

Strategic Biorefinery Analysis: Review of Existing Biorefinery Examples

January 24, 2002 – July 1, 2002

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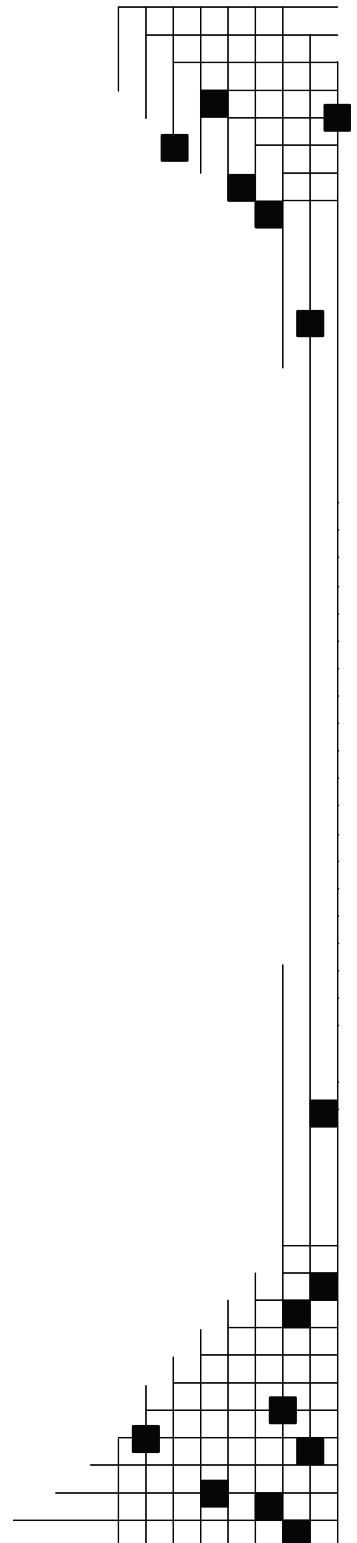
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EXECUTIVE SUMMARY

Throughout history, there have been many examples of processes designed to convert a given raw material into numerous “refined” products while making efficient use of the resource. Two modern refinery examples include petroleum refining and corn wet milling. Both of these industries produce fuel as a primary product and, in both cases, the cost of feedstock represents a majority (60 to 70 percent) of the total product value. Because of this, they represent useful examples for the development of the biorefinery, a highly anticipated application of the refinery concept consisting of a processing facility that produces multiple products from cellulosic biomass feedstocks. This report—the first in a two-part strategic analysis of biorefineries—presents a review of petroleum refining and corn wet milling. In the review, we provide an overview of these industries, including a description of processes and product slate selection, a synopsis of past economic performance, and a calculation of processing margin for each industry.

Several key features of the refinery approach as employed by these industries were identified:

- product slates of refineries typically become increasingly diversified over time;
- product slate selection depends on many factors such as market demand, feedstock composition, and available processing equipment and capacity;
- operating flexibility enables refineries to shift outputs over time;
- process improvement invariably makes the cost of raw material the dominant factor in overall refinery economics.

Low profitability has stalled petroleum refinery expansion during the past 25 years, largely because capital intensity has increased while refining margins have declined. Government regulations—especially environmental mandates—have been a major source of capital expenditures. The corn wet milling industry has fared better during this period—especially during the 1970s and 1980s—but, during the last decade, has also experienced low returns.

There are several implications, in light of this review, for the biorefining industry: Mature biorefineries will likely produce diverse product slates and, like petroleum refineries, will be designed to accommodate a variety of feedstocks. Product slate selection will represent a complex optimization problem involving many variables such as market demand, feedstock price and availability, and available processing equipment. Biorefining companies, to survive in an extremely competitive and rapidly changing marketplace such as exists today—especially for commodity fuels where relative processing margins are razor thin—must be efficiently managed.

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Introduction

Throughout history, there have been many examples of processes designed to convert a given raw material into numerous “refined” products while making efficient use of the resource. The ancient Chinese, for instance, not only domesticated the soybean over 5,000 years ago, they also developed soy processing—extracting protein to make bean curd, fermenting carbohydrate into wine and miso, pressing oil, and using residual material as fertilizer for crops (1, 2). Native Americans of the plains had hundreds of uses for bison, finding function for every part of the animal: meat and hide fed and clothed the tribes; bones were made into tools, horns into utensils, and hair into rope. They even powdered their infants with finely ground buffalo chip and silt (3, 4).

Two modern refinery examples include petroleum refining and corn wet milling. Both of these industries produce fuel as a primary product and, in both cases, the cost of feedstock represents a majority (60 to 70 percent) of the total product value (more detailed data on the processing margin for these industries is presented below). Because of this, they represent useful examples for the development of the biorefinery, a highly anticipated application of the refinery concept consisting of a processing facility that produces multiple products from cellulosic biomass feedstocks.

This report—the first in a two-part strategic analysis of biorefineries—presents a review of petroleum refining and corn wet milling. (We submit that paper making is not a relevant example in this context: material rather than fuel is the primary product, and feedstock cost represents a small percentage—less than 10 percent—of the total product value. Therefore, we have chosen not to review this industry.) In the review, we provide an overview of these industries, including a description of processes and product slate selection, a synopsis of past economic performance, and a calculation of processing margin for each industry.

Examples of Existing Refineries

Table 1 summarizes important features for two existing industries that employ a multiproduct refinery approach: petroleum refining and corn wet milling. A synopsis of our review follows. A more complete account is provided in Appendix A.

Table 1. Important features of petroleum refining and corn wet milling.

- **Diversification** over time is a key characteristic of refineries: operations shift from those designed to produce single products—e.g. kerosene and starch—to those seeking optimum use and maximum value from each fraction of the feedstock.
- **Product slate selection** is a function of: 1) market demand; 2) feedstock availability, composition, and price; 3) available processing equipment and capacity; 4) operating costs; 5) competitive positioning; and 6) government regulations. Linear programming algorithms and other sophisticated analytical techniques are used to help optimize refinery product slates.
- **Operating flexibility** enables refineries to shift outputs over time—on a daily basis for certain petroleum refineries.
- **Process improvement** invariably makes the cost of raw material the dominant factor in overall refinery economics.
- **Low profitability** has stalled petroleum refinery expansion during the past 25 years, largely because capital intensity has increased while refining margins have declined. Government regulations—especially environmental mandates—have been a major source of capital expenditures. The corn wet milling industry has fared better during this period—especially during the 1970s and 1980s—but, during the last decade, has also experienced low returns.

Product Diversity

Petroleum refining and corn wet milling were both born in the middle of the 19th century: the first wet mill opened in 1844 (5); the first petroleum refinery in 1861 (6). Both began by producing single products—kerosene and starch. Each has since evolved continuously, creating increasingly diverse product portfolios in response to an ever-changing marketplace. Tables 2 and 3 present timelines for key historical developments in each industry. Figures 1a, 1b, 2a, and 2b illustrate the wide array of products offered by each industry today. It's worth noting that the annual percentage yields of refined petroleum products in the U.S. have been relatively constant over the past 40 years, changing little from the yields presented in Figure 1a for 2000 (7). Annual percentage yields of corn wet milling products have been more variable over time—from 1992 to 2001, for example ethanol yield increased from 0.067 to 0.078 lb/lb feed, or 16 percent (calculated using yields from 5). It should also be noted that biologically derived products other than ethanol—organic acids, amino acids, and sugar alcohols, for example—though not shown in Figure 2a, represent an increasingly important category of products in the corn wet milling industry (8).

Table 2. Historical timeline for U.S. petroleum refining industry (6).

1861 □	First petroleum refinery opens, producing kerosene—a better and cheaper source of light than whale oil—by atmospheric distillation. Naptha and tar produced as by-products.
1870 □	Vacuum distillation developed, enabling production of lubricating oils. Asphalt produced as by-product.
1890s □	The emergence of the internal combustion engine creates demand for diesel fuel and gasoline; demand for kerosene declines with the invention and proliferation of the electric light.
1913 □	Thermal cracking developed—in response to increased demand for gasoline due to mass production manufacturing and the outbreak of World War I—enabling refiners to produce additional gasoline and distillate fuels by subjecting heavy crude fractions to high pressures and temperatures.
1930s □	Many advances made to improve gasoline yield and properties in response to development of higher-compression engines: catalytic cracking, thermal reforming, and catalytic polymerization to improve octane number; hydrogenation to remove sulfur; coking to produce gasoline basestocks; solvent extraction to improve viscosity index; and solvent dewaxing to improve pour point. By-products produced include residual fuel oil, coke, aromatics, waxes, and petrochemical feedstocks.
1940s □	The demands of World War II spurred yet more refining innovations: alkylation, for example, which produced high-octane aviation gasoline and petrochemical feedstock for explosives and synthetic rubber, and catalytic isomerization, which produced increased quantities of alkylation feedstock.
1950s – 1970s □	Following the war, various reforming processes were developed to improve gasoline quality and yield and produce higher-quality products: deasphalting, catalytic reforming, hydrodesulfurization, and hydrocracking, for example.

Table 3. Historical timeline for U.S. corn wet milling industry (5). □

1844	Wm. Colgate & Company builds first dedicated corn starch plant. □
1866	Dextrose produced from corn for the first time. □
1882	Refined anhydrous sugar first manufactured. Industry also begins producing corn □ gluten feed, realizing the value of non-starch parts of corn.
1889 □	First commercial production of corn oil.
1893 □	Industry begins recovering and condensing steepwater for use in feed products.
1921 □	Corn syrup technology advances significantly with the introduction of enzyme- hydrolyzed products such as crystalline dextrose hydrate.
1950s □	Technology for commercially preparing low conversion products such as maltodextrin developed. For the first time, corn-based sweeteners could compete in some sugar industry markets.
1967 □	First commercial shipment of high fructose corn syrup (HFCS) produced via enzyme catalyzed isomerization of dextrose to fructose.
1970s □	Fuel ethanol becomes a major product.
1980s □	HFCS becomes the sweetener of choice for the U.S. soft drink industry.
1990s - present	Industry focuses on developing new biologically produced products such as organic acids and degradable replacements for chemical products.

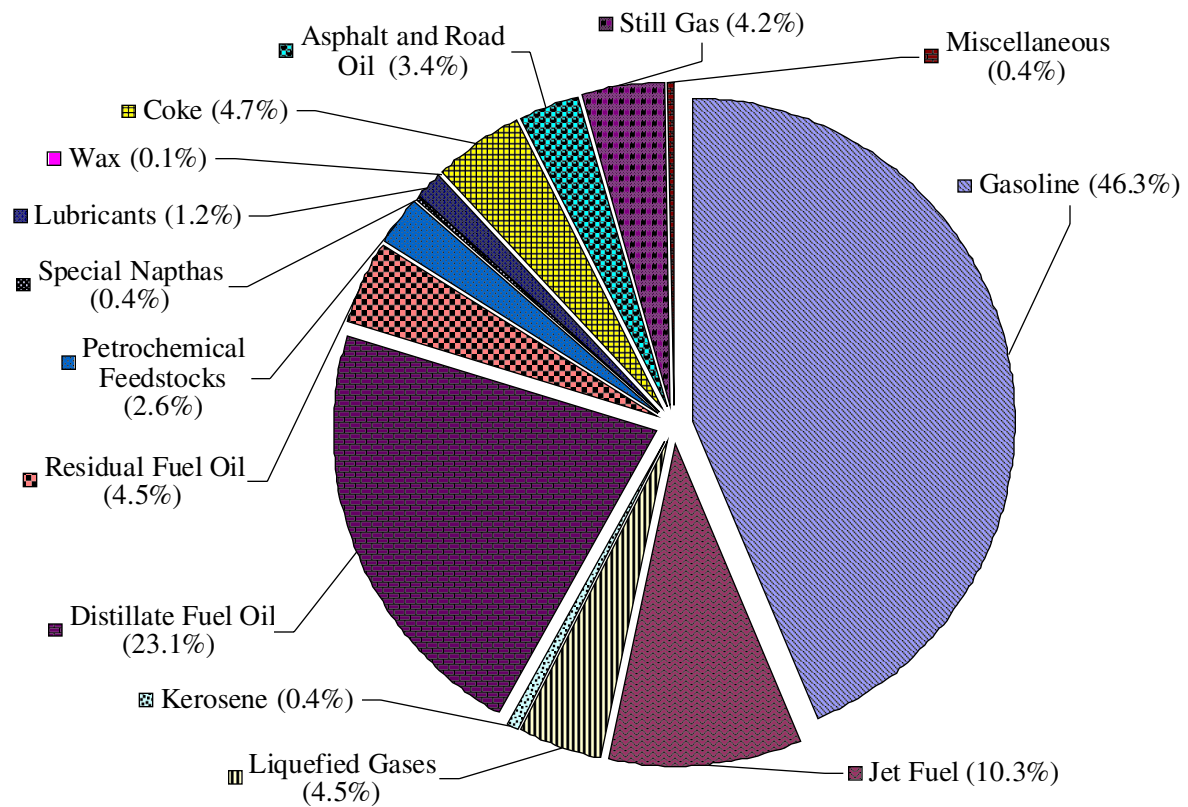


Figure 1a. U.S. petroleum refining yields (industry-wide; volume basis), 2000. Note: ethylene is categorized as a subset of “Liquefied Gases.” Source: (7).

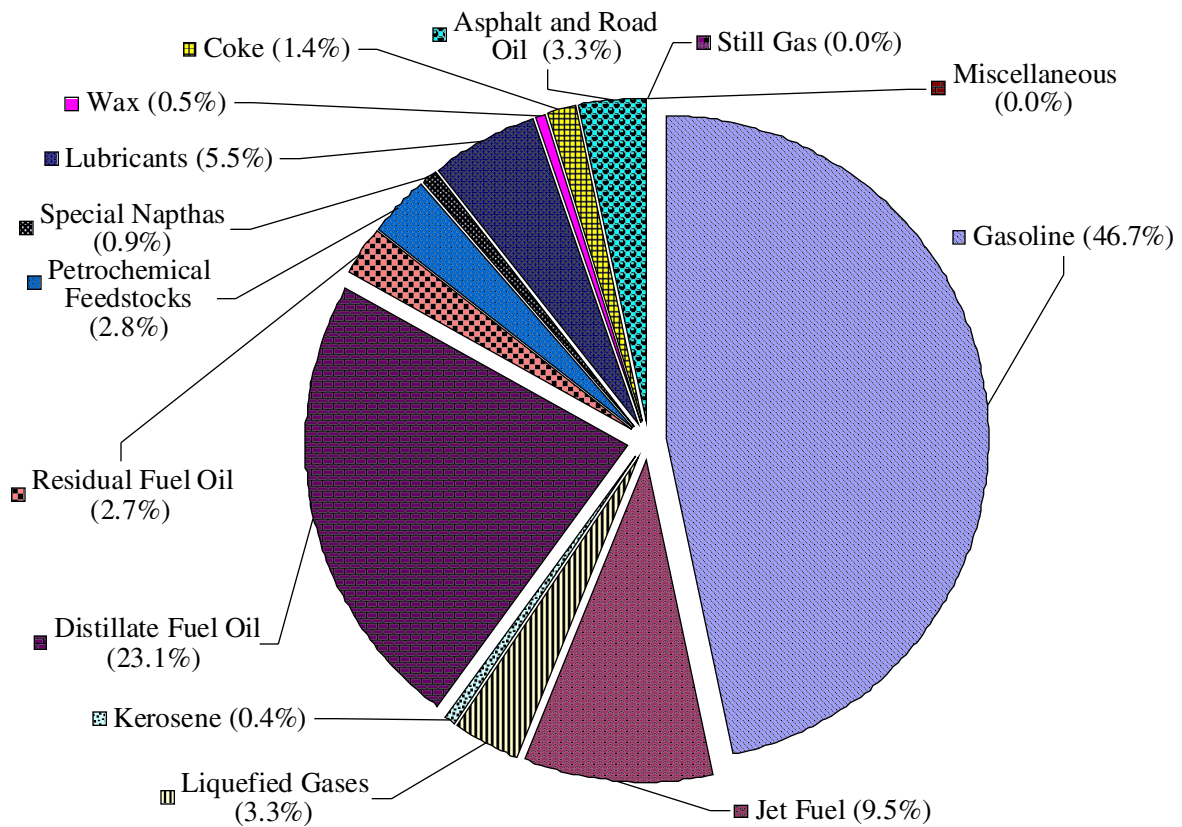


Figure 1b. U.S. petroleum refining product values (industry-wide, percent of total value). Source: major products—gasoline, jet fuel, kerosene, distillate fuel oil, residual fuel oil—(9); minor products—liquefied gases, petrochemical feedstocks, special napthas, lubricants, wax, coke, asphalt and road oil, still gas—(11). Price (\$/MMBTU) multiplied by thermal conversion factors from (12). Product price for year 2000 calculated as follows price = [14 year average(product price/crude price)]*crude price, 2000.

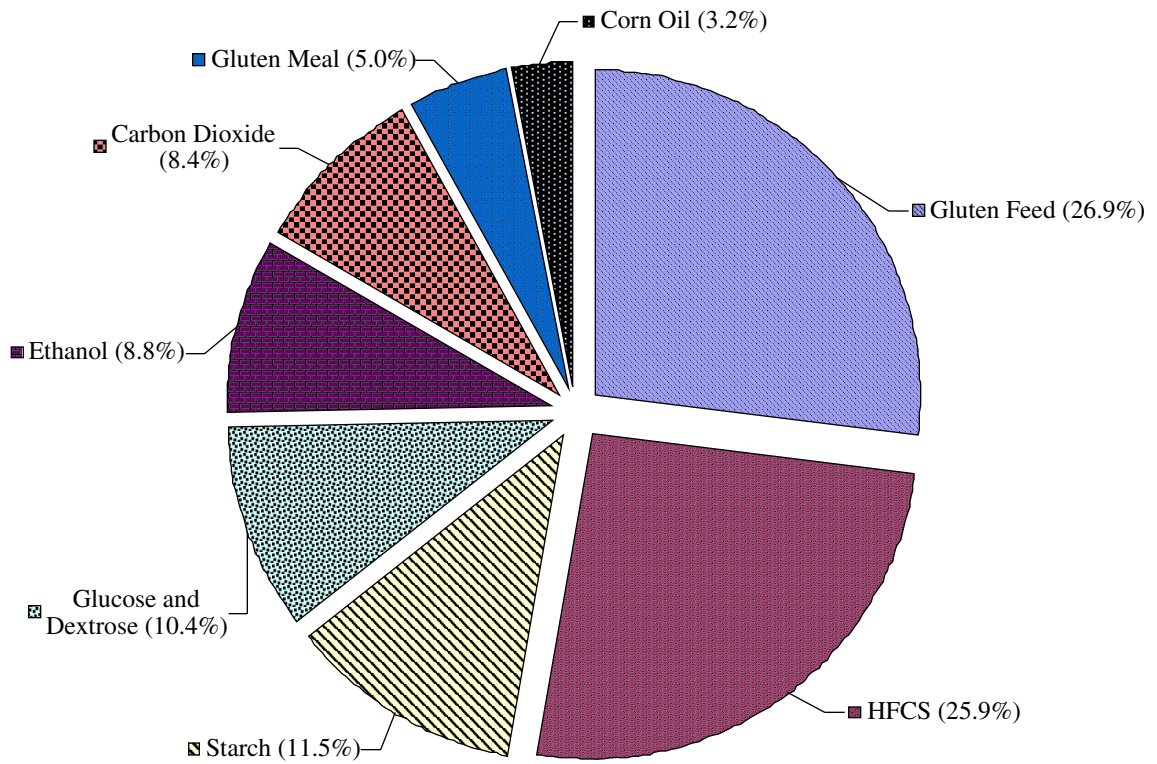


Figure 2a. U.S. corn wet milling yields (industry-wide, mass basis), 2001. Starch products based on values from (8), assuming 50 percent of ethanol produced from wet mills, 50 percent from dry mills. Corn oil, gluten feed, and gluten meal based on yields from (5). Stoichiometric CO₂ yield assumed).

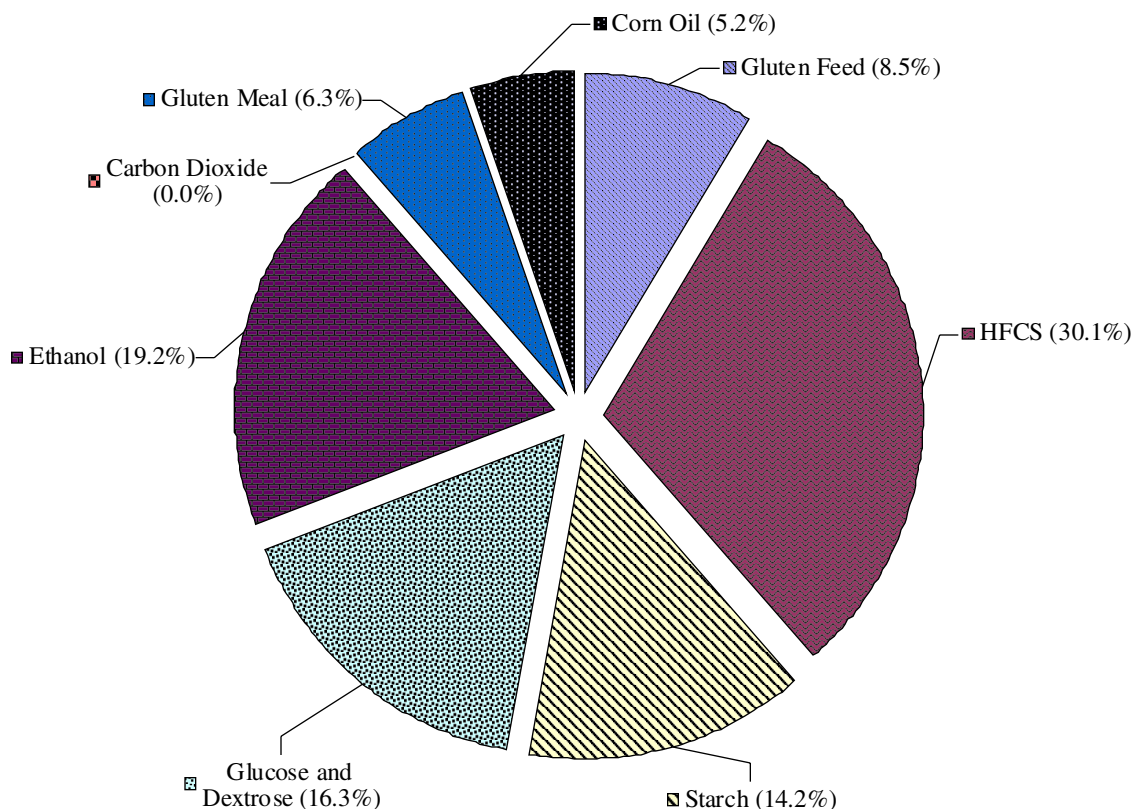


Figure 2b. U.S. corn wet milling product values (industry-wide, percent of total value). Price sources: HFCS (12), U.S. spot price for HFCS-42, Midwest markets, dry basis; dextrose (12), 400-600 sack cars, dry basis; starch (13); ethanol (14), average rack prices; corn oil (15); gluten meal (13); gluten feed (13).

The product slates of individual refineries and wet mills can vary widely from plant to plant. Calumet Lubricants, for example, specializes in lubricant oils and solvents; Citgo Asphalt Refining Co. manufactures primarily asphalt. Within the corn wet milling industry, National Starch & Chemical’s plant in Indianapolis makes specialty starches, while its Kansas City plant concentrates on adhesives. Corn Products International, Inc. produces sweeteners, starches, and corn oil, but not ethanol. Minnesota Corn Processors, meanwhile, makes sweeteners, starches, and ethanol, but not corn oil (8).

It should be noted at the outset that the major driving force behind the multi-product refinery concept is improved process economics. A petroleum refinery, for example, can significantly improve its profit margin by coproducing high value products such as lubricants. An examination of Figures 1a and 1b reveals that, in 2000, lubricants accounted for 5.5 percent of the total product value for the petroleum refining industry as a whole, while making up only 1.2 percent of the total petroleum product volumetric yield. Many refineries produce petrochemicals to improve their bottom line. Benzene, xylene, and toluene, for instance—chemicals generally

priced \$0.10 to \$0.30 per gallon higher than motor fuels (16)—can be extracted from the product of catalytic reforming, a process that produces high octane gasoline (17). This theme will be developed more fully in Report 2: Analysis of Integrated Biorefinery Configurations.

Overview of Industries

The production facilities within these industries have also become increasingly diverse. Within the petroleum refining business, process configuration varies from plant to plant according to its size, complexity, and product slate. There are small refineries—1,500 to 5,000 barrels per day (BPD)—and large ones that process in excess of 500,000 BPD (18). Some, such as those with integrated petrochemical processing capabilities, are extremely complex. Others are comparatively simple—those producing only fuels, for example. About 60 percent are part of major, integrated oil companies engaged in all aspects of the petroleum industry—from exploration and crude oil production to refining to transportation and marketing of petroleum products (19). The rest are owned by independent refiners that only manufacture refined products. By comparison, corn wet mills are fewer in number—25 operating wet mills (20) versus 150 petroleum refineries (18) in the U.S.—and more uniform in terms of processing: all wet mills have the same basic configuration (20). They do, however, vary in size: daily dry grind capacities range from 35,000 bushels per day to more than 500,000 bushels per day (20, 21).

Description of Processes

Modern refinery and wet mill operations have become increasingly complex, as they have changed and matured over time. Petroleum refining, for example, consists of five basic process areas (6,17):

- fractionation whereby crude oil is separated via distillation;
- conversion processes—catalytic cracking¹ and reforming, for example—that change the size and/or structure of hydrocarbon molecules;
- treatment processes such as desalting and hydrodesulfurizing that prepare streams for additional processing or produce finished products;
- blending in which fractions, additives, and other components are combined to produce finished products with specific performance properties;
- other refining operations, such as light-ends recovery, waste treatment, and storage.

Corn wet milling, though simpler than petroleum refining, nonetheless requires several processing steps (5, 22):

- steeping, in which corn is soaked in warm, sulfur dioxide-stabilized, water, making the kernels amenable to subsequent separation;
- germ separation and oil extraction;
- fine grinding and screening of the corn slurry;

¹ Vapors from cracking processes are sent to a fractionation tower for separation into stream having the desired boiling ranges.

- starch separation;
- syrup conversion;
- fermentation.

We refer the reader to Gary and Handwerk (17) and Hosenev (22) for more comprehensive treatments of petroleum refining and corn wet milling operations, respectively.

It should also be noted that another type of corn processing also exists: dry milling. In dry milling, corn is ground dry and then cooked in water to form a mash. While cooking, enzymes are added to the mash to hydrolyze starch to glucose. The mash is then fermented to ethanol using yeast. Ethanol is then recovered via distillation (23). Though the process does produce a coproduct—distillers dried grains, the residual solids by-product—dry milling does not represent a “refinery” in the same sense that petroleum refining and corn wet milling do, since it does not produce a slate of multiple products that can be adjusted to respond to market conditions. For this reason, we have not completed a comprehensive review of the dry milling industry.

Product Slate Selection

The business of managing a refinery or wet mill has also become increasingly complex. Production facilities in each industry strive to maximize profitability by continually monitoring market demand and adjusting their product slates accordingly—slates which have been developed over time—working within the constraints of available processing equipment, production capacity limitations, and contractual obligations. The ideal operating scenario is to meet product demand while operating at full capacity. Plants, however, can accommodate less-than-full capacity processing when necessary for economic reasons.

For petroleum refineries, determining the appropriate feedstock type and source represents another significant operating logistics variable. When sales forecasts are made, refinery planners decide which crude best meets the forecasted product demand. The purchasing group then determines the availability and cost of that particular crude and buys it if available at an affordable price. If the crude is not available, the purchasing group must locate an alternative crude with similar characteristics. The planning group must then revise its plan, making adjustments to the product slate if necessary (24). The frequency with which the product slate is adjusted due to market conditions or crude changes varies from refinery to refinery: some modify their product slates on a daily basis; others try to maintain more constant operations (25). Refinery managers and engineers routinely use linear programming (LP) algorithms when determining the optimal product slate and when making other decisions such as whether to enter new product markets. Maiti et al. (20) provide a useful example of the use of LP in refinery planning. Other analytical tools used to assist both operational and economic decision-making include everything from pencil-and-paper, order of magnitude estimates to non linear programming (27) and ASPEN process simulations (28).

Product slate selection is more straight forward for corn wet milling than for petroleum refining, largely because variability in feedstock composition is not a major concern, processing is far less complex, and there are fewer major products from which to choose. Key variables include market demand, consumer demographics, plant capacity, distribution costs, and sales contract requirements. Based upon forecasted demand, executives negotiate sales contracts to optimize asset use and minimize inventories. Their goal is to maximize throughput while timing the finishing operations to correspond to predictable demand cycles (20). Three years is considered by many to be the longest outlook for planning purposes for new capital projects (29, 30) due to the rapid pace of change in product markets; this requires short payoff period for new projects. Yearly business plans are typically subjected to quarterly profit/loss reviews, at which time product slate adjustments can be considered depending on market conditions (29).

Economic Performance

Over the last 25 years, U.S. demand for refined petroleum products has outpaced its domestic refining capacity (31)—since 1976, consumption has increased by 20 percent; domestic refining capacity by 8 percent. The U.S. now relies on overseas refineries for 11 percent of its refined products (31). The last domestic grassroots refinery was built in 1976 by Marathon Oil (32). Also during this time, many smaller refineries have shut down—from 1976 to 2000, the number of U.S. refineries has dropped from 276 to 158 (33). New capacity has come from expansion in downstream processing units (34). Low profitability has been the primary reason for this sluggish expansion in production capacity. From 1977 to 1999, return on investment for major domestic petroleum refineries averaged less than 6 percent (35).

Petroleum refining, as an industry, is generally less profitable than most other sectors. From 1985 to 2000, for example, oil company profit rates—measured as profits divided by net investment in place—averaged 7.2 percent compared with 11.7 for industry overall (36). The primary reason the petroleum refining industry has realized low returns is that capital intensity has increased dramatically while refining margins have declined (37). In the late 1970s and early 1980s, U.S. refiners deployed capital to upgrade their capability to use heavier, more sulfurous crude oils (37); in the 1990s, refiners stepped up their capital expenditures to comply with government regulations, spending about \$30 billion during the decade to comply with mandates—largely environmental (38).

The corn wet milling industry has generally fared better financially during the same 25-year period, especially during the 1970s when high fructose corn syrup (HFCS) emerged as a major new market segment, and the 1980s when the market for corn sweeteners continued to expand—HFCS-55 became the sweetener of choice for the U.S. soft drink industry in the mid 1980s—as did the market for ethanol which grew five-fold during the decade (39). During this time, more than a dozen new wet mills were constructed (8) to help meet rising demand for corn refinery products, which increased from 639 million bushels per year (b.p.y.) in 1980 to 1,354 MM b.p.y. in 1990 (8). Many wet milling companies achieved 15 percent or greater return on investment during this period (40). The industry, however, has not performed as well during the last decade,

largely because of intense competition resulting from over-expansion during the boom years and lower corn sweetener prices (40). As a result, only two new corn wet mills have been constructed in the last 10 years (20, 21).

Much of the increased demand for ethanol during the past decade has been met by expanding corn dry milling capacity—15 new dry mills have opened since 2000, increasing U.S. ethanol production by more than 550 million gallons, about 20 percent (41). The primary advantages of a corn dry mill relative to a wet mill are lower per bushel capital cost—\$3.25/bushel for a 30 MMgal ethanol/yr dry mill vs. \$4.26/bushel for a 100 MMgal/yr wet mill (42)—and higher ethanol yield per bushel—2.7 gal/bushel (23) vs. 2.5 gal/bushel (5). These advantages allow dry mills to be commercialized at a smaller scale than wet mills—30 MMgal/year versus 100 MMgal/year for a typical wet mill (23).

Processing Margin

An important outcome of technological advancement within a refinery is that it invariably lowers the cost of processing, making the cost of raw material the dominant factor in overall refinery economics. We propose the following framework to quantify the contribution of the primary feedstock and externally produced process energy to the total value of a biorefinery:

$$M_A = V - (F + E) \quad [1]$$

$$M_R = \frac{M_A}{(F + E)} \quad [2]$$

where

V = value of all products (\$/ton feedstock)

M_A = absolute process margin (\$/ton feedstock)

F = cost of primary feedstock (\$/ton)

E = cost of purchased, externally produced process energy (\$/ton feedstock)

The absolute margin includes all components of value exclusive of the cost of primary feedstock and purchased process energy (i.e. steam and electricity that is not derived from primary feedstock)—operating costs, capital recovery, profit, labor, maintenance, taxes, insurance, and depreciation, for example. (Note: For both petroleum refining and biomass refining, all process energy is derived internally from the feedstock—an important advantage relative to corn wet milling in which process energy must be purchased externally.) Total product value, V , is defined as:

$$V = SY_{P/F} \left\{ 1 - \sum_i f_i \right\} + \frac{\sum_i S_i f_i Y_i}{E} \quad [3]$$

where

- S = selling price of the primary product (\$/unit product) □
- f_i = fraction of feedstock devoted to production of i^{th} coproduct □
- $Y_{P/F}$ = yield of primary product (unit/ton feedstock) □
- S_i = selling price of the i^{th} coproduct (\$/unit product) □
- $Y_{i/F}$ = yield of the i^{th} coproduct (unit/ton feedstock) □

Low values of M_R correspond to processes where raw material costs are dominant. Therefore, as commodity refining processes mature, the relative margin can be expected to decrease, approaching an asymptotic value. Examination of the petroleum and corn refining industries provides insight into what this asymptotic value might be for mature biorefineries. During the last decade, the U.S. petroleum refining industry realized an average relative margin of 0.46 ± 0.09 . The average relative margin for U.S. corn dry milling during this period was 0.61 ± 0.20 . For wet milling, the value depends upon the product slate: if starch is converted exclusively to ethanol, the relative margin is the same as for dry milling, 0.61 ± 0.24 ; the relative margin increases to 1.27 ± 0.25 , however, if sweeteners, starch, and ethanol are produced. This is to be expected given that corn starch and sweeteners are higher-value products than fuels. Relative margin data for petroleum and corn refining are presented in Appendix B. Table 4 presents a summarized comparison of key characteristics of the petroleum refining and corn wet milling industries presented here.

Table 4. Key characteristics of petroleum refining and corn wet milling industries.

Characteristic	Petroleum Refining	Corn Wet Milling
Year Started	1861 ^a	1844 ^b
Total Number of Plants	158 ^c	25 ^d
Plant Capacity Range	225 - 75,000 tons/day ^e	980 – 14,000 tons/day ^f
New Plants Built	1 since 1976 ^g	12 during 1980s ^h ; 2 since 1992 ⁱ
Growth in Capacity	8% since 1976 ^j	200% since 1980 ^k
Return on Investment	< 6%, 1977-1999 ^l	~15%, 1980s; lower after 1994 ^m
Relative Processing Margin ⁿ	0.46 ± 0.09	0.61 ± 0.24 (ethanol only) 1.31 ± 0.40 (HFCS only) 1.27 ± 0.25 (all products)

^aSource: (6).

^bSource: (5).

^cSource: (33)

^dSource: (20).

^eSource: (18).

^fSource: (20, 21).

^gSource: (32).

^hSource: (8).

ⁱSource: (20, 21).

^jSource: (33).

^kValue represents increase in wet milling corn grind. Source: (43). □

^lSource: (35). □

^mSource: (40). □

ⁿSee Appendix B for product yield and price sources used to calculate processing margins. □

Conclusions

There are several implications, in light of this review, for the biorefining industry: Mature biorefineries will likely produce diverse product slates and, like petroleum refineries, will be designed to accommodate a variety of feedstocks. Product slate selection will represent a complex optimization problem involving many variables such as market demand, feedstock price and availability, and available processing equipment. Biorefining companies, to survive in an extremely competitive and rapidly changing marketplace such as exists today—especially for commodity fuels where relative processing margins are razor thin—must be efficiently managed.

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Appendix A: Petroleum Refining and Corn Wet Milling Reviews

I. Petroleum Refining

I.1. Brief History

A brief history, focussing on the advent of key refining operations, is presented here. The text is an edited version of the historical review published in (6).

Petroleum refining has evolved continuously in response to changing consumer demand. Kerosene— a cheaper and better source of light than whale oil—was the first refinery product. The invention and development of the airplane created a need for high-octane aviation gasoline, and later, for jet fuel. Present-day refineries produce a variety of products (see Figure 1a of main report). Table A.1 provides brief descriptions of the major refinery products. Table 1 in the main report presents a timeline for the key historical developments in each industry.

Table A.1. Major petroleum refinery products. Source: (6).

•**Gasoline.** The most important refinery product is motor gasoline, a blend of hydrocarbons with boiling ranges from ambient temperatures to about 400 °F. The important qualities for gasoline are octane number (antiknock), volatility (starting and vapor lock), and vapor pressure (environmental control). Additives are often used to enhance performance and provide protection against oxidation and rust formation.

•**Kerosene.** Kerosene is a refined middle-distillate petroleum product that finds considerable use as a jet fuel and around the world in cooking and space heating. When used as a jet fuel, some of the critical qualities are freeze point, flash point, and smoke point. Commercial jet fuel has a boiling range of about 375°-525° F, and military jet fuel 130°-550° F. Kerosene, with less-critical specifications, is used for lighting, heating, solvents, and blending into diesel fuel.

•**Liquefied Petroleum Gas (LPG).** LPG, which consists principally of propane and butane, is produced for use as fuel and is an intermediate material in the manufacture of petrochemicals. The important specifications for proper performance include vapor pressure and control of contaminants.

•**Distillate Fuels.** Diesel fuels and domestic heating oils have boiling ranges of about 400°-700° F. The desirable qualities required for distillate fuels include controlled flash and pour points, clean burning, no deposit formation in storage tanks, and a proper diesel fuel octane rating for good starting and combustion.

•**Residual Fuels.** Many marine vessels, power plants, commercial buildings and industrial facilities use residual fuels or combinations of residual and distillate fuels for heating and processing. The two most critical specifications of residual fuels are viscosity and low sulfur content for environmental control.

•**Coke and Asphalt.** Coke is almost pure carbon with a variety of uses from electrodes to charcoal briquets. Asphalt, used for roads and roofing materials, must be inert to most chemicals and weather conditions.

•**Solvents.** A variety of products, whose boiling points and hydrocarbon composition are closely controlled, are produced for use as solvents. These include benzene, toluene, and xylene.

•**Petrochemicals.** Many products derived from crude oil refining, such as ethylene, propylene, butylene, and isobutylene, are primarily intended for use as petrochemical feedstock in the production of plastics, synthetic fibers, synthetic rubbers, and other products.

•**Lubricants.** Special refining processes produce lubricating oil base stocks. Additives such as demulsifiers, antioxidants, and viscosity improvers are blended into the base stocks to provide the characteristics required for motor oils, industrial greases, lubricants, and cutting oils. The most critical quality for lubricating-oil base stock is a high viscosity index, which provides for greater consistency under varying temperatures.

Distillation Processes. The first refinery, which opened in 1861, produced kerosene by simple atmospheric distillation and generated tar and naphtha as by-products. Refiners soon discovered that high-quality lubricating oils could be produced by distilling petroleum under vacuum. For the next 30 years, however, kerosene received the greatest consumer demand. Two significant events changed this: the invention of electric light decreased the demand for kerosene, and the invention of the internal combustion engine created a demand for diesel fuel and gasoline (naphtha).

Thermal Cracking Processes. The number of gasoline-powered vehicles increased dramatically with the advent of mass production and the demands of World War I. Demand for gasoline grew accordingly. Early distillation processes, however produced a limited fraction of gasoline from crude oil. In 1913, the thermal cracking process was developed, which subjected heavy fuels to both pressure and intense heat. This served to physically break large molecules into smaller ones, producing additional gasoline and distillate fuels. Visbreaking, another form of thermal cracking, was developed in the late 1930's.

Catalytic Processes. Higher-compression gasoline engines required higher-octane gasoline with better antiknock characteristics. The introduction of catalytic cracking and polymerization processes in the mid- to late 1930's met this demand by providing improved gasoline yields and higher octane values. Alkylation—another catalytic process developed in the early 1940's—produced high-octane aviation gasoline and petrochemical feedstock for explosives and synthetic rubber. Catalytic isomerization was then developed to produce increased quantities of alkylation feedstock. Improved catalysts and process methods such as hydrocracking and reforming became widely used during the 1960's to increase gasoline yields and improve antiknock characteristics. These catalytic processes formed the basis of the modern petrochemical industry.

Treatment Processes. Throughout the history of petroleum refining, various treatment methods have been used to remove components that adversely affect the properties of finished products or reduce the efficiency of the conversion processes. Treatment processes can involve chemical reaction or physical separation, or both. Typical examples include chemical sweetening, acid treating, clay contacting, caustic washing, hydrotreating, drying, solvent extraction, and solvent dewaxing. Sweetening compounds and acids, for example, desulfurize crude oil before processing and treat products during and after processing.

Since Second World War, various reforming processes have been developed to improve gasoline quality and yield, and produced higher-quality products. Some of these have involved the use of catalysts or hydrogen, or both, to change molecules and remove sulfur. A number of the more commonly used treating and reforming processes are described in (6) and (17).

I.2. Process Description

Petroleum refining begins with the distillation, or fractionation, of crude oils into separate hydrocarbon groups. The resultant products are directly related to the characteristics of the crude processed. Most distillation products are further converted into more usable products by changing the size and structure of the hydrocarbon molecules through cracking, reforming, and other conversion processes. These converted products are then subjected to various treatment and separation processes such as extraction, hydrotreating, and sweetening to remove undesirable constituents and improve product quality. Integrated refineries incorporate fractionation, conversion, treatment, and blending operations and may also include petrochemical processing. Table A.2. presents a synopsis of refinery operations; a process flow diagram is presented in Figure A.1.

Table A.2. Petroleum refining process areas. Source: (6).

•**Fractionation** is the separation of crude oil in atmospheric and vacuum distillation towers into groups of hydrocarbon compounds of differing boiling-point ranges called "fractions" or "cuts."

•**Conversion** processes change the size and/or structure of hydrocarbon molecules. These processes include: decomposition by thermal and catalytic cracking; unification through alkylation and polymerization; and alteration with isomerization and catalytic reforming.

•**Treatment** processes are intended to prepare hydrocarbon streams for additional processing and to prepare finished products. Treatment may include the removal or separation of aromatics and naphthenes as well as impurities and undesirable contaminants. Treatment may involve chemical or physical separation such as dissolving, absorption, or precipitation using a variety and combination of processes including desalting, drying, hydrodesulfurizing, solvent refining, sweetening, solvent extraction, and solvent dewaxing.

•**Blending** is the process of mixing and combining hydrocarbon fractions, additives, and other components to produce finished products with specific performance properties.

•**Other refining operations** include: light-ends recovery; sour-water stripping; solid waste and wastewater treatment; process-water treatment and cooling; storage and handling; product movement; hydrogen production; acid and tail-gas treatment; and sulfur recovery.

•**Auxiliary operations** and facilities include: steam and electricity generation; process and fire water systems; flares and relief systems; furnaces and heaters; pumps and valves; supply of steam, air, nitrogen, and other plant gases; alarms and sensors; noise and pollution controls; sampling, testing, and inspecting; and laboratory, control room, maintenance, and administrative facilities.

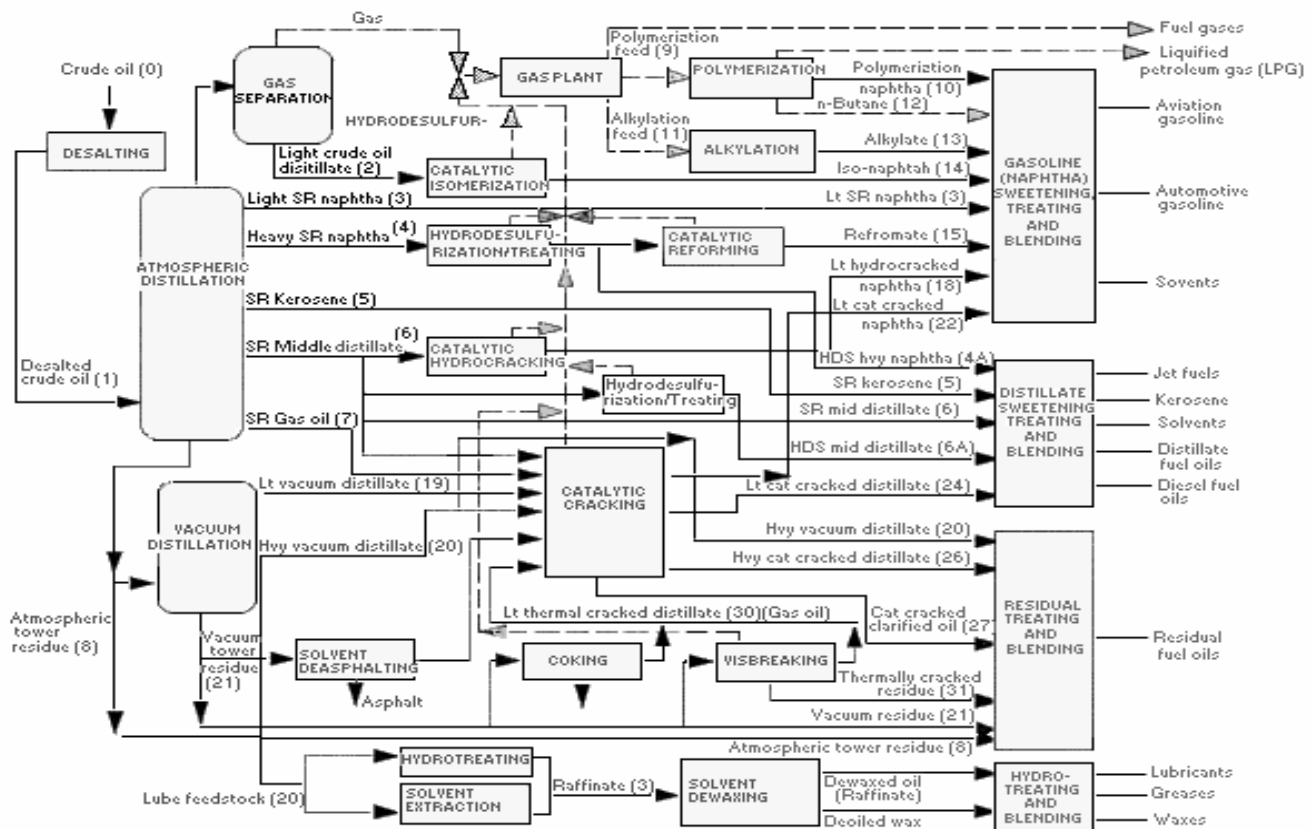


Figure A.1. Process flow diagram of petroleum refining operations. Source: (6).

I.3. Industry Overview

Within the petroleum refining industry, there are small refineries—1,500 to 5,000 barrels per day (BPD)—and large ones that process in excess of 500,000 BPD (18). Some, such as those with integrated petrochemical processing capabilities, are extremely complex. Others are comparatively simple—those producing only fuels, for example. About 60 percent are part of major, integrated oil companies engaged in all aspects of the petroleum industry—from exploration and crude oil production to refining to transportation and marketing of petroleum products (19). The rest are owned by independent refiners that only manufacture refined products.

I.4. Refinery Product Slate Selection

Petroleum refineries strive to maximize return on investment by continually monitoring market demand and adjusting their product slates accordingly, working within the constraints of available processing equipment, production capacity limitations, and contractual obligations. The ideal operating scenario is to meet product demand while operating at full capacity. Plants, however, can accommodate less-than-full capacity processing when necessary for economic reasons.

Determining the appropriate feedstock type and source represents another significant operating logistics variable. When sales forecasts are made, refinery planners decide which crude best meets the forecasted product demand. The purchasing group then determines the availability and cost of that particular crude and buys it if available at an affordable price. If the crude is not available, the purchasing group must locate an alternative crude with similar characteristics. The planning group must then revise its plan, making adjustments to the product slate if necessary (24). The frequency with which the product slate is adjusted due to market conditions or crude changes varies from refinery to refinery: some modify their product slates on a daily basis; others try to maintain more constant operations (25). Refinery managers and engineers routinely use linear programming (LP) algorithms when determining the optimal product slate and when making other decisions such as whether to enter new product markets. Maiti et al. (26) provide a useful example of the use of LP in refinery planning. Other analytical tools used to assist both operational and economic decision-making include everything from pencil-and-paper, order of magnitude estimates to non linear programming (27) and ASPEN process simulations (28).

II. Corn Wet Milling²

II.1. Product Slate Selection

A corn refinery produces a limited number of commodity products in large volume. The three primary products are ethanol, corn syrup, and corn starch. Corn syrup is a general term covering a wide range of products, the most significant of which, by far, is high fructose corn syrup (HFCS). Coproducts of the operation, corn gluten feed (CGF), gluten meal and corn oil, occur as a fixed fraction of raw material (corn kernels) processed to produce the carbohydrate feed for the primary products. The product slate decisions in operation of the refinery are made prior to plant construction (or expansion) and can be adjusted subsequently with added investment.

The HFCS, corn syrup, and paper—the largest user of corn starch—markets are mature and predictable, according to Mr. Larry Cunningham, Senior Vice President, Archer Daniels Midland, but the unsettled fuel ethanol situation clouds that demand outlook with uncertainty. Product slate selection is straight forward based upon maximizing return on assets (ROA) within the production capacity constraints. Annual sales contracts are negotiated to optimize asset utilization and minimize inventories. The attempt is to maximize grind capacity while timing the finishing operations to correspond to predictable demand cycles.

Change is rapid so planning for new capital projects can only look out three years with any predictability. Mr. Lynn Grider, President, A. E. Staley Manufacturing Company, a Tate & Lyle North America business, says that yearly business plans are subjected to a product line P&L review on a quarterly basis. At the quarterly review product slate adjustments can be considered, factoring in externals such as emerging market conditions and other issues.

² The corn wet milling review was largely written by project consultant Donald L. Johnson.

Mr. Gage Kent, CEO of Grain Processing Corporation, a large corn wet miller, agrees that three years is the longest that predictability allows. A three year cash flow cycle also requires a shorter payoff on new capital projects. He adds that they, GPC, view the demographics of the customer base as important and like to see dispersion rather than concentration. Distribution costs are also a significant factor. Although many factors influence the product slate selection, like any other large commodity operation, maximizing return on assets is the goal.

The following discussion describes a corn refinery and how carbohydrate (starch) refining options, economy of scale, and seasonal variability of the product demand impact product slate selection.

II.2. Corn Refining Process Description

There are two kinds of corn processing plants, excluding the less significant flour mills and food corn operations. A dry mill, or “mash” plant as it is commonly called, is limited to two products: ethanol and distillers dried grains. Such a plant is not usually considered a corn refinery because of that limitation. Although some dry mills separate germ and recover corn oil, they still are not considered a corn refinery.

A wet milling operation, which is the focus of this discussion, is a refinery in the sense that the raw material, corn, is separated into its components, starch (carbohydrate), gluten (protein), hull (fiber) and germ (corn oil). Moreover, the carbohydrate fraction, which is the most significant part of the corn composition, is further processed and refined into such products as native and modified starch, dextrose, high fructose corn sweetener (HFCS), ethanol, glucose syrup and specialty hydrolyzates. Currently, there are 25 wet mills operating in the U.S. (Table A.4) with daily dry grind capacities ranging from 35,000 bushels per day to more than 500,000 bushels per day (20, 21).

Table A.3 lists product yields for a typical corn wet milling operation. Figure A.2. presents a block flow diagram of the process.

Table A.3. Product yields for a typical corn wet mill.

Product	Yield (lb/lb feed)
Starch	0.684
Corn Gluten Feed (60% protein) (Corn Steep Liquor)	0.237 (0.070) ^a
Gluten Meal	0.045
Corn Oil	0.034

^aValue listed as dry solids corn steep liquor (CSL). If not sold as CSL or used internally, it is combined with corn gluten feed (CGF); CSL is listed here as a subset of CGF.

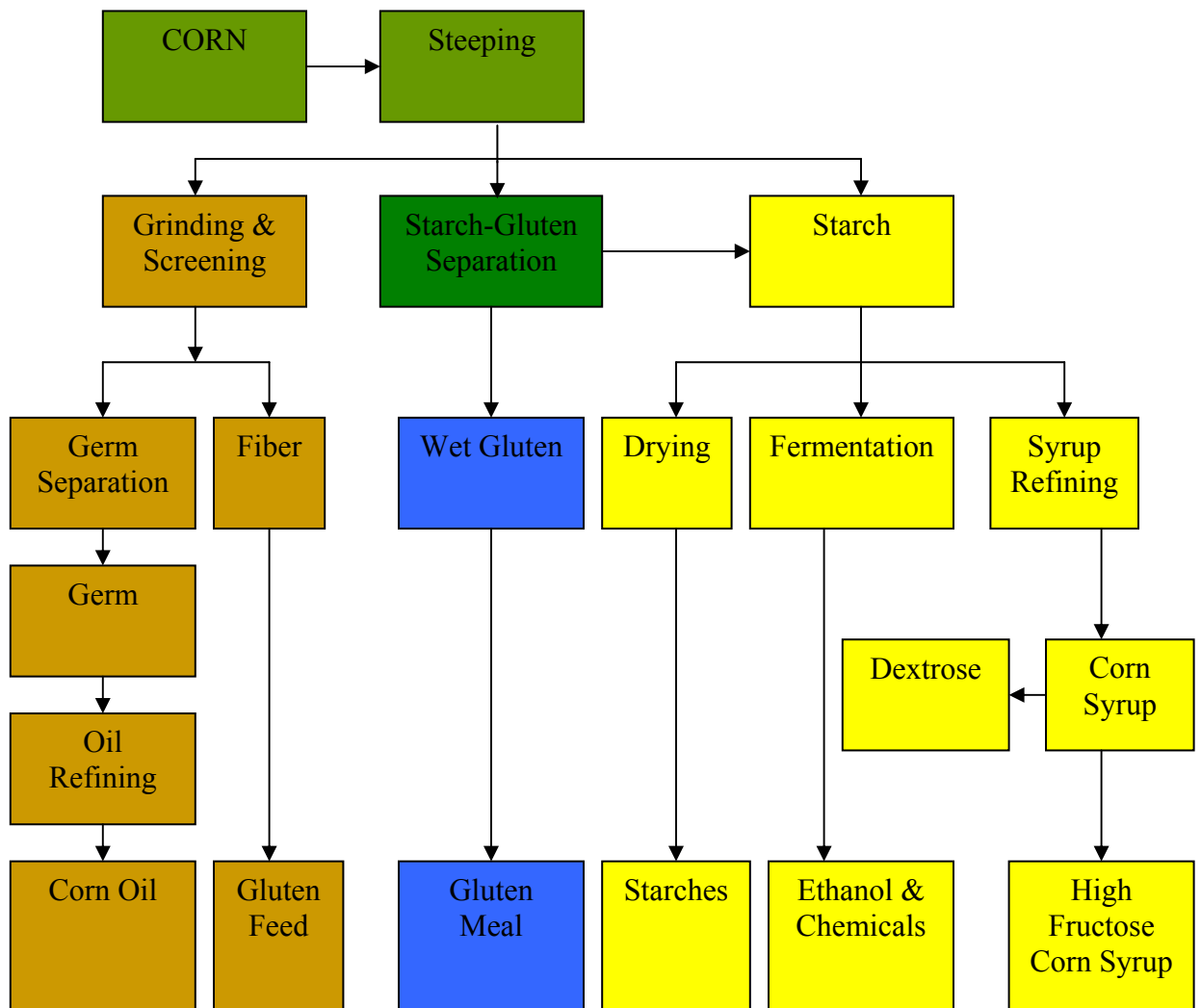


Figure A.2. Block diagram of corn wet milling process.

Corn wet milling begins with steeping, from which arises an additional product, corn steep liquor (CSL). The steeping process is just that: corn is soaked in warm, sulfur dioxide-stabilized water for 15 to 30 hours, softening the kernel and making it amenable to the subsequent separation. The nutrient rich CSL can be concentrated and sold as condensed fermented corn extractives. That which is not used internally or sold as CSL to other fermenters is combined with corn germ meal—germ from which the oil has been extracted—and hulls constituting CGF.

The quantity of each coproduct produced is a fixed fraction of starch produced. A slight variation in amount of CGF can be obtained by grinding the corn more lightly which reduces the amount of starch in the primary stream, while increasing starch content in the CGF stream. Since starch and its derivatives are more valuable than CGF, such is seldom done. Corn oil is more valuable on a per pound basis than either CGF or starch, and often gluten meal. While maximum recovery is desired, corn oil is only a small percentage of the raw material. Additional cost to increase separation is not considered worthwhile. Some refiners sell dry germ to other facilities for subsequent oil extraction and refining rather than expending their capital and operating costs to realize such a small benefit. Unless the value of corn oil increases dramatically, even “high oil” corn is of little value to the wet miller. While a futuristic corn oil containing a valuable hydrophobic component such as a pharmaceutical could prompt additional investment oil recovery, the market volume for the product of interest would have to be considerable to warrant such investment, given the typical scale of corn wet mills. A “boutique” plant where this may make sense is beyond the scope of this discussion.

II.3. Carbohydrate Refining Options

The more versatile option in operating a corn refinery is the downstream processing of the primary product, the carbohydrate. The granular starch slurry can simply be dried producing native, or “pearl” corn starch. Or, it can be processed, chemically or physically, into starch derivatives. Although important, the over nine billion pounds of corn starch used industrially in the year 2000 (5) is still a distant third to that quantity used for producing fuel alcohol or sweeteners.

Over 80 percent of the wet milled corn starch is converted to sweeteners or ethanol (5). In this process, the granular corn starch slurry is dissolved and saccharified using a combination of heat, acid and/or enzymes. The process of saccharification hydrolyzes the starch polymer, converting it to short chain carbohydrates. The degree of hydrolysis—quantified as dextrose equivalent (DE)—determines whether it is a corn syrup (20 to 70 DE) or dextrose syrup (94 to 98 DE). DE represents the percentage hydrolysis of the glycosidic linkages present and is defined as follows:

$$DE = 100 * \left(\frac{\text{number of glycosidic bonds cleaved}}{\text{initial number of glycosidic bonds}} \right) \quad [1]$$

In practice, this is usually determined analytically by use of the closely related, but not identical, expression:

$$DE = 100 * \left(\frac{\text{reducing sugar, expressed as glucose}}{\text{total carbohydrate}} \right) \quad [2]$$

Corn sweeteners are sold as a wide range of glucose or dextrose syrups depending upon DE and purity. These hydrolyzates are mechanically clarified and refined with carbon and ion exchange to produce the desired syrups. Converting to 95 or higher DE dextrose provides three options:

- refine the product as dextrose or 95 DE corn syrup;
- convert via fermentation to ethanol;
- isomerize the material to HFCS.

Having a high DE corn syrup stream adds flexibility in the choice of an ethanol fermentation process as well. Batch, semi-continuous or continuous fermentation are options available with a 95 DE syrup stream. Large refiners producing both HFCS and ethanol provide a common stream which allows production swings, 50 percent in some cases, from HFCS to ethanol and vice versa as demand dictates. Hence, some of either capacity is idle at times. That “idle capacity” investment is a small part of the overall plant investment, however, and considered a small price to pay for increased flexibility.

HFCS requires a 95 DE glucose or higher feed to the isomerization reactors, the higher the better (while avoiding isomaltose reversion, which is discussed later). These fixed enzyme reactors produce a 42 percent fructose syrup, the balance being glucose and any higher sugars which were present in the feed stream. The product is refined with carbon and ion exchange, and concentrated. Additionally, large chromatographic columns are used in an enriching process where the components—fructose, glucose and higher sugars—are separated. An 85 to 90 percent fructose product results. This product is blended with 42 percent fructose syrup to produce a range of fructose compositions. The preponderance of product is 55 percent fructose syrup, an extensively used sweetener in the huge soft drink industry.

The other commodity product produced in a corn refinery is glucose syrup. This covers a broad range of products ranging from 20 DE to 70 DE, as mentioned earlier. Such products are widely used in the baking, canning and confectionery industries.

As can be gleaned from the previous sections, once starch converters and refining capacity are in place, a wide range of products can be produced to meet market demand. The product slates of individual wet mills can vary widely from plant to plant. National Starch & Chemical’s plant in Indianapolis, for example, makes specialty starches, while its Kansas City plant concentrates on adhesives. Corn Products International, Inc. produces sweeteners, starches, and corn oil, but not ethanol. Minnesota Corn Processors, meanwhile, makes sweeteners, starches, and ethanol, but not corn oil (8).

If a hydrolyzate is to be converted to ethanol, some manufacturers will provide a somewhat lower DE stream to the fermenter to avoid isomaltose, a reversion sugar of glucose which occurs through an equilibrium reaction at high DE. Higher sugars are hydrolyzed to fermentables in the fermenter and the fermenting organism consumes the glucose and other fermentable sugars. Thus, reversion conditions are avoided and overall yields can be improved.

Having appropriate converter capacity also allows the option of other fermentation products. Some vitamins and amino acids may require a highly pure dextrose, while a simultaneous saccharification-fermentation process can readily utilize a low DE syrup. The range of choices is broad and as new industrial organisms are introduced, even more options will become available.

Large refiners generally do not pursue products with market values under \$100 million. In large commodity operations, operating the refinery at maximum capacity to produce one high-volume starch-derived product—and select higher-value coproducts with significant market sizes such as citric acid and sorbitol—maximizes return on assets (ROA).³ In reality, market cycles seldom allow such operation. Swing capacity with two or more large-volume commodities is the next best option for minimizing operating costs and maximizing ROA.

Another strategy employed by some of the smaller wet mills is to target niche products having a \$10 to 20 million market—too small to attract the interest of giant refiners. Smaller more flexible refiners can pursue such a strategy with favorable results. These usually are more sophisticated products such as unique hydrolyzates, special modifications of either starch or glucose, or even specialty fermentations. Examples include cyclodextrins, alkylpolyglycides, and erythorbic acid, among others.

II.4. Economy of Scale

Large refineries producing commodity products strive to be the lowest cost producer. Primary contributors to production costs, excluding raw material costs, are those related to investment, labor, and conversion. Investment related costs include maintenance, insurance and property tax, and general plant costs. Doubling the plant capacity generally increases investment required by only 50 percent, so costs per unit of production decrease with plant size. In a simplistic sense, one operator can run a process whether the unit produces a thousand liters/minute, or two thousand liters/minute, thus unit labor costs decrease as production capacity increases. Conversion costs include utilities such as steam, electricity, and water, which are generally insensitive to volume on a cost per pound basis.

Transporting agricultural raw materials presents a significant cost compared to the value of the material and must be considered in the economy of scale. Domestic refiners generally purchase

³ Citric acid has a North American market volume of over 600 MMlbs and sells for \$0.50 per pound (44); sorbitol has a U.S. demand of more than 550 MMlbs and sells for \$0.35/lb (45).

corn locally. If a plant gets larger than can be supported by nearby production, the cost of purchasing a more distant raw material may become non-competitive. Thus, feedstock availability is a limiting factor in determining the maximum size of a wet mill.

In the investment planning stage, the product mix decisions are affected by many factors and economy of scale is a significant one. The size of the wet milling portion of the plant—i.e. the steeping, grinding, and separation unit operations—determines the overall capacity and product mix flexibility depends upon how much the investors are willing to spend on finishing capacity. As mentioned previously, the most cost efficient plant would have a product slate consisting of one high-volume starch-derived commodity—not several—and select higher-value coproducts with significant market sizes (i.e. > \$100 million) issuing from a gigantic plant run by as few people as possible. In the real world, many factors—too numerous to describe adequately here—influence the decision on size. Corn refinery capacity is traditionally stated in “bushels per day” grind. The generally accepted definition of a “scale” plant is between 70,000 to 100,000 bushels/day grind (1780 to 2500 tons/day). In addition to the conversion cost factors discussed above, standard, off-the-shelf equipment such as boilers, centrifuges, dryers, pumps, tanks, etc., are available at this scale—an important consideration, given that non-standard sizes requiring custom fabrication are significantly more expensive.

Most large corn refineries evolved from one or two primary starch-derived products by adding finishing capacity to support a new product with a corresponding expansion in grind to support the new capacity. For example, a burgeoning HFCS market supported new syrup refining capacity with attendant grind expansions at existing syrup manufacturers. In this HFCS case, dramatic growth spurred green-field plant construction dedicated solely to HFCS production at the scale mentioned above (70,000 bpd to 100,000 bpd). Even those plants now produce additional products.

II.5. Seasonal Market Variability

Like the petroleum refining industry, the corn refining industry has seasonal market cycles. HFCS, a 20 billion pound per year domestic market, is extensively used in the soft drink industry. Demand is heaviest in the warm summer months. Because glucose syrups are heavily used in canning, additional demands are placed on syrup production by the late summer canning season. As previously mentioned, the glucose used in producing HFCS is also used as a fuel ethanol raw material in several large ethanol plants. Fortunately, there is some seasonal variability in fuel ethanol demand because it is used as an oxygenate during the winter months in some non-attainment areas, such as Denver, Colorado. Surprisingly, a seasonal effect is discerned in the largest consumer of industrial starch, the pulp and paper industry. Paper mills shut down for maintenance and personnel vacations in the late spring and again in the fall, coinciding with the hunting season and the slowdown in demand for corrugated board, for example.

Table A.4. U.S, corn wet mills as of July, 2002.^a

Company	Site	State	Capacity	
			Grind ^a (bushels/day)	Ethanol ^g (MMgal/yr)
Archer Daniels Midland Co.				950 (total)
	Cedar Rapids	IA	450,000	n.a.
	Clinton	IA	350,000	n.a.
	Decatur	IL	555,000	n.a.
Cargill, Incorporated	Montezuma	NY ^b	-	-
	Blair	NE	n.a.	75
	Cedar Rapids	IA	n.a.	0
	Dayton	OH ^c	-	-
	Eddyville	IA	n.a.	35
	Memphis	TN	n.a.	0
	Wahpeton	ND	n.a.	0
Cerestar USA, Inc. ^d			250,000	
	Decatur	IL	n.a.	0
	Dimmit	TX ^e	-	-
Corn Products International, Inc.	Hammond	IN	n.a.	0
	Bedford Park	IL	n.a.	0
	Stocton	CA	n.a.	0
	Winston-Salem	NC	n.a.	0
Grain Processing Corp	Muscatine	IA	n.a.	10
	Washington	IN	n.a.	0
Minnesota Corn Processors	Columbus	NE	200,000	100
	Marshall	MN	160,000	40
National Starch and Chemical Company	Indianapolis	IN	n.a.	0
	North Kansas City	MO	n.a.	0
Penford Products Company	Cedar Rapids	IA	n.a.	0
Roquette America, Inc.	Keokuk	IA	n.a.	0
A. E. Staley Manufacturing Company ^f	Decatur	IL	220,000	0
	Lafayette, North	IN	55,000	0
	Lafayette, South	IN	150,000	0
	Loudon	TN	150,000	60

n.a. means "not available." ^aSource: Don Johnson, personal communication. Capacities are unpublished estimates—except for Minnesota Corn Processors, which published its capacities on its website. ^bNot currently operating as corn refinery. ^cNot currently operating; on standby. ^dRecently purchased by Cargill. ^eOn partial shutdown. ^fSubsidiary of Tate & Lyle, PLC. ^gSource: (49).

Appendix B: Relative margin data for petroleum refining, corn wet milling, and corn dry milling.

Table B.1. Yield, price, and product value data for U.S. petroleum refining industry from 1990-2000.

Product	1990			1991		
	Yield ^a (gal/gal crude)	Price ^b (\$/gal)	Value (\$/gal crude)	Yield (gal/gal crude)	Price (\$/gal)	Value (\$/gal crude)
Gasoline	0.458	0.786	0.36	0.459	0.699	0.32
Jet Fuel	0.107	0.773	0.08	0.103	0.650	0.07
Liquefied Gases	0.036	0.415	0.01	0.038	0.419	0.02
Kerosene	0.003	0.839	0.00	0.003	0.722	0.00
Distillate Fuel Oil	0.209	0.767	0.16	0.213	0.674	0.14
Residual Fuel Oil	0.068	0.413	0.03	0.067	0.314	0.02
Petrochemical Feedstocks	0.029	0.750	0.02	0.029	0.644	0.02
Special Napthas	0.004	1.214	0.00	0.004	1.214	0.00
Lubricants	0.012	2.108	0.03	0.011	2.425	0.03
Wax	0.001	1.944	0.00	0.001	2.153	0.00
Coke	0.039	0.193	0.01	0.001	0.165	0.00
Asphalt & Road Oil	0.032	0.477	0.02	0.041	0.496	0.02
Still Gas	0.048	0.000	0.00	0.031	0.000	0.00
Miscellaneous	0.005	0.000	0.00	0.047	0.000	0.00
TOTAL VALUE			0.73			0.64
CRUDE PRICE ^a			0.53			0.45
RELATIVE MARGIN			0.37			0.42

^aSource: (7).

^bPrice data sources: major products—gasoline, jet fuel, kerosene, fuel oils—(9); minor products—LPG, petrochemical feedstocks, napthas, lubricants, wax, coke, asphalt & road oil, still gas—(10); Prices listed (\$/MMBTU) were multiplied by thermal conversion factors from Energy Information Administration/Annual Energy Review, 2000. Minor product prices for year 2000 were estimated as follows: product price = [14 year average(product price/crude price)]*year 2000 crude price.

Year	1992			1993		
Product	Yield ^a (gal/gal crude)	Price ^b (\$/gal)	Value (\$/gal crude)	Yield (gal/gal crude)	Price (\$/gal)	Value (\$/gal crude)
Gasoline	0.462	0.677	0.31	0.463	0.626	0.29
Jet Fuel	0.099	0.605	0.06	0.100	0.577	0.06
Liquefied Gases	0.043	0.380	0.02	0.041	0.377	0.02
Kerosene	0.003	0.632	0.00	0.003	0.604	0.00
Distillate Fuel Oil	0.212	0.619	0.13	0.219	0.603	0.13
Residual Fuel Oil	0.064	0.308	0.02	0.058	0.293	0.02
Petrochemical Feedstocks	0.033	0.622	0.02	0.030	0.554	0.02
Special Napthas	0.004	1.214	0.00	0.004	1.214	0.00
Lubricants	0.011	2.645	0.03	0.011	2.738	0.03
Wax	0.001	3.262	0.00	0.001	2.518	0.00
Coke	0.042	0.123	0.01	0.043	0.102	0.00
Asphalt & Road Oil	0.030	0.395	0.01	0.032	0.459	0.01
Still Gas	0.047	0.000	0.00	0.046	0.000	0.00
Miscellaneous	0.003	0.000	0.00	0.003	0.000	0.00
TOTAL VALUE			0.62			0.59
CRUDE PRICE ^a			0.44			0.39
RELATIVE MARGIN			0.41			0.50

Year	1994			1995		
Product	Yield ^a (gal/gal crude)	Price ^b (\$/gal)	Value (\$/gal crude)	Yield (gal/gal crude)	Price (\$/gal)	Value (\$/gal crude)
Gasoline	0.457	0.599	0.27	0.466	0.626	0.29
Jet Fuel	0.101	0.534	0.05	0.098	0.539	0.05
Liquefied Gases	0.042	0.413	0.02	0.045	0.407	0.02
Kerosene	0.004	0.618	0.00	0.004	0.580	0.00
Distillate Fuel Oil	0.223	0.569	0.13	0.218	0.578	0.13
Residual Fuel Oil	0.057	0.317	0.02	0.054	0.363	0.02
Petrochemical Feedstocks	0.029	0.527	0.02	0.029	0.582	0.02
Special Napthas	0.004	1.214	0.00	0.003	1.214	0.00
Lubricants	0.012	2.760	0.03	0.012	2.803	0.03
Wax	0.001	3.262	0.00	0.001	3.149	0.00
Coke	0.043	0.110	0.00	0.043	0.129	0.01
Asphalt & Road Oil	0.031	0.463	0.01	0.032	0.503	0.02
Still Gas	0.046	0.000	0.00	0.045	0.000	0.00
Miscellaneous	0.003	0.000	0.00	0.003	0.000	0.00
TOTAL VALUE			0.57			0.59
CRUDE PRICE ^a			0.37			0.41
RELATIVE MARGIN			0.53			0.44

Year	1996			1997		
Product	Yield ^a (gal/gal crude)	Price ^b (\$/gal)	Value (\$/gal crude)	Yield (gal/gal crude)	Price (\$/gal)	Value (\$/gal crude)
Gasoline	0.459	0.713	0.33	0.459	0.700	0.32
Jet Fuel	0.104	0.646	0.07	0.103	0.613	0.06
Liquefied Gases	0.045	0.508	0.02	0.046	0.458	0.02
Kerosene	0.004	0.714	0.00	0.004	0.653	0.00
Distillate Fuel Oil	0.227	0.702	0.16	0.225	0.663	0.15
Residual Fuel Oil	0.050	0.420	0.02	0.047	0.387	0.02
Petrochemical Feedstocks	0.027	0.699	0.02	0.029	0.643	0.02
Special Napthas	0.003	1.214	0.00	0.003	1.214	0.00
Lubricants	0.012	2.900	0.03	0.012	2.596	0.03
Wax	0.002	3.026	0.01	0.002	3.245	0.01
Coke	0.045	0.250	0.01	0.046	0.242	0.01
Asphalt & Road Oil	0.031	0.520	0.02	0.032	0.559	0.02
Still Gas	0.045	0.000	0.00	0.044	0.000	0.00
Miscellaneous	0.003	0.000	0.00	0.003	0.000	0.00
TOTAL VALUE			0.69			0.66
CRUDE PRICE ^a			0.49			0.45
RELATIVE MARGIN			0.40			0.47

Year	1998			1999		
Product	Yield ^a (gal/gal crude)	Price ^b (\$/gal)	Value (\$/gal crude)	Yield (gal/gal crude)	Price (\$/gal)	Value (\$/gal crude)
Gasoline	0.462	0.526	0.24	0.465	0.645	0.30
Jet Fuel	0.099	0.450	0.04	0.102	0.533	0.05
Liquefied Gases	0.044	0.348	0.02	0.045	0.402	0.02
Kerosene	0.005	0.465	0.00	0.004	0.550	0.00
Distillate Fuel Oil	0.223	0.476	0.11	0.223	0.585	0.13
Residual Fuel Oil	0.050	0.280	0.01	0.046	0.354	0.02
Petrochemical Feedstocks	0.030	0.423	0.01	0.027	0.591	0.02
Special Napthas	0.004	1.214	0.00	0.006	1.214	0.01
Lubricants	0.012	2.754	0.03	0.012	2.418	0.03
Wax	0.001	2.651	0.00	0.001	2.708	0.00
Coke	0.046	0.201	0.01	0.047	0.208	0.01
Asphalt & Road Oil	0.033	0.543	0.02	0.033	0.523	0.02
Still Gas	0.043	0.000	0.00	0.043	0.000	0.00
Miscellaneous	0.004	0.000	0.00	0.003	0.000	0.00
TOTAL VALUE			0.51			0.60
CRUDE PRICE ^a			0.30			0.42
RELATIVE MARGIN			0.69			0.45

Product	Year	2000	
	Yield ^a (gal/gal crude)	Price ^b (\$/gal)	Value (\$/gal crude)
Gasoline	0.463	0.96	0.45
Jet Fuel	0.103	0.88	0.09
Liquefied Gases	0.045	0.70	0.03
Kerosene	0.004	0.97	0.00
Distillate Fuel Oil	0.231	0.96	0.22
Residual Fuel Oil	0.045	0.57	0.03
Petrochemical Feedstocks	0.026	1.03	0.03
Special Napthas	0.004	2.20	0.01
Lubricants	0.012	4.35	0.05
Wax	0.001	4.39	0.00
Coke	0.047	0.28	0.01
Asphalt & Road Oil	0.034	0.92	0.03
Still Gas	0.042	0.00	0.00
Miscellaneous	0.004	0.00	0.00
TOTAL VALUE			0.96
CRUDE PRICE ^a			0.67
RELATIVE MARGIN			0.42

^aSource: (7).

^bPrice data sources: major products—gasoline, jet fuel, kerosene, fuel oils—(9); minor products—LPG, petrochemical feedstocks, napthas, lubricants, wax, coke, asphalt & road oil, still gas—(10); Prices listed (\$/MMBTU) were multiplied by thermal conversion factors from Energy Information Administration/Annual Energy Review, 2000. Minor product prices for year 2000 were estimated as follows: product price = [14 year average(product price/crude price)]*year 2000 crude price.

Table B.2. Yield, price, and product value data for U.S. corn wet milling industry from 1992-2001.

Year	1992				
	Yield ^a (lb/lb feed)	Price ^b (\$/lb)	Value All Products (\$/lb feed)	EtOH Only ^c Value (\$/lb feed)	HFCS Only ^d Value (\$/lb feed)
Ethanol	0.07	0.20	0.0135	0.0594	0.0000
HFCS	0.22	0.17	0.0372	0.0000	0.1007
Glucose and Dextrose	0.11	0.25	0.0276	0.0000	0.0000
Starch	0.12	0.11	0.0129	0.0000	0.0000
Carbon Dioxide	0.06	-	0.0000	0.0000	0.0000
Corn Oil	0.03	0.24	0.0068	0.0081	0.0081
Gluten Meal	0.04	0.13	0.0058	0.0058	0.0058
Gluten Feed	0.24	0.05	0.0124	0.0122	0.0122
TOTAL VALUE			0.1162	0.0855	0.1268
CORN PRICE ^e			0.0370	0.0370	0.0370
EXTERNAL ENERGY ^f			0.0062	0.0089	0.0054
RELATIVE MARGIN			1.69	0.87	1.99

Year	1993				
	Yield ^a (lb/lb feed)	Price ^b (\$/lb)	Value All Products (\$/lb feed)	EtOH Only ^c Value (\$/lb feed)	HFCS Only ^d Value (\$/lb feed)
Ethanol	0.0675	0.1760	0.0119	0.0518	0.0000
HFCS	0.2208	0.1572	0.0347	0.0000	0.0926
Glucose and Dextrose	0.1114	0.2450	0.0273	0.0000	0.0000
Starch	0.1164	0.1175	0.0137	0.0000	0.0000
Carbon Dioxide	0.0645	-	0.0000	0.0000	0.0000
Corn Oil	0.0286	0.2152	0.0061	0.0073	0.0073
Gluten Meal	0.0446	0.1483	0.0066	0.0067	0.0067
Gluten Feed	0.2411	0.0440	0.0106	0.0104	0.0104
TOTAL VALUE			0.1109	0.0762	0.1171
CORN PRICE ^e			0.0446	0.0446	0.0446
EXTERNAL ENERGY ^f			0.0062	0.0089	0.0054
RELATIVE MARGIN			1.18	0.42	1.34

Year	1994				
Product	Yield ^a (lb/lb feed)	Price ^b (\$/lb)	Value All Products (\$/lb feed)	EtOH Only ^c Value (\$/lb feed)	HFCS Only ^d Value (\$/lb feed)
Ethanol	0.0752	0.1806	0.0136	0.0531	0.0000
HFCS	0.2212	0.1877	0.0415	0.0000	0.1106
Glucose and Dextrose	0.1099	0.2589	0.0285	0.0000	0.0000
Starch	0.1026	0.1250	0.0128	0.0000	0.0000
Carbon Dioxide	0.0719		0.0000	0.0000	0.0000
Corn Oil	0.0286	0.2722	0.0078	0.0093	0.0093
Gluten Meal	0.0446	0.1313	0.0059	0.0059	0.0059
Gluten Feed	0.2411	0.0448	0.0108	0.0106	0.0106
TOTAL VALUE			0.1208	0.0789	0.1364
CORN PRICE ^e			0.0404	0.0404	0.0404
EXTERNAL ENERGY ^f			0.0062	0.0089	0.0054
RELATIVE MARGIN			1.59	0.60	1.98

Year	1995				
Product	Yield ^a (lb/lb feed)	Price ^b (\$/lb)	Value All Products (\$/lb feed)	EtOH Only ^c Value (\$/lb feed)	HFCS Only ^d Value (\$/lb feed)
Ethanol	0.0639	0.1745	0.0112	0.0513	0.0000
HFCS	0.2370	0.1563	0.0370	0.0000	0.0921
Glucose and Dextrose	0.1165	0.2550	0.0297	0.0000	0.0000
Starch	0.1028	0.1410	0.0145	0.0000	0.0000
Carbon Dioxide	0.0612	-	0.0000	0.0000	0.0000
Corn Oil	0.0286	0.2667	0.0076	0.0091	0.0091
Gluten Meal	0.0446	0.1220	0.0054	0.0055	0.0055
Gluten Feed	0.2411	0.0442	0.0106	0.0105	0.0105
TOTAL VALUE			0.1161	0.0764	0.1171
CORN PRICE ^e			0.0579	0.0579	0.0579
EXTERNAL ENERGY ^f			0.0062	0.0089	0.0054
RELATIVE MARGIN			0.81	0.14	0.85

Year	1996				
Product	Yield ^a (lb/lb feed)	Price ^b (\$/lb)	Value All Products (\$/lb feed)	EtOH Only ^c Value (\$/lb feed)	HFCS Only ^d Value (\$/lb feed)
Ethanol	0.0653	0.2049	0.0134	0.0603	0.0000
HFCS	0.2360	0.1446	0.0341	0.0000	0.0852
Glucose and Dextrose	0.1152	0.2550	0.0294	0.0000	0.0000
Starch	0.1024	0.1605	0.0164	0.0000	0.0000
Carbon Dioxide	0.0625		0.0000	0.0000	0.0000
Corn Oil	0.0286	0.2452	0.0070	0.0083	0.0083
Gluten Meal	0.0446	0.1662	0.0074	0.0075	0.0075
Gluten Feed	0.2411	0.0581	0.0140	0.0138	0.0138
TOTAL VALUE			0.1217	0.0899	0.1148
CORN PRICE ^e			0.0484	0.0484	0.0484
EXTERNAL ENERGY ^f			0.0062	0.0089	0.0054
RELATIVE MARGIN			1.23	0.57	1.13

Year	1997				
Product	Yield ^a (lb/lb feed)	Price ^b (\$/lb)	Value All Products (\$/lb feed)	EtOH Only ^c Value (\$/lb feed)	HFCS Only ^d Value (\$/lb feed)
Ethanol	0.0697	0.1745	0.0122	0.0513	0.0000
HFCS	0.2334	0.1070	0.0250	0.0000	0.0631
Glucose and Dextrose	0.1042	0.2550	0.0266	0.0000	0.0000
Starch	0.1069	0.1370	0.0146	0.0000	0.0000
Carbon Dioxide	0.0667	-	0.0000	0.0000	0.0000
Corn Oil	0.0286	0.2487	0.0071	0.0085	0.0085
Gluten Meal	0.0446	0.1726	0.0077	0.0078	0.0078
Gluten Feed	0.2411	0.0420	0.0101	0.0100	0.0100
TOTAL VALUE			0.1033	0.0775	0.0892
CORN PRICE ^e			0.0434	0.0434	0.0434
EXTERNAL ENERGY ^f			0.0062	0.0089	0.0054
RELATIVE MARGIN			1.08	0.48	0.83

Year	1998				
Product	Yield ^a (lb/lb feed)	Price ^b (\$/lb)	Value All Products (\$/lb feed)	EtOH Only ^c Value (\$/lb feed)	HFCS Only ^d Value (\$/lb feed)
Ethanol	0.0730	0.1593	0.0116	0.0469	0.0000
HFCS	0.2377	0.1058	0.0251	0.0000	0.0623
Glucose and Dextrose	0.0980	0.2979	0.0292	0.0000	0.0000
Starch	0.1025	0.1220	0.0125	0.0000	0.0000
Carbon Dioxide	0.0698	-	0.0000	0.0000	0.0000
Corn Oil	0.0286	0.2990	0.0085	0.0102	0.0102
Gluten Meal	0.0446	0.1303	0.0058	0.0059	0.0059
Gluten Feed	0.2411	0.0324	0.0078	0.0077	0.0077
TOTAL VALUE			0.1007	0.0706	0.0861
CORN PRICE ^e			0.0346	0.0346	0.0346
EXTERNAL ENERGY ^f			0.0062	0.0089	0.0054
RELATIVE MARGIN			1.46	0.62	1.15

Year	1999				
Product	Yield ^a (lb/lb feed)	Price ^b (\$/lb)	Value All Products (\$/lb feed)	EtOH Only ^c Value (\$/lb feed)	HFCS Only ^d Value (\$/lb feed)
Ethanol	0.0752	0.1487	0.0112	0.0438	0.0000
HFCS	0.2338	0.1171	0.0274	0.0000	0.0690
Glucose and Dextrose	0.0961	0.1917	0.0184	0.0000	0.0000
Starch	0.1037	0.1120	0.0116	0.0000	0.0000
Carbon Dioxide	0.0720	-	0.0000	0.0000	0.0000
Corn Oil	0.0286	0.2359	0.0067	0.0080	0.0080
Gluten Meal	0.0446	0.1159	0.0052	0.0052	0.0052
Gluten Feed	0.2411	0.0294	0.0071	0.0070	0.0070
TOTAL VALUE			0.0876	0.0640	0.0892
CORN PRICE ^e			0.0325	0.0325	0.0325
EXTERNAL ENERGY ^f			0.0062	0.0089	0.0054
RELATIVE MARGIN			1.26	0.55	1.35

Year	2000					
	Product	Yield ^a (lb/lb feed)	Price ^b (\$/lb)	Value All Products (\$/lb feed)	EtOH Only ^c Value (\$/lb feed)	HFCS Only ^d Value (\$/lb feed)
	Ethanol	0.0784	0.2049	0.0161	0.0603	0.0000
	HFCS	0.2319	0.1132	0.0263	0.0000	0.0667
	Glucose and Dextrose	0.0928	0.1575	0.0146	0.0000	0.0000
	Starch	0.1026	0.1239	0.0127	0.0000	0.0000
	Carbon Dioxide	0.0750	-	0.0000	0.0000	0.0000
	Corn Oil	0.0286	0.1466	0.0042	0.0050	0.0050
	Gluten Meal	0.0446	0.1188	0.0053	0.0053	0.0053
	Gluten Feed	0.2411	0.0259	0.0062	0.0061	0.0061
	TOTAL VALUE			0.0854	0.0767	0.0832
	CORN PRICE ^e			0.0330	0.0330	0.0330
	EXTERNAL ENERGY ^f			0.0062	0.0089	0.0054
	RELATIVE MARGIN			1.17	0.83	1.16

Year	2001					
	Product	Yield ^a (lb/lb feed)	Price ^b (\$/lb)	Value All Products (\$/lb feed)	EtOH Only ^c Value (\$/lb feed)	HFCS Only ^d Value (\$/lb feed)
	Ethanol	0.0784	0.2246	0.0176	0.0661	0.0000
	HFCS	0.2319	0.1190	0.0276	0.0000	0.0701
	Glucose and Dextrose	0.0928	0.1613	0.0150	0.0000	0.0000
	Starch	0.1026	0.1269	0.0130	0.0000	0.0000
	Carbon Dioxide	0.0750	-	0.0000	0.0000	0.0000
	Corn Oil	0.0286	0.1668	0.0048	0.0057	0.0057
	Gluten Meal	0.0446	0.1295	0.0058	0.0058	0.0058
	Gluten Feed	0.2411	0.0323	0.0078	0.0077	0.0077
	TOTAL VALUE			0.0915	0.0852	0.0893
	CORN PRICE ^e			0.0339	0.0339	0.0339
	EXTERNAL ENERGY ^f			0.0062	0.0089	0.0054
	RELATIVE MARGIN			1.27	0.99	1.27

^aCalculated using lb/bushel yields from (5) and carbohydrate allocation values from (8). Assumes 50% of ethanol produced from wet mills, 50% from dry mills. CO₂ yield calculated using stoichiometric etoh: CO₂ mass ratio. □

^bSources: HFCS: (12), U.S. spot price for HFCS-42, Midwest markets, dry basis; dextrose: dextrose (12), 400-600 sack cars, dry basis; starch: 1992-1999 (46), per hundredweight commercial, 12% moisture; 2000-2001 (13); ethanol (14), average rack prices; corn oil (15); gluten meal (13); gluten feed (13). □

^cAssumes ethanol yield of 0.29 lb/lb feed; source: (5). □

^dAssumes HFCS yield of 0.59 lb/lb feed; source: (5). □

^eSource: (13). □

^fSource: Ethanol (47); HFCS: (48). Weighted average energy input used when calculating margin for case of all products. □

Table B.3. Yield, price, and product value data for U.S. corn dry milling industry from 1992-2001.

Year	1992		1993		1994	
Product	Price ^b (\$/lb)	Value (\$/lb feed)	Price ^b (\$/lb)	Value (\$/lb feed)	Price ^b (\$/lb)	Value (\$/lb feed)
Ethanol ^a	0.2018	0.0641	0.1760	0.0559	0.1806	0.0574
Distillers Dried Grains ^a	0.0615	0.0195	0.0620	0.0197	0.0535	0.0170
Carbon Dioxide ^a	-	0.0000	-	0.0000	-	0.0000
TOTAL VALUE		0.0837		0.0756		0.0744
CORN PRICE ^c		0.0370		0.0446		0.0404
EXTERNAL ENERGY ^d		0.0078		0.0078		0.0078
RELATIVE MARGIN		0.87		0.44		0.54

Year	1995		1996		1997	
Product	Price ^b (\$/lb)	Value (\$/lb feed)	Price ^b (\$/lb)	Value (\$/lb feed)	Price ^b (\$/lb)	Value (\$/lb feed)
Ethanol ^a	0.1745	0.0554	0.2049	0.0651	0.1745	0.0554
Distillers Dried Grains ^a	0.0755	0.0240	0.0715	0.0227	0.0550	0.0175
Carbon Dioxide ^a	-	0.0000	-	0.0000	-	0.0000
TOTAL VALUE		0.0794		0.0878		0.0729
CORN PRICE ^c		0.0579		0.0484		0.0434
EXTERNAL ENERGY ^d		0.0078		0.0078		0.0078
RELATIVE MARGIN		0.21		0.56		0.42

Year	1998		1999		2000	
Product	Price ^b (\$/lb)	Value (\$/lb feed)	Price ^b (\$/lb)	Value (\$/lb feed)	Price ^b (\$/lb)	Value (\$/lb feed)
Ethanol ^a	0.1593	0.0506	0.1487	0.0473	0.2049	0.0651
Distillers Dried Grains ^a	0.0425	0.0135	0.0415	0.0132	0.0365	0.0116
Carbon Dioxide ^a	-	0.0000	-	0.0000	-	0.0000
TOTAL VALUE		0.0641		0.0604		0.0767
CORN PRICE ^c		0.0346		0.0325		0.0330
EXTERNAL ENERGY ^d		0.0078		0.0078		0.0078
RELATIVE MARGIN		0.51		0.50		0.88

Product	Year	2001	
		Price ^b (\$/lb)	Value (\$/lb feed)
Ethanol ^a		0.2246	0.0714
Distillers Dried Grains ^a		0.0450	0.0143
Carbon Dioxide ^a		-	0.0000
TOTAL VALUE			0.0857
CORN PRICE ^c			0.0339
EXTERNAL ENERGY ^d			0.0078
RELATIVE MARGIN			1.05

^aEthanol yield: 0.32 lb/lb feed; DDG yield: 0.30 lb/lb feed; Source: (23). CO₂ yield calculated using stoichiometric □
etoh: CO₂ mass ratio. □

^bSource: Ethanol (14); DDG (13). □

^cSource: (13). □

^dSource: (47). □

REPORT DOCUMENTATION PAGE

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