanol industry ownership has changed significantly during the last 15 years. Initially, most ethanol capacity was owned by Archer Daniels Midland (ADM), and related to wet corn milling. Farmer-owned ethanol capacity was only 4 percent of total ethanol production in 1990.

Gradually, farmer-owned operations began to emerge, especially from existing farmer cooperatives that were linked to the production of corn. By 2006, farmer-owned ethanol capacity had expanded to 37 percent of total industry capacity (Figure 66). This farmer-owned growth was particularly strong in farm oriented states such as Minnesota, Nebraska, and Illinois.

As average capacity for new corn based ethanol operations grows, so will capital costs. The commercial sector and ADM may be able to more easily raise capital funds than the farm sector, and so their share of capacity will begin to grow. Another factor that will likely induce more large scale ethanol facilities is the anticipated emergence of integrated biorefineries where corporate joint ventures between Fortune 500 companies will require sizable capital investments.

**Figure 66: Evolution of Ethanol Production Capacity: Farmer-Owned, Commercial, and ADM**



Source: Renewable Fuels Association and Informa Economics.

## IX. Policy Context

### A. Background

The emergence in recent years of a growing and innovative biobased products' industry is due principally to the convergence of four factors. First, as world demand for oil and natural gas has risen sharply in response to world economic growth, coupled with political tensions in a number of major petroleum and natural gas producing countries, petrochemical feedstock prices in the United States have risen to the point that biobased products have become more cost competitive. Second, researchers have learned how to unlock biobased material to extract the building blocks for a wide range of biobased products. Third, efforts to improve environmental sustainability and human health have spurred a shift to biobased products and renewable energy. Fourth, policy makers have supported that research and have recognized the positive environmental and public health benefits associated with biobased products.

Three forces have had and will continue to have the greatest impact on the growth of biobased products' industry: oil prices, government policies, and advances in biosciences. The shift toward greater use of biobased products will be strongly linked to the development of biorefineries capable of producing both liquid fuels and streams of feedstocks for a wide range of biobased products.

Public sector investments in research and product development have played an important role in developing biobased products and will continue to do so, especially with the increased public sector attention to early commercialization issues. The biobased products industry (especially biofuels) would not be at the present stage of development if not for significant support from local, state, and Federal governments.

Clean air and energy concerns have importantly driven biobased product policies in the United States. Concerns about the 1973 and 1979 oil embargoes led to the creation of Federal programs that supported a wide variety of regional and state projects, as well as research initiatives. A series of federal incentive programs encouraged production of biobased fuels, with a focus on transportation fuels made from renewable organic matter instead of petroleum.

In spite of the sharply increased research efforts and incentive programs, biofuel production grew slowly through the 1980s, constrained by low petroleum prices. Until recently, ethanol prices could not compete with gasoline and market growth depended heavily on government policies - especially policies to improve air quality. Much of the current interest in biofuels and biobased products has been driven by high petroleum prices. In August 2006, oil prices reached \$70 a barrel, and the Energy Information Administration (EIA) forecasted that oil prices would move down from that level to the \$ 40-50 per barrel range (inflation adjusted) level for the next 25 years.

Biofuel policies in other countries have been mainly driven by concerns about controlling greenhouse gases and diversifying fuel supplies. Canada's biofuels policy was primarily established through the Action Plan 2000 on Climate Change. The European Union's biofuel policies were influenced by the 2000 Green Paper, *Towards a European strategy for energy supply*. The European Union highlighted its dependence on external energy sources, and emphasized the need to comply with emissions reduction commitments in the Kyoto Protocol.

None of the developed countries in Asia (Japan, South Korea, and Taiwan) has a fully developed biofuel strategy. Grain and oilseed exporting countries, with their abundant stocks, have an advantage in the production of biofuels from grains and oilseeds. Asian grain and oilseed importers do not have surplus feedstocks, so biofuel policies depend more on cost competitiveness with petroleum.

By contrast, some developing countries in Asia and South America have abundant land, tropical climates, and high rainfall, which provide them with a competitive advantage in the production of low-cost biofuel feedstocks - both carbohydrates and cellulose. They are generally building on this potential, and either have or expect to produce biobased fuel that is competitive both with temperate-zone biofuels and petroleum based fuels. Biofuels from developing countries are moving rapidly to replace petroleum imports. Brazil, in particular, is a significant ethanol producer. China also is an important biofuel producer, although a distant third after the United States and Brazil. Malaysia is a low-cost producer of palm oil, which can be used in biodiesel. Several current biofuel projects in Asia involve the construction of biodiesel plants that would use Malaysian palm oil as a feedstock.

Appendix 2 provides additional information on the policies of other countries.

## **B. Policies in the United States**

Government legislation and regulations have played an important role in the growth of biofuels and biobased products over the past two decades. The economics of biofuel and biobased product production necessitated the assistance of public policy in the development of the industry and for market penetration; additionally government incentives have been invaluable in helping biofuels compete with less costly petroleum based fuels. Major motivations behind this legislation have been enhancing national energy security, improving the environment, and stimulating the agricultural economy, through value-added agricultural processing and manufacturing in rural communities. The opportunity to better manage the carbon cycle is also inherent in the production of biobased products, which essentially recycle atmospheric carbon in contrast to products made from petrochemical sources.

The policy discussion that follows is divided into 1) biomass and biobased product policies, 2) biofuel policies and 3) climate change policy.

## 1. Federal Biomass and Biobased Products Policies

Executive Order 13134, “Developing and Promoting Biobased Products and Bioenergy,” issued in 1999, set as an objective the development of a comprehensive national strategy that includes research, development, and private sector incentives to stimulate the creation and early adoption of technologies needed to make biobased products and bioenergy cost-competitive in national and international markets. The Biomass Research and Development Act of 2000, title III of the Agricultural and Risk Protection Act of 2000 (ARPA) established the Biomass Initiative and created the Technical Advisory Committee and the Biomass Research and Development Board to provide oversight to the effort.

The Biomass Research and Development Act of 2000 directed the Secretaries of Agriculture and Energy to cooperate and coordinate policies to promote research and development leading to the promotion of biobased products. Additionally it defined research and development to include research, development and demonstration. Under the biomass research and development initiative, financial assistance was awarded to public and private entities for research on biobased products. Its goal was to promote research partnerships between private and public entities, enhance biomass processing and make possible low-cost, sustainable biobased industrial production. USDOE undertook research activities under the Statute. A joint program between USDA and USDOE was implemented after the Farm Security and Rural Investment Act of 2002 (2002 Farm Bill) amended the Biomass Research and Development Act of 2000 and included funding for USDA.

The 2002 Farm Bill contained the first energy title in a Farm Bill. Programs relevant to the promotion of the production and use of bioenergy and biobased products include:

- The Renewable Energy Systems and Energy Efficiency Improvements Program provides financial support to farmers, ranchers, and rural small businesses for developing value-added products such as ethanol and biodiesel.
- The 2002 Farm Bill formalized the Biobased Products and Bioenergy Coordination Council (BBCC) within USDA. The BBCC enables USDA agencies to coordinate and facilitate research, development, transfer of technology, commercialization, and marketing of biobased products and bioenergy using renewable domestic agricultural and forestry materials.
- The 2002 Farm Bill created the BioPreferred™ program (earlier called Federal Biobased Product Procurement Preference Program) and a voluntary biobased product labeling program. USDA’s BioPreferred™ program, led by the Office of Energy Policy and New Uses and Departmental Administration, requires all federal agencies to give procurement preference to biobased products designated by USDA. Federal agencies are not required to give

preference to biobased products when the products are not available, are too costly, or do not meet the reasonable performance standards established by the agencies. Since the Federal government purchases billions of dollars of products and services each year, the procurement program has the potential of sparking the biobased industry by providing increased demand for biobased products. Final Guidelines for Designating Biobased Products for Federal Procurement were published in the Federal Register on January 11, 2005, and applicable provisions that extended the preferred procurement requirement to Federal contractors were outlined in the Energy Policy Act of 2005 (EPACT) and implemented by interim final rule on July 17, 2006.

The Energy Policy Act of 2005 (EPACT) included provisions to promote research and commercialization of biobased products:

- The Biomass Research and Development Act of 2000 was further amended. One important amendment expanded research and development in four new areas: (1) developing crops and systems that improve feedstock production and processing, (2) converting recalcitrant cellulosic biomass into intermediates that can be used to produce biobased fuels and products, (3) developing technologies that yield a wide range of biobased products that increase the feasibility of fuel production in a biorefinery, and (4) analyzing biomass technologies for their impact on sustainability and environmental quality, security, and rural economic development.
- EPACT authorized three USDA grant programs. Small business biobased product marketing and certification grants assist small biobased businesses with marketing and certification of biobased products. Regional bioeconomy development grants assist regional development associations and Land Grant institutions in supporting and promoting the growth of regional bioeconomies. Preprocessing and harvesting demonstration grants fund demonstrations by farmer-owned enterprises of innovations in pre-processing of feedstocks and multiple crop harvesting techniques to add value and lower the investment cost of feedstock processing at the biorefinery
- The USDOE is authorized to partner with industrial and academic institutions to advance the development of biofuels, biobased products, and biorefineries. Goals include using biotechnology and other advanced processes to make biofuels from lignocellulosic feedstocks cost competitive with gasoline and diesel, increasing production of biobased products that reduce the use of fossil fuels in manufacturing facilities, and demonstrating the commercial application of integrated biorefineries that use a wide variety of lignocellulosic feedstocks to produce liquid transportation fuels, high-value chemicals, electricity, and useful heat.

The EPACT highlighted the development of new and innovative biobased products made from raw agricultural commodities. To ensure a balanced and focused

research and development approach, EPACT requires funding to be distributed by technical area (20 percent to feedstock production, 45 percent to overcoming biomass recalcitrance, 30 percent to product diversification, and 5 percent to strategic guidance), and within each technical area by value category (15 percent to applied fundamentals, 35 percent to innovation, and 50 percent to demonstration).

## **2. Federal Biofuel Policies**

Biofuels are the most widely recognized biobased products. As the biofuel industries continue to develop, multiple streams of biobased products can emerge from integrated production within biorefineries. Consequently the future of biobased products is tightly linked to developments in the biofuels sector.

Several types of federal policy tools (mandates, economic incentives, and guaranteed loan programs) have been used to encourage bioenergy development. Federal incentive programs for corn ethanol production started in the 1970s as the experience the OPEC oil embargos of the time and subsequent price shocks fueled a search for alternatives to petroleum based fuels. The Energy Tax Act of 1978 authorized a motor fuel excise tax exemption for ethanol blends, providing a \$0.40 per gallon exemption from the Federal motor fuels tax for ethanol blends of at least 10 percent ethanol by volume. In 1980, the Energy Security Act offered guaranteed loans to small ethanol plants producing less than 1 million gallons a year. Since then, various tax laws have changed the level of the ethanol tax credit which currently, and up to 2010, is \$0.51 per gallon of pure ethanol blended into gasoline. The Energy Policy Act of 1992 allowed lower blends of 7.7 percent and 5.7 percent ethanol to receive a prorated fuel tax exemption. Legislation was also passed to give income tax credits and loan guarantees to small ethanol producers (producers of up to 60 million gallons a year).

Much of the federal legislation is currently focused on securing the Country's energy supply, but in the 1990s biofuel production and use was driven by policies aimed at reducing air pollution. Ethanol was first used as a fuel additive in the late 1970s as a result of the phasing out of lead in gasoline as an octane enhancer. The Clean Air Act Amendments of 1990 (CAA90) established the Oxygenated Fuels Program and the Reformulated Gasoline (RFG) Program to control carbon monoxide emissions and ozone problems created by motor fuels. Areas in "non-attainment" were required to add oxygen to gasoline: 2.7 percent by weight for the oxygenated fuel program and 2.0 percent by weight for the RFG. These provisions led to a major expansion in ethanol production.

Refiners blended cleaner burning oxygenates into gasoline to meet the requirements mandated by CAA90. Ethanol and the petroleum based additive methyl tertiary butyl ether (MTBE) were most commonly used. MTBE's contamination of drinking water was found to be long-lasting and possibly carcinogenic. MTBE is currently being phased out and replaced with ethanol. Many states have banned MTBE's use, most notably California, New York, and Pennsylvania. Blenders generally phased out the use of MTBE, which led to another surge on demand for ethanol. The Energy Policy

Act of 2005 ended the Oxygenated Fuels Program and replaced it with a nationwide renewable fuels standard.

USDA initiated the Bioenergy Program in 2000 to stimulate crop demand, alleviate crop surpluses, and encourage new biofuel production. Ethanol producers and Biodiesel producers were eligible for payments based on the increase of production compared with the previous year. Producers with less than 65 million gallons of annual production capacity were reimbursed on a ratio of 1 feedstock unit for every 2.5 feedstock units used, while larger facilities were reimbursed on a ratio of 1 to 3.5. When total incentive payments exceeded appropriated funding, individual payments were prorated.

Title IX, the energy title, of the Farm Security and Rural Investment Act of 2002 (2002 Farm Bill) continued the Bioenergy Program through 2006. It also broadened the list of eligible feedstocks to include animal byproducts and fat, oils, and greases (including recycled fats, oils, and greases).

The 2002 Farm Bill created the Biodiesel Fuel Education Program, which awards competitive grants to educate governmental and private entities with vehicle fleets and the public about the benefits of biodiesel use. It also established the Biorefinery Development Program, a competitive grant program to support development of biorefineries to convert biomass into multiple products such as fuels, chemicals, and electricity. Additionally, it amended the Value-Added Grant Program (VAGP) to financially assist farm families and rural businesses develop new value-added products, such as ethanol and biodiesel.

The American Jobs Creation Act of 2004 granted biodiesel blenders a tax credit of \$1.00 per gallon of biodiesel made from oil crops and animal fats and a \$0.50 per gallon tax credit for biodiesel made from recycled fats and oils. Largely due to this tax credit and other government incentives, biodiesel production has grown from about 500,000 gallons in 1999 to 91 million gallons in 2005. The Energy Policy Act of 2005 (EPACT) extended the biodiesel fuel excise tax credit through 2008 and authorized a \$0.10 per gallon income tax credit to small biodiesel producers.

A recently adopted EPA diesel fuel standard of 15 ppm of sulfur emission that require refiners to remove most of the sulfur from diesel fuel could further increase biodiesel demand, as refiners can blend biodiesel with petroleum diesel to increase lubricity lost when sulfur is removed to meet low sulfur standards (biodiesel contains no sulfur and is an excellent lubricity agent). The U.S. EPA's low-sulphur highway diesel fuel regulation became effective July 2006 and the non-road diesel fuel regulations will become effective in June 2010.

The EPACT included several provisions to help diversify domestic energy production through the development of renewable fuels. EPACT mandates a renewable fuel phase-in called the renewable fuels standard (RFS), requiring U.S. fuel use to include a minimum amount of renewable fuel each year, starting at 4 billion gallons

in 2006 and reaching 7.5 billion gallons in 2012. EPACT also created the Cellulosic Biomass Program to encourage the production of cellulosic ethanol and fund research on conversion technology. Under this program, every one gallon of ethanol made from biomass, such as switchgrass, crop residues, and tree crops, counts as 2.5 gallons towards satisfying the RFS. Additionally it expanded coverage of the small-ethanol producer tax credit to producers of up to 60-million gallons a year (from 30-million gallons). Additionally, the EPACT directed the Secretary of Energy to establish a program of production incentives to deliver the first billion gallons of annual cellulosic biofuels production.

Overall the EPACT authorized \$5 billion (over 5 years) in tax incentives that encourage investments in energy efficiency and alternative renewable energy sources. The Advanced Energy Initiative of 2006, announced during the President's 2006 State of Address, elevated the importance of investments in renewable energy by directing USDOE to accelerate energy technologies, including bioenergy, by increasing the funding for clean energy technology research by 22 percent. Focus was placed on cellulosic ethanol and biomass.

### **3. Climate Change Policy**

Although biobased products eventually release carbon into the atmosphere, the origin of the carbon in biobased products is biogenic rather than fossil. Plants capture atmospheric carbon as they grow. As a result, using biobased products essentially recycles atmospheric carbon, while petrochemical products result in new releases of fossilized carbon into the atmosphere. Furthermore, biobased production processes have demonstrated the potential for emitting fewer, or no more, greenhouse gasses than petrochemical based production processes. Greenhouse gas emissions from the production and use of biodiesel have been shown to be 40 to 60 percent lower than those from conventional diesel. Emissions associated with the lifecycle of grain ethanol are 20 to 40 percent lower than gasoline emissions (International Energy Agency). Cellulosic ethanol can achieve even greater reductions in greenhouse emissions than corn ethanol - over 80 percent relative to gasoline (Wang).

The U.S. climate change policy is science based, and encourages research and technological innovation, relying on market forces to bring technologies into widespread use. It is also strongly tied to biofuel and renewable energy policies. The EPACT and the Advanced Energy Initiative of 2006 directed USDOE (in partnership EPA, USDA, and other federal agencies) to pursue many energy supply technologies with comparatively low or zero carbon dioxide emissions profiles, such as solar, wind, geothermal, bioenergy, and combined heat and power.

In 2002, the United States committed to an 18 percent reduction goal of the greenhouse gas intensity of the economy by 2012 (White House News Releases). Greenhouse gas intensity is a measure of GHG emissions per unit of economic output. The Climate Change Science Program (CCSP), a multi-agency research program led by the U.S. Department of Commerce, investigates natural and human-



induced changes in the Earth's global environmental system, to monitor, understand, and predict global change. The Climate Change Technology Program (CCTP) is a complementary multi-agency program that focuses on accelerating the development and deployment of key technologies that can achieve substantial greenhouse gas emissions reductions. This includes the development and use of biofuels and biobased products. Amongst the many programs that constitute the CCTP voluntary programs, such as the Climate “Vision” Partnership and the Climate Leaders partnership, are also included.

Although in 2001 the United States chose not to meet the requirements from the Kyoto Protocol, it does have an international presence which is based on bilateral and multilateral partnerships. The collaborations focus on expanding and accelerating investments in existing and new technologies. Examples of these efforts include the Asia-Pacific Partnership on Clean Development and Climate, the Methane to Markets Partnership, the Renewable Energy and Energy Efficiency Partnership, and the Carbon-Sequestration Leadership Forum. Since the Asia-Pacific Partnership on Clean Development and Climate was established in 2005, the United States is working closely with key world leaders in the Asia-Pacific region to facilitate the development, deployment, and transfer of more energy efficient and cleaner technologies to allow emissions to be reduced without undue cost to the member countries' economic growth. Multilaterally, the United States is a signatory to the United Nations Framework Convention on Climate Change (UNFCCC) and supports the Intergovernmental Panel on Climate Change (IPCC).

## X. Conclusions

The U.S. biobased industry is poised for substantial growth between now and 2025. The science and technology for producing biobased products have advanced to the point that a wide array of products can be produced from biobased feedstocks. Moreover, these products can compete on a performance basis with products made from petrochemical feedstocks.

Current prices for oil and natural gas have spurred new interest on the part of chemical and other product manufacturers in the use of biobased feedstocks to manufacture their products. In addition, in some cases, the manufacturing processes may be less costly and involve fewer steps than is the case for petrochemical feedstocks.

It is expected that the shift toward greater use of biobased products will be strongly linked to the development of biorefineries capable of producing both liquid fuels and streams of feedstocks for a wide range of biobased products. For example, the global chemical industry is projected to grow 3 - 6 percent per year through 2025, with the biobased chemicals share of that market rising from 2 percent currently to 22 percent or more by 2025.

Corn will continue to be the primary feedstock for the biorefinery platform for the next 10 to 20 years, with oilseed crops playing a growing role. However for biobased products and biofuels to continue to expand in the market place, a much broader range of feedstocks is needed. Economically viable cellulosic conversion will be crucial for the expansion of the industry to continue.

A number of scientific and processing hurdles must be cleared to achieve the forecast growth in biobased products' production and use. These include development of improved batch and continuous flow fermentation processes and improved biocatalysts. The economically feasible use of thermochemical conversion techniques awaits integration of biomass conversion into large-scale biorefineries. Economically viable cellulosic conversion of biomass will open up a large and diverse array of feedstocks ranging from crop residues to forest resources to dedicated grass production. Finally, more effective pretreatment processes for biomass are needed to support economically viable cellulosic conversion.

Public sector investments in research and product development have played an important role in developing biobased products, and will likely continue to do so.

Development of the biobased products industry can be expected to spur increased investment in processing and manufacturing facilities in rural America. This investment will both grow employment opportunities for rural residents and spur demand for farm products.

## Appendix 1: State Biofuel Programs

Economics, environmental goals, and energy independence have all pushed individual states to enact their own biofuel programs. In some regards, states have outpaced the Federal Government in the development of such programs.

Currently, five states (California, Ohio, Hawaii, Minnesota, and Montana) either have a Renewable Portfolio Standard (RPS) or have passed legislation to promote use of biofuels.<sup>27</sup> Many more states provide biomass incentives to stimulate demand or to help new biofuel producers get established. For instance, Oklahoma has a tax credit of 20 cents a gallon for biodiesel producers, with a maximum annual payment of \$5 million.

In addition, 21 states have an RPS - a requirement that a certain share of a utility's overall energy capacity or energy sales be derived from renewable resources, including biomass. For example, Iowa provides two separate production tax credits for electricity generated by eligible renewable energy facilities, including solar thermal electric, photovoltaics, landfill gas, wind, biomass, hydrogen, and anaerobic digestion.

All 50 states have at least one ethanol promotion program in place, and most have several (Table 56). Additional detail regarding state ethanol incentives is provided in Table 57.

The following are examples of the more significant state biofuel programs.

**Biodiesel Mandate - Minnesota.** In March 2002, Minnesota enacted the Nation's first biodiesel mandate that would require nearly all diesel fuel sold in the state to contain at least 2 percent biodiesel by 2005 (earlier if certain conditions are met). Proponents argued that the mandate will be a boon for the state's farmers and increase the state's use of alternative fuels.

**Biodiesel Use By School Districts - Missouri.** In 2001, Missouri passed a law encouraging school districts to purchase biodiesel fuel for their bus fleets. The law began with the 2002 - 03 school year and lasted through the 2005 - 06 school year. Any school district may contract with an eligible new-generation cooperative to purchase biodiesel fuel for its buses with a minimum of 20 percent biodiesel (B-20). The state then reimburses the school district so that the net price to the contracting district for biodiesel will not exceed the rack price of regular diesel.

**Ethanol and Biodiesel Incentives - Missouri.** In 2002, Missouri enacted two programs to promote in-state, cooperatively owned biofuel production. Targeted at increasing homegrown production of ethanol and biodiesel, the 5-year incentive

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<sup>27</sup> In addition, a number of states are currently considering State-level ethanol mandates, including Iowa, Illinois, Missouri, Nebraska, Washington, and Oregon.

programs provide grants to producers that are at least 51 percent owned by agricultural producers actively engaged in agricultural production for commercial purposes in the state. Ethanol incentives include a payment of 20 cents a gallon for the first 12.5 million gallons and 5 cents a gallon for the next 12.5 million gallons. Biodiesel incentives are 30 cents a gallon for up to 15 million gallons of production.

**Ethanol Production Incentives - North Dakota.** In April 2003, the Ethanol Production Incentive bill established the first program in the Nation to create a market based support system for the growing ethanol industry. The ethanol incentive is countercyclical and market based. A payment is provided to an ethanol facility when the price of ethanol drops or the price of corn increases to levels that make ethanol production less profitable. Incentives are based on a price of \$1.80 a bushel for corn and \$1.30 a gallon (rack price) for ethanol at the terminal.

**Ethanol Investment Tax Credits - Hawaii.** In early 2000, Hawaii passed legislation to provide tax credits for the production of ethanol in the state. The new law will help sugar growers on Kauai and Maui by offering incentives to use molasses and other wastes as the feedstock for ethanol. Supporters also hope the potential use of municipal solid waste as a feedstock will cut down on the amount of waste being sent to landfills. A requirement that at least 85 percent of all gasoline in the state contain 10 percent ethanol went into effect in April 2006.

**Ethanol Program - Minnesota.** To meet its goal of replacing 10 percent of its fuel needs with ethanol; in the late 1980s Minnesota instituted a producer payment program of 20 cents a gallon on up to 15 million gallons of ethanol a year for a maximum of 10 years. The payment is limited to instate producers, and the small scale requirement has resulted in the formation of more than a dozen farmer-owned ethanol processing cooperatives.

**Ethanol Program - Wisconsin.** Wisconsin's Act 55 gives ethanol producers a credit much like Minnesota's. Beginning July 1, 2000, it provided 20 cents a gallon for no more than 15 million gallons of production. The feedstock must come from a local source.

**Incentives for Schools to Use Biodiesel - West Virginia.** West Virginia provides a financial incentive for schools to fuel their bus fleets with alternative fuels. Under the state formula, counties receive about 85 cents for every dollar in transportation costs. The reimbursement increases to 95 cents if counties switch to alternative fuels like biodiesel blends or compressed natural gas.

Table 56: State Ethanol Programs

State	Producer Incentive Payments	Retailer Incentives for Ethanol Blends and E-85	State RFS	MTBE Ban Passed	Retail Pump Label Requirement	State Fleet Fuel Purchase Requirement	Winter Oxygenate Program
Alabama					X		
Alaska		X			X		
Arizona				X	X		
Arkansas					X		
California				X			
Colorado				X	X		
Connecticut				X	X		
Delaware					X		
District of Columbia							
Florida					X		
Georgia					X		
Hawaii		X	X				
Idaho		X			X		
Illinois		X		X	X		
Indiana	X			X		X	
Iowa		X		X	X	X	
Kansas	X			X		X	
Kentucky				X			
Louisiana							
Maine		X		X	X		
Maryland	X						
Massachusetts					X		
Michigan				X			
Minnesota	X	X	X	X			
Mississippi	X				X		
Missouri	X			X			

Table 56: State Ethanol Programs (Continued)

State	Producer Incentive Payments	Retailer Incentives for Ethanol Blends and E-85	State RFS	MTBE Ban Passed	Retail Pump Label Requirement	State Fleet Fuel Purchase Requirement	Winter Oxygenate Program
Montana	X		X	X	X		
Nebraska				X	X		
Nevada					X		X
New Hampshire				X	X		
New Jersey				X	X		X
New Mexico					X		X
New York				X	X		
North Carolina				X			
North Dakota	X	X			X		
Ohio				X			
Oklahoma	X	X					
Oregon					X		
Pennsylvania	X				X		
Rhode Island				X	X		
South Carolina					X		
South Dakota	X	X		X	X		
Tennessee					X		
Texas	X				X		
Utah					X		
Vermont				X	X		
Virginia					X		
Washington				X	X		
West Virginia					X		
Wisconsin	X			X	X		
Wyoming	X				X		

Source: Informa Economics et al., Biobased Multi-Client Study, March 2006.

Table 57: State Incentives for the Production and Use of Ethanol

State	State Excise Tax Exemption	State Producer Credits	Special Information
Alaska	\$.06 per gallon tax exemption	No producer credit	Tax exemption applies only in Anchorage and only during the winter months. No sunset.
Connecticut	\$.01 per gallon tax exemption	No producer credit	No sunset
Hawaii	4 percent tax exemption	No producer credit	No sunset. Administrative rules signed 9/20/04 require that beginning 4/06, 85 percent of all gasoline sold in the state contain 10 percent ethanol. Implements the ethanol requirement originally included in legislation signed in 1994.
Idaho	Tax exemption is to equal the amount of ethanol blended in a gallon of gasoline – not to exceed 10 percent. Average exemption is \$.023 per gallon.	No producer credit	No sunset
Illinois	2 percent sales tax exemption; average exemption is \$.01 to \$.015 per gallon. Extended in 2003 to include E-85 and biodiesel.	No producer credit	A \$15-million grant fund, the Renewable Fuels Development Program, was created in 2003 to support the construction of new ethanol/biodiesel plants and expansions; to qualify, a project must increase capacity by at least 30 mgy; sunsets in 2013.
Indiana	No tax exemption	12.5 cent per gallon producer credit	Credit applies to facilities that increase production by at least 40 mgy. Total per facility not to exceed \$5 million for all taxable years. Total program not to exceed \$10 million.
Iowa	\$.01 tax exemption	No producer credit	Sunset 2007. Income tax credit available to retailers who sell more than 60 percent ethanol-blended fuel at their station, including E85. State fleet vehicles shall operate on 10 percent ethanol blends when commercially available.
Kansas	No tax exemption	Average 7 cent per gallon producer credit	Provides \$.05 per gallon for producer in operation prior to July 1, 2001, during FY 2002-2004. Increased capacity of 5 mgy or more on or after July 1, 2001, receives \$.075 per gallon, limited to 15 mgy. Producers who begin production on or after July 1, 2001, are eligible for \$.075 per gallon, limited to 15 mgy. State's bulk fuel purchases for use in state motor fleet shall contain 10% ethanol, unless the premium for ethanol-blended fuel is more than \$.10 per gallon; same requirement for individual fuel purchases for fleet vehicles.

**Table 57: State Incentives for the Production and Use of Ethanol (continued)**

State	State Excise Tax Exemption	State Producer Credits	Special Information
Maine	Renewable fuels, including ethanol and biodiesel produced in the state are exempt from state's motor fuel excise tax.		
Maryland	No tax exemption	\$.20 per gallon producer credit for ethanol produced from small grains (winter grain); \$.05 per gallon producer credit for ethanol from other agricultural products.	Maximum total payment of \$3 million/year for all ethanol produced. To reach maximum, would need at least 15 mgy of ethanol from small grains in a facility that began operating or expanded after 12/31/04. Sunsets 12/31/2017.
Minnesota	No tax exemption on 10% blend; 5.8 cent tax exemption on E-85	\$.20 per gallon producer credit; subject to reduction pending on state budget	Producer credit applies to the first 15 million mgy, with a \$3 million annual cap per plant. Statewide requirement to blend 10% ethanol in conventional gasoline; legislation enacted in 2005 to increase blend requirement to 20% beginning in 2013 if waiver is received from EPA.
Mississippi	No tax exemption	\$.20 per gallon producer credit	Maximum payment of \$6 million per producer of anhydrous ethanol and \$37 million total per fiscal year. Provides formula for credit for "wet" alcohol. Sunset is June 30, 2015.
Missouri	No tax exemption	\$.20 per gallon applies to the first 12.5 million gallons. \$.05 per gallon to the next 12.5 million gallons produced.	Producer credit applies to the first 60 months of plant production
Montana	No tax exemption	\$2 million per plant per year producer incentive	To receive producer incentive, plant must use Montana-produced grains: 20 percent in first year of production, 25 percent in 2nd year, 35 percent in 3rd year, and increasing by 10 percent per year until plant uses 65 percent Montana grains. Provides for 10% ethanol mandate within 15 months of the state producing 40 mgy. Exempts 91 octane.
Nebraska	No tax exemption	No producer credit	\$.18 per gallon producer incentive program expired in June 2004.



**Table 57: State Incentives for the Production and Use of Ethanol (continued)**

State	State Excise Tax Exemption	State Producer Credits	Special Information
North Dakota	No tax exemption	\$.40 per gallon producer credit	2005 legislation establishes producer payments for 2005-07 biennium (and not beyond) for plants that were in operation by 7/1/95 (less than 15 mgy = \$900,000 and greater than 15 mgy = \$400,000). Also provides incentives for increased production by the littlest of 10 mgy or 50 percent. Exempts E-85 from all but \$.01 per gallon of state's fuel tax, up to 1.2 million gallons.
Oklahoma	No tax exemption	\$.20 per gallon producer credit	For production in place between 12/31/03-12/31/06, maximum of \$25 million per facility per year, with total maximum per facility of \$125 mil. Credit of \$.075 for new production after 1/1/11, for up to 10 mgy per facility for 3 years.
Pennsylvania	No tax exemption	\$.05 per gallon producer credit	Up to 12.5 million gallons of renewable fuel per year produced by a qualified renewable fuels producer. Money provided from Alternative Fuel Incentive Fund.
South Dakota	\$.02 tax exemption	\$.20 per gallon producer credit	416,667 gallons per month maximum allowable to ensure equal distribution among all producers.
Texas		\$.20 per gallon producer credit for ethanol and biodiesel	Credit applies to first 18 mgy of production per plant for 10 years. Imposes a fee on ethanol and biodiesel producers of \$.032 for each gallon produced up to 18 million gallons per facility.
Wisconsin	No tax exemption	\$.20 per gallon producer credit	\$3 million per year, per plant (limited to first 15 mgy)
Wyoming	No tax exemption	40cent per gallon producer credit	Program has a \$4 million per year cap. Plants constructed after 7/1/03 eligible for 15 years. Plants in existence prior to 7/1/03 eligible until 6/30/09, unless they expand by at least 25 percent, in which case they are eligible for 15 years following the date of expansion.

Source: Informa Economics et al., Biobased Multi-Client Study, March 2006.

## **Appendix 2: Biofuel Policies and Use in Other Countries**

Many countries besides the United States, both developed and developing, have established policies to promote the production and use of biofuels. Brazil adopted an ambitious biofuels program in the 1980s. Many other countries have launched their policies more recently, focused especially on controlling greenhouse gas emissions and diversifying fuel supplies.

### **A. Canada**

Canada produced an estimated 66 million gallons of biofuels in 2004 and has pledged to raise the renewable fuels incorporation target to 5 percent (from the current 3.5 percent). If implemented, this would raise Canada's production of renewable fuels to 370 million gallons by 2007 and 820 million gallons by 2010.

In 2003, the Canadian Government announced the Ethanol Expansion Program. The program is intended to expand fuel ethanol production and use in Canada and reduce transportation-related greenhouse gas emissions. Under the first round, C\$72 million has been allocated to six projects across Canada. This second round invests an additional C\$46 million.

The Ethanol Expansion Program builds on the Future Fuels Initiative, which was announced under the Action Plan 2000 on Climate Change. That initiative provides up to C\$140 million in contingent loan guarantees to encourage investment in new ethanol production facilities, fund analytical research, and sponsor public awareness activities.

Funding under the Ethanol Expansion Program is part of a larger biofuels strategy that also includes the extension of the National Biomass Ethanol Program, research and development under the biotechnology component of the Technology and Innovation Strategy, and investment in biodiesel.

Provincial governments have also introduced biofuel programs. For example, in 2005, Ontario approved a 5 percent ethanol mandate for all gasoline fuel by 2007, despite strong objections from the major oil companies in Canada. Ontario believes this commitment would more than triple the market for renewable fuels in Ontario, to 793 million liters by 2007. The main constraint to Ontario's plan is the concern that much of this demand would initially be met with imports from the United States and Brazil, rather than from domestic production.

### **B. The European Union**

The European Union (EU) has implemented a number of policies to expand use of biobased fuels, including a nonbinding target for a 5.75 percent biofuel share of total gasoline and diesel consumption by 2010 - targets it is considering making mandatory. Total EU gasoline and diesel consumption for transportation purposes

in 2010 is projected to be 389 million tons, so a 5.75 percent target would amount to 22.4 million tons, about 7.5 billion gallons of biofuel, or 6.7 billion gallons of biodiesel.

Eighty percent of biofuel production in the EU is biodiesel. The EU produced 574 million gallons of biodiesel in 2004, a 27 percent increase from 2003. Ethanol production was about 130 million gallons in 2005.

In 2003 the European Commission (EC) adopted the Promotional Directive and the Directive on the Taxation of Energy Products. These followed the 2000 Green Paper, *Towards a European strategy for energy supply*, which highlighted the EU's dependence on external energy sources, compounded by its eastern expansion. Import dependence was expected to reach 70 percent in 2030, versus 50 percent in 2000. The EC also has emphasized the need to comply with emissions reduction commitments in the Kyoto Protocol. Although not explicitly mentioned in the Green Paper, the EU's biofuels policy also aims at creating a stimulus for the rural economy.

Under the Promotional Directive, which entered into force in May 2003, member states shall achieve a 2 percent share of renewable fuels (pure biofuels, blended fuel, or ETBE<sup>28</sup>) by the end of 2005 and a 5.75 percent share by end 2010. These are indicative rather than mandatory targets based on the energy content of all petrol and diesel for transport purposes placed on the market.

The Directive on the Taxation of Energy Products, in force since October 2003, allows member states to exempt from taxation, in full or in part, products that contain renewable substances such as biodiesel. Some states, including Spain, France, and Sweden, already had such a tax exemption.

The EU also supports research projects on biofuels. For example, a 4-year project to develop cost-effective and environmentally friendly methods to produce ethanol as motor fuel is being funded with 12.8 million Euros and conducted by 21 universities, research institutes, and companies.

The latest reform of the EU Common Agricultural Policy in June 2003 maintained a provision to allow the production of energy crops (except for sugarbeets) on set-aside land added a new form of financial support to farmers growing energy crops as feedstocks for biofuel production. A carbon credit payment of €45/hectare was introduced for land grown with energy crops (excluding sugarbeets) that are processed to fuel or gas, on condition that the farmer contracts with a processor. Payments are subject to an upper EU-wide area limit of 1.5 million hectares. The exclusion of sugarbeets from the carbon credit and set-aside payment will most likely change once the sugar market organization has been reformed.

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<sup>28</sup> Ethyl Tertiary Butyl Ether, an oxygenated additive for petrol.

The combination of high oil prices and the ratification of the Kyoto Protocol in 2005 provided the incentive necessary for the EU to push for more biofuels production. In early 2006, the EU adopted a formal biofuels strategy, based on its need to substitute biofuels for oil imports and to comply with the Kyoto Protocol.

Late in 2005, the EU developed a Biomass Action Plan and an overall Strategy for Biofuels, both very new policy commitments. It heralded the use of biomass as a key part of the EU's future energy strategy and indicated that any use of agriculture to increase renewable energy would be done in a sustainable manner.

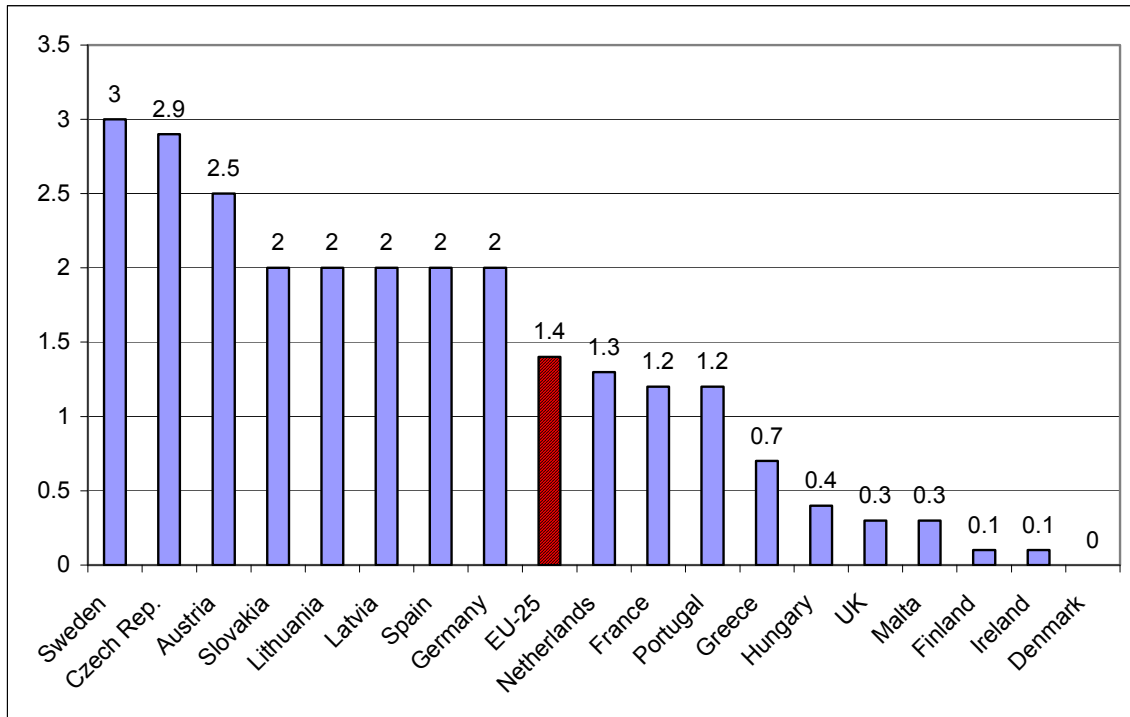
The plan set out 20 actions to increase the use of energy from forestry, agriculture, and waste materials. The Commission's aim is to double the share of renewable energy sources in the EU in the next 5 years, from 6 percent in 2005 to 12 percent by 2010. The EU implemented its *Strategy for Biofuels* in February 2006. It includes a range of market based, legislative, and research measures to boost production of fuels from agricultural raw materials. The strategy has three main aims: (1) to promote biofuels in both the EU and developing countries; (2) to prepare for large-scale use of biofuels by improving their cost-competitiveness and increasing research into second generation fuels; and (3) to support developing countries where biofuel production could stimulate sustainable economic growth. Stated benefits to the EU include reduced dependence on fossil fuel imports, lower greenhouse gas emissions, new outlets for farmers, and expansion of economic opportunities in several developing countries.

One key action is the promotion of biofuels to fulfill the Commission's goal that all diesel and petrol gasoline contain 2 percent biofuel by the end of 2005, rising to 5.75 percent by 2010. Based on reports by member states submitted to the European Commission in November 2005, the EU had only reached a 1.4 percent share of renewable fuels by the end of 2005. Biofuel targets for each member state are based on plans developed by the national governments Figure 67. Targets are not mandatory; so the 2005 share of biofuels may be lower than 1.4 percent.

Some market experts are skeptical that the EU has the feedstocks necessary to meet its biofuel targets. Nevertheless, biofuel production has increased significantly over the last 10 years especially for biodiesel - a market that is continuing to grow while the gasoline market contracts. Annual biodiesel output is now close to 2 million tons a year, while production capacity in 2004 was about 2.4 million tons. Germany, France, and Italy are the main producers of biodiesel, while Spain and France are the largest ethanol producers.

In addition, air quality standards in European legislation include volatility (evaporation) criteria that bioethanol based mixes (up to 5 percent) cannot meet. This suggests that its greenhouse gas emission goals will require either changes in European standards that increase acceptable fuel volatility levels, or use of ethanol mixes that do meet standards for evaporation.

**Figure 67: EU Biofuel Market Share Targets, 2005**



Source: Informa Economics et al., Biobased Multi-Client Study, March 2006.

### C. Brazil

By far the largest producer of biofuels, Brazil used abundant and cheap sugarcane feedstock to produce 3.9 billion gallons of ethanol in 2004, exporting 613 million gallons. While the ethanol industry in Brazil was started with significant government intervention, direct subsidies for ethanol production were removed in the 1990s. Brazilian environmental policies require gasoline to contain specific amounts of alcohol, with the amount established each year. Currently, ethanol production and exports are almost entirely market driven.

After the oil shocks of the 1970s, Brazil implemented an aggressive strategy to encourage the use of ethanol in domestic transportation fuels (PROALCOOL), mainly by funding investments in ethanol distilleries, regulating the price of ethanol relative to gasoline, and increasing the capacity of the vehicle fleet to consume ethanol by subsidizing production of “flexifuel” cars. In the late 1980s, sugar prices rose and oil prices fell, making the PROALCOOL program prohibitively expensive. In 1998 the price of ethanol was liberalized and all subsidies associated with the program were gradually eliminated.

Brazil has several advantages in ethanol production: existing infrastructure, accumulated knowledge (from the PROALCOOL program), low-cost feedstock, and

high production efficiency. Brazil's ethanol exports grew nearly 300 percent from 2003 to 2005, mostly from increased exports to Japan and the EU.

## **D. Asia**

Developing countries frequently lack the resources to provide subsidies and other tax incentives to produce biofuels. Consequently, the biobased product strategy in many of the larger biofuel producing countries like China, India, and Malaysia are often small.

Asian biofuels became more active in 2005, although feedstock shortages remain a key issue. In India, the fuel ethanol program is starting to take off, buoyed by a bumper sugarcane crop, initially in the southern state of Tamil Nadu. India's 2005/06 sugar production could reach 18.0 million tons, up 47 percent from last season owing to good rainfall in sugar producing states. China has now mandated the use of ethanol-supplemented petrol in several provinces and the program is being rolled out further as concerns about urban pollution, oil demand, and fuel shortages escalate. China also plans to build four biodiesel plants, using Malaysian palm oil as feedstock.

None of the developed countries in Asia (Japan, South Korea, Taiwan) has a full-blown biofuels strategy. Nor do they have surplus production of subsidized feedstocks, so biofuel policies are more dependent on cost competitiveness. Japan is conducting some tests using a 3 percent ethanol mix (E-3), but it looks as though it will be some time before biofuels demand takes hold in that potential key market. Taiwan is already conducting tests with a 20 percent biodiesel mix (B-20), while South Korea started some biodiesel trials in January 2006. In September 2005, the Australian Government set a target of 92.4 million gallons of biofuel use by 2010.

### **1. China**

The world's second-largest oil consumer, China, launched its fuel ethanol program in 2000 in order to address the rapidly growing demand for transportation fuels, tackle surplus grain stocks, reduce air pollution in big cities, and support the rural economy. It began blending gasoline with ethanol for use in automobiles in 2001 and invested more than \$620 million that year to set up four ethanol plants with the capacity to process 3 million tons of corn (for 1 million tons of ethanol). China has set a target of producing 15 percent of its energy from renewable sources by 2020, up from around 7 percent currently.

Fuel ethanol is exempt from consumption tax (5 percent) and value-added tax (17 percent). Biofuel producers have priority in obtaining feedstock released from the state grain reserves at competitive prices. Currently, five provinces blend 10 percent ethanol into all their petrol (Jilin, Heilongjiang, Liaoning, Henan, and Anhui); and four provinces sell an E-10 blend in part of their territory (Shandong, Jiangsu, Hebei, and

Hubei). E-10 consumption was over 10 million tons, or a quarter of total petrol consumption, by the end of 2005.

The biodiesel program is not as developed as bioethanol. A few small plants (capacity of 0.5 - 6.6 million gallons/year) operate, using mainly waste cooking oil but also oilseeds as feedstock. China, which is already Malaysia's top palm oil buyer plans to build four biodiesel plants with combined production capacity of 400,000 tons/year, likely using palm oil as feedstock due its price advantage over soybean oil.

Under China's Renewable Energy Plan, the Government set a target of 11 million tons of biofuel (bioethanol and biodiesel) production by 2020. Total transport fuel (petrol and diesel) consumption is expected to reach 228 million tons in 2020. Fuel ethanol demand will continue to expand in China as more provinces introduce the compulsory use of ethanol-blended petrol.

## 2. India

The second largest producer of ethanol in Asia, India also is one of the world's largest sugar producers. Installed ethanol production capacity amounts to approximately 700 million gallons, but utilization rates are low (ethanol production in 2004 was 450 million gallons). In 2004, only 26 million gallons of ethanol were used for blending with gasoline. Assuming that the ethanol program is implemented as envisaged by the Government, the projected demand for fuel ethanol will be 396 million gallons in 2010 if E-10 is sold, as is now planned.

A fuel ethanol program was introduced in India in 2003. Measures currently in place include an excise tax reduction for E-5, the obligation to blend all petrol with 5 percent ethanol in certain regions (since January 2003) and government regulation of the ethanol selling price on the basis of ethanol production costs. Currently, 5 percent ethanol blends are used<sup>29</sup> in 10 sugar producing states and 3 contiguous Union Territories.<sup>30</sup> In addition, several Indian states have also attempted to support local ethanol production through the use of additional fiscal measures.

However, the Indian fuel ethanol program suffered a recent crisis. Following a drought, 2003/04 and 2004/05 sugar crop output was unusually low, which resulted in sharply increased feedstock prices for ethanol production. As a result, producers in India's southern states concentrated on production of industrial and potable alcohol. The ethanol blending obligation was temporarily suspended in the autumn 2004. In the meantime, India has become increasingly dependent on molasses and ethanol imports to meet its ethanol requirements. It is likely that the molasses supply will increase substantially over the coming years with the recovery of cane production.

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<sup>29</sup> Under normal conditions, the blending of 5 percent ethanol is mandatory, however, the blending obligation was suspended in late 2004.

<sup>30</sup> Andhra Pradesh, Damman and Diu, Goa, Dadra and Nagar Haveli, Gujrat, Chandigarh, Haryana, Pondicherry, Karnataka, Maharashtra, Punjab, Tamilnadu, Uttar Pradesh.

The Government is currently developing a biodiesel support program. According to Petroleum Ministry officials, biodiesel is likely to be fully exempt from excise duty in 2006. Under the Government's new biodiesel (vegetable oil) purchasing policy, public sector oil firms will purchase straight vegetable oil - extracted from plants such as jatropha and pongamia - for mixing in diesel at INR25 (55 cents) a liter beginning January 2006. At first, 5 percent vegetable oil will be mixed with diesel during trial runs, increasing to 20 percent in phases. In 2003, India's Planning Commission drafted plans to encourage the widespread planting of *Jatropha curcas* trees and use the oil produced for blending with conventional diesel, with a target of 13 million tons of vegetable oil for fuel use per year. In Bangalore, there are plans to transform a plant producing straight vegetable oil (from karanja and jatropha) into a biodiesel refinery.

The Government plans to achieve a countrywide ethanol-petrol blending rate of 5 percent in the near future, which would require 132 million gallons of ethanol. Later on, it plans to increase the ethanol content in petrol to 10 percent and to blend conventional diesel with 5 percent ethanol. The Planning Commission proposes increasing the proportion of biofuels used from 5 percent to 20 percent by 2012.

### **3. Japan**

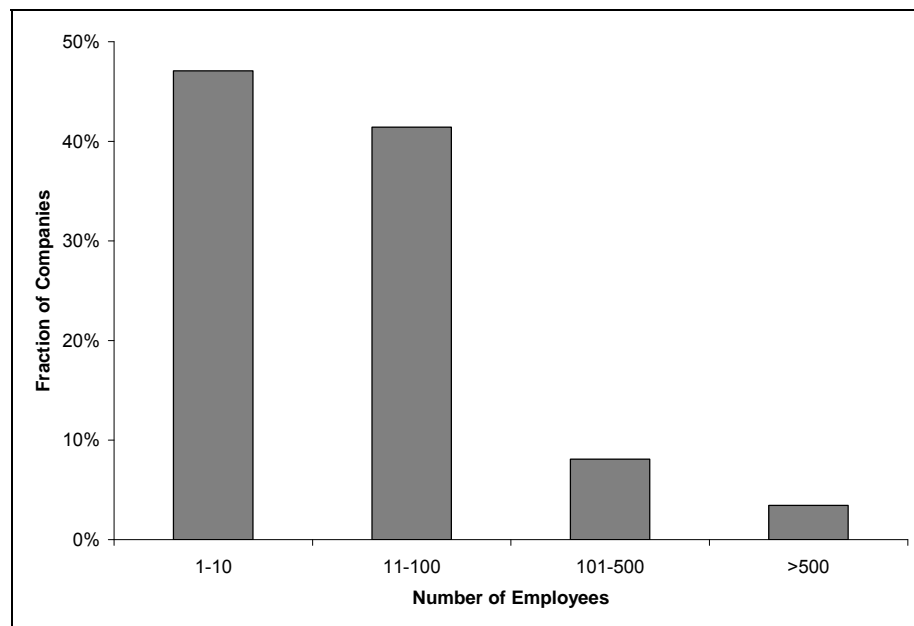
Under pressure to meet its Kyoto targets, Japan has proposed a target of 500 megaliters (132 million gallons) of biomass-derived fuels by 2010. This would equate to about 1 percent of projected fuel use. To encourage the uptake of ethanol, the Government proposed an E3 standard in 2004 as a prelude to a national E10 blend standard by 2010. An E3 standard would imply a market of about 470 million gallons. Currently legislators are discussing whether to increase the cap to 10 percent. In mid-2005, Reuters reported that Japan was considering a 7 percent ETBE standard rather than E3 after strong industry opposition to costs and concerns about environmental impacts (Informa Economics et. al., *Biobased Multi-Client Study*, March 2006). Industry claims that ethanol would require blending at the service station while ETBE would reportedly be made using idle facilities previously being used to make MTBE. The ETBE would be blended with gasoline at the refinery. The Brazilian company Petrobras has started a joint venture to produce ethanol for the Japanese market.



## Appendix 3: Iowa State University Preliminary Review of U.S. Biobased Products Companies

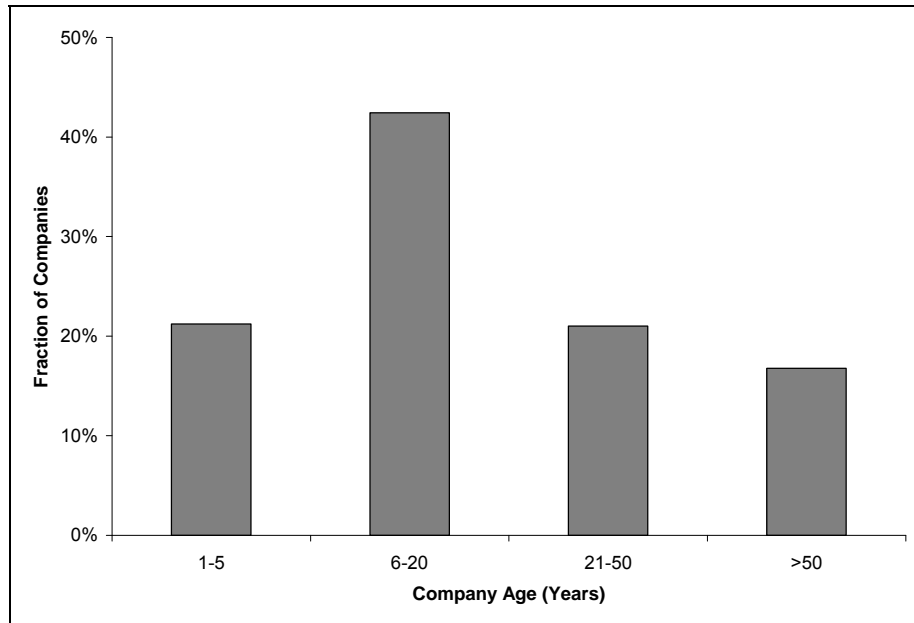
The Center for Industrial Research and Service of Iowa State University has been involved with USDA's Office of Energy Policy and New Uses in the development of a database of companies that are part of the BioPreferred™ Program, USDA's preferred procurement program for biobased products. The database has not been completed; however, a significant number of observations and statistics have been collected concerning the companies. Some of the preliminary findings are presented in the following four figures.

**Figure 68: Distribution of Biobased Companies by Size**



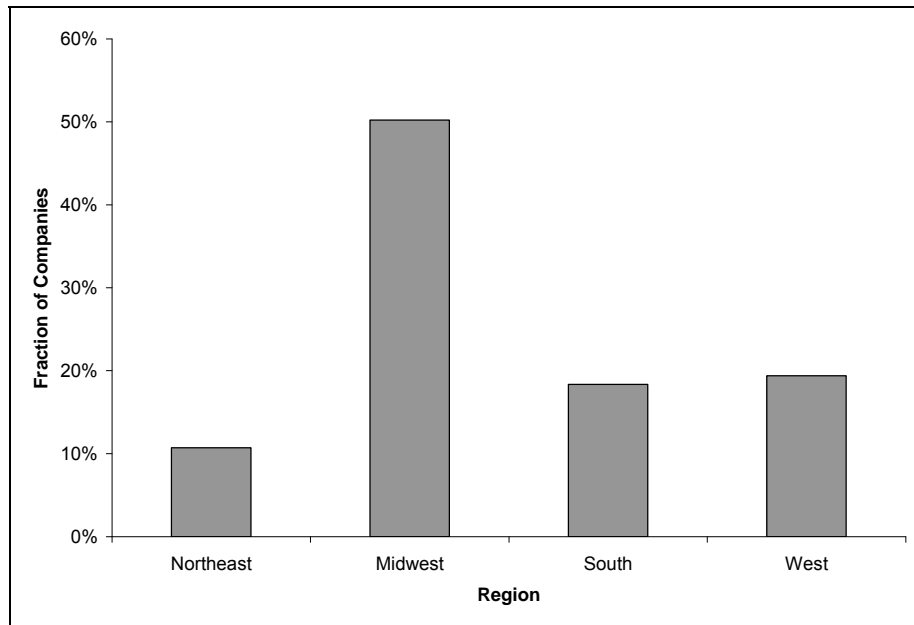
Source: Center for Industrial Research and Service, Iowa State University.

**Figure 69: Distribution of Biobased Products Companies by Company Age**



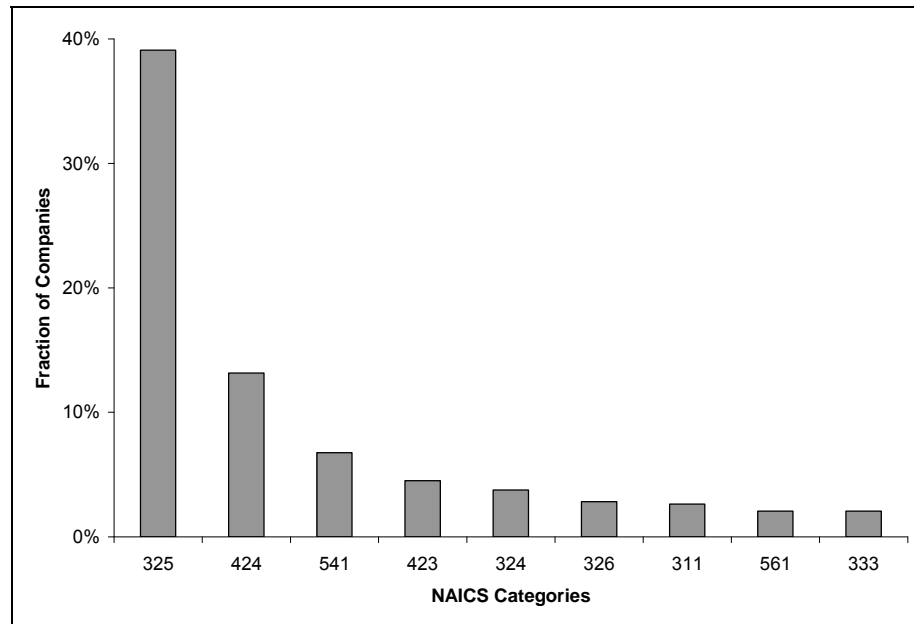
Source: Center for Industrial Research and Service, Iowa State University.

**Figure 70: Distribution of Biobased Products Companies by Location**



Source: Center for Industrial Research and Service, Iowa State University.

**Figure 71: Distribution of Biobased Companies by NAICS Classification\***



- \* North American Industrial Classification System Categories
- 325 Chemical Manufacturing
- 424 Merchant Wholesalers, Nondurable Goods
- 541 Professional, Scientific, and Technical Services
- 423 Merchant Wholesalers, Durable Goods
- 324 Petroleum and Coal Products Manufacturing
- 326 Plastics and Rubber Products Manufacturing
- 311 Food Manufacturing
- 561 Administrative and Support Services
- 333 Machinery Manufacturing

Source: Center for Industrial Research and Service, Iowa State University.

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## Glossary

AACC	American Association of Cereal Chemists	CGF	Corn Gluten Feed
ABE	Acetone, butanol and ethanol	CH <sub>4</sub>	Methane
ADM	Archer Daniels Midland	CH <sub>2</sub> O	Formaldehyde
AFEX	Ammonia Fiber Explosion	CHP	Combined Heat and Power
AMD	Advanced Micro Devices, Inc.	CIF	Commodity, Insurance and Freight
AMFE	Ammonia Fiber Explosion	CIRAS	Center for Industrial Research and Service
AMG	Agro Management Group	CNQ	Canadian Natural Resources
AMT	Alternative Minimum Tax	CNS	Central Nervous System
AN	Acrylonitrile	CO <sub>2</sub>	Carbon dioxide
ARP	Ammonia Recycle Percolation	COPE	Copolyester Ethers
ASTM	American Society for Testing and Materials	CRI	Carpet Recovery Institute
ATP	Adenosinetriphosphate	CRP	Conservation Reserve Program
B-2	Two percent biodiesel	CSP	Conservation Security Program
B-20	Twenty percent biodiesel	DALA	Delta-aminolevulinic Acid
B <sub>100</sub>	Full biodiesel	DDG	Dried Distillers Grains
BA	Butyric Acid	DDGS	Dried Distillers Grains with Solubles
BDO	4-butanediol	DDS	Dried Distillers Solubles
BPH	Benign Prostatic Hyperplasia	E <sub>85</sub>	Blend of 85 percent Ethanol and 15 percent gasoline
BPX	Broin Project X	EBI	Environmental Benefits Index
BR	Polybutadiene	EC	European Commission
BT	Butanetriol	ECA	Encana
BTL	Biomass-to-liquids	EERE	Energy Efficiency and Renewable Energy Program
BTTN	Butanetriol trinitrate	EG	Ethylene Glycol
Btu	British thermal units	EIA	U.S. Energy Information Administration
CAA90	Clean Air Act	EPA	Environmental Protection Agency
CAFI	Biomass Refining Consortium for Applied Fundamentals and Innovation	EPACT	The Energy Policy Act
CAGR	Compound Annual Growth Rate	EQIP	Environmental Quality Incentives Program
CBOT	Chicago Board of Trade	ERMCO	Electric Research and Manufacturing Cooperative
CCA	Copper Chrome Arsenate	ETBE	Ethyl Tertiary Butyl Ether
CCC	Commodity Credit Corporation	EtOH	Production of Ethanol
CCSP	Climate Change Science Program	ETP	Engineered Timber Products
CCTP	The Climate Change Technology Program	EU	European Union
C/D	Construction/Demolition	FDCA	Furan Dicarboxylic Acid
CDS	Condensed Distillers Solubles		

FFA	Free Fatty Acids	NASS	National Agricultural Statistics Service
FOSHU	Foods for Specified Health Uses	NEB	National Energy Board of Canada
FSA	Farm Service Agency	NMP	N-methyl pyrrolidone
FTE	Full-Time-Equivalent Worker	NO <sub>x</sub>	Nitrogen Oxides
GATT	General Agreement on Tariffs and Trade	NRCS	The Natural Resources Conservation Service
GBL	Gamma-butyrolactone	NREL	National Renewable Energy Laboratory
GDP	Gross Domestic Product	NSW	New South Wales
GHE	Greenhouse Gas Emissions	NXY	Nexen
GHG	Greenhouse Gas	Nylon 6	Polyamide-6
GTL	Gas-to-liquids	OEPNU	Office of Energy Policy and New Uses
HBL	Hydroxybutyrolactone	OFEE	Office of the Federal Environmental Executive
HDPE	High-Density Polyethylene	OPEC	Organization of Petroleum Exporting Countries
HTF	Highway Trust Fund	OSB	Oriented Strand Board
hl	hectoliter	OXY Program	The Oxygenated Fuels Program
IDN	Injectable Disc Nucleus	P	Phosphorus
IFT	The Fertilizer Institute	PBS	Polybutylene Succinate
IPCC	Intergovernmental Panel on Climate Change	PBSA	Polybutylene Succinate Adipate
IPCI	International Polyol Chemicals Inc.	PBT	Polybutylene Terephthalate
K	Potassium	PDO	Propanediols
KOH	Potassium Hydroxide	PEP	Phosphoenol Pyruvate
LA	Lactic Acid	PET	Polyethylene Terephthalate
LDPE	Low-density Polyethylene	PG	Propylene Glycol
LOSP	Light Organic Solvent Preservative	PHA	Polyhydroxyalkanoate
LVL	Laminated Veneer Lumber	PLA	Poly-lactic Acid
MA	Maleic Anhydride	PMTG	Polytetramethylene Glycol
MBI	Michigan Biotechnology Institute	PPTI	Protein Polymer Technology
MDI	Methylene Diisocyanate	PTMG	Polytetramethylene Glycol
MGY	Million Gallons/Year	PTT	Trimethylene Terephthalate
MIU	Moisture, Insolubles and Unsaponifiables	PUR	Polyurethane
MMA	Methyl Methacrylate	Pyr	Pyruvic Acid
MTBE	Methyl Tertiary Butyl Ether	RFG	Reformulated Gasoline Program
MSG	Monosodium Glutamate	RFS	Renewable Fuels Standard
MSW	Municipal Solid Waste	RFTO	Renewable Transport Fuels Obligation
MTHF	Methyltetrahydrofuran	RLI	Renewable Lubricants, Inc.
MW <sub>h</sub>	Megawatt-hours	RPS	Renewable Portfolio Standard
MW <sub>th</sub>	Megawatts Thermal	SBM	Soybean Meal
N	Nitrogen	SBO	Soybean Oil
NAICS	North American Industrial Classification System	SBR	Styrene-butadiene

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	Copolymers
SS	Suspended Solids
SSA	Succinic Acid
SU	Suncor Energy
TATB	1,3,5-trinitro-2,4,6-triaminobenzene
THFT	Tetrahydrofuran
TITER	Fat or Oil Solidification Point Degrees C (rough measure of the oil or fat saturation level)
TNF	Tumor Necrosis Factor
TNT	Trinitrotoluene
TPU	Thermoplastic Polyurethanes
TVA	Tennessee Valley Authority
ULSD	Ultra-Low-Sulfur Diesel
UNFCCC	United Nations Framework Convention on Climate Change
USDOE	U.S. Department of Energy
USDA	U.S. Department of Agriculture
USSC	Urethane Soy Systems Company
VEETC	Volumetric Ethanol Excise Tax Credit
VOCs	Volatile Organic Compounds
WCGF	Wet Corn Gluten Feed
WDGS	Wet Distillers Grains with Solubles
WTI	West Texas Intermediate