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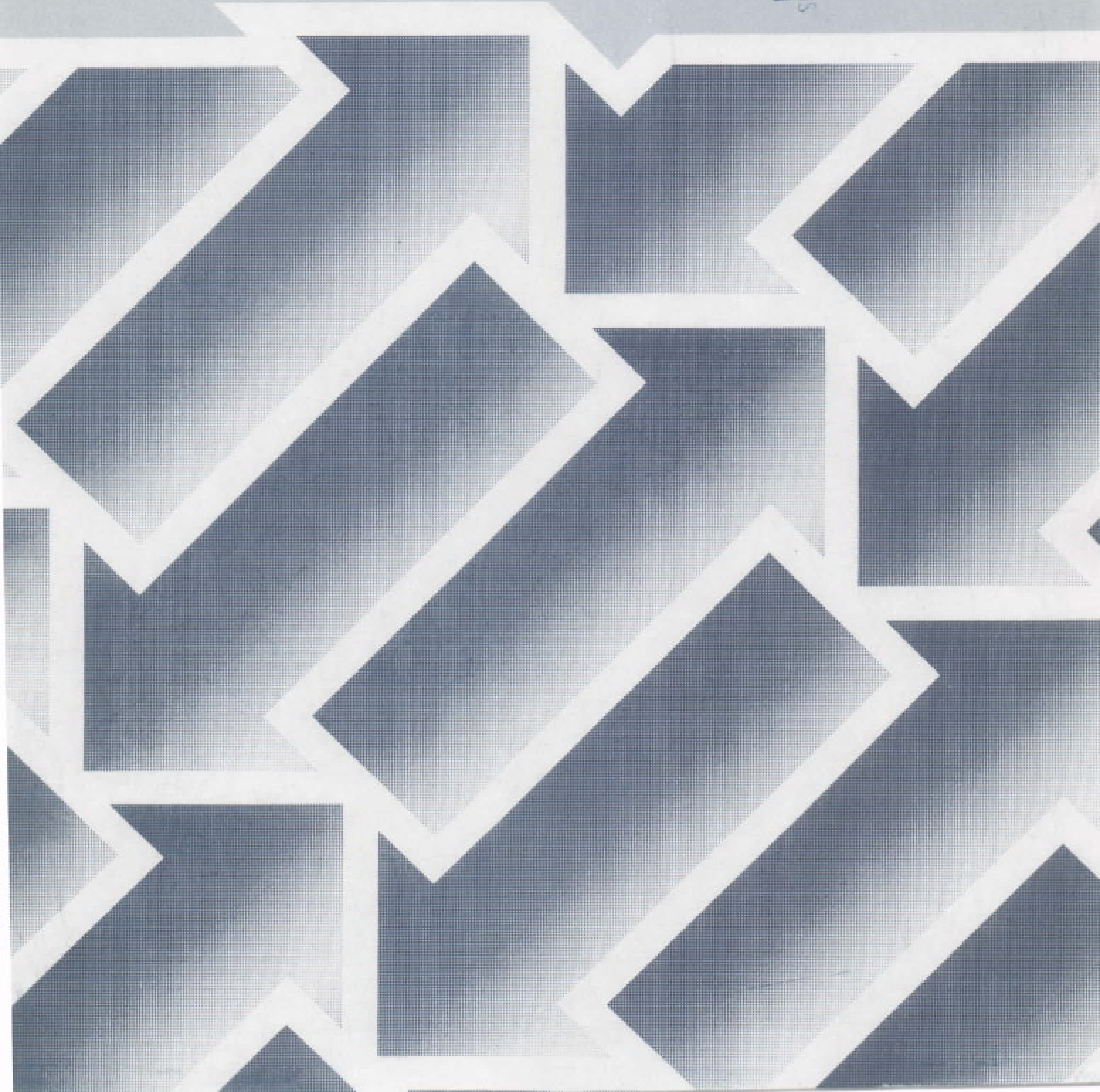
Economics of Ethanol Production in the United States

Sally M. Kane and John M. Reilly



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ABSTRACT

Expansion of the U.S. ethanol industry hinges largely on extension of the Federal fuel excise tax exemption and corn prices. For ethanol to be competitive in the 1990's without the Federal subsidy, crude oil prices would have to increase substantially. This report examines production costs and the relative competitiveness of the ethanol industry. The report evaluates structural characteristics of the industry, including economies of scale and the relative economics of the two primary manufacturers, wet- and dry-mill plants.

Keywords: Ethanol, liquid fuel, production costs, production technology, future technology.

NOTE

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SUMMARY

Technological improvements could reduce ethanol production costs in the future. But, expansion of the U.S. ethanol industry hinges largely on corn prices and extension of the Federal fuel excise tax exemption, scheduled to expire in 1993.

With $2-per-bushel corn and the existing Federal subsidy, ethanol produced under average existing technology is competitive with crude oil at about $24 per barrel. State-of-the-art technology, an improvement over average existing technology, makes ethanol competitive with petroleum at $20 per barrel. Additional technological improvements within the next few years could make ethanol competitive at $18 per barrel of crude oil. For ethanol to be competitive in the 1990's without the Federal subsidy, even with state-of-the-art technology, crude oil prices would have to increase to $40 per barrel.

This report examines production costs and future technological improvements in the ethanol industry. The report evaluates structural characteristics of the industry, including economies of scale and the relative economics of the two primary methods of production, wet- and dry-mill plants.

A plant (40 million gallons per year capacity for dry milling or 90-100 million gallons for wet milling) containing the best designed production components could achieve an estimated 19-percent reduction in operating costs compared with average existing plants, reducing costs from 47 cents per gallon of ethanol (net of the cost of corn) to 38 cents per gallon.

The greatest absolute savings, at 6 cents per gallon, result from reductions in energy costs. The net cost of corn, which is the cost of corn minus the value of byproducts produced, is the most important variable cost factor. The swing in corn prices between 1987 and 1988 exemplified the variability in net corn costs. Record stock levels at the end of 1986 and a good harvest in 1987 decreased corn prices to well below $2 per bushel. The 1988 drought and declining stock levels, however, raised corn prices above $3 per bushel by the third quarter of 1988. Since 1980, the net cost of corn has ranged from under 10 cents to over 70 cents per gallon of ethanol produced.

Future capital costs will likely range from 19 cents per gallon to nearly 50 cents per gallon depending on the ability of future plants to adapt existing industrial infrastructure for ethanol production. The full cost of production from a stand-alone plant has ranged from as low as 85 cents per gallon, with the unusually high byproduct prices of early 1987, to as high as $1.40-$1.50 per gallon during 1981, 1983, and 1984. An ethanol plant added to an existing wet mill could achieve costs that are 20 cents per gallon lower due to capital cost savings.

Economics of Ethanol Production in the United States

Sally M. Kane
John M. Reilly

INTRODUCTION

Attention has refocused on alcohol fuels for several reasons in the 1980's. U.S. petroleum imports were growing and approaching levels of the early 1970's, raising concerns about U.S. vulnerability to foreign energy supply disruptions. As corn stocks reached record levels by the mid-1980's, prices fell to well below $2 per bushel, their lowest level in more than a decade. Several bills were introduced in Congress to encourage ethanol production with the intent of increasing the demand for corn and stabilizing prices while reducing dependence on foreign oil. The drought of 1988 and falling corn stocks, however, combined to push corn prices back above $3 per bushel, emphasizing the variability of the corn cost component of ethanol production.

Ethanol can be added to gasoline to boost the oxygen content. Environmental benefits of oxygenated (containing oxygen) fuels, such as an ethanol/gasoline blend, include reducing carbon monoxide emissions from automobiles. These benefits have led several States to develop oxygenated fuel programs. The first mandated program was instituted in the Denver, CO, metropolitan area and surrounding counties in the Front Range. The program, in effect during January and February 1988, led to an 8- to 10-percent reduction in ambient carbon monoxide levels. Mandated oxygenated fuels programs have recently been established for Phoenix, AZ, and Albuquerque, NM, and are expected to go into effect in October 1989. The programs form a component of regional air quality plans designed to bring ambient carbon monoxide levels below the standards established by the Clean Air Act.

This paper presents information on the production costs and competitiveness of the U.S. fuel ethanol industry. As background, we present an economic history of the industry and the role of the Federal Government in supporting plant construction. We evaluate structural characteristics of the industry, including economies of scale and the relative economics of wet- and dry-mill plants, and review cost savings associated with future technologies. This report provides more detailed analysis of data that formed the basis of (13).1/

1/ Underlined numbers in parentheses cite sources listed in the References section.

The U.S. ethanol industry was created 10 years ago from a mix of Federal and State subsidies, loan programs, and other incentives. The industry continues to depend on Federal and State subsidies. Ethanol production had increased from 20 million gallons in 1979 to about 850 million gallons by the end of 1987, with over 50 ethanol production-related facilities operating. Current production, however, is less than 1 percent of all petroleum products used in transportation.

The relatively smooth growth at the industry level masks considerable turmoil. The industry has been unable to achieve consistent profitability because of changing economic conditions and technological problems. Eighty-eight plants have shut down, with a quarter unlikely to reopen (8). Most of the small plants that received Federal loan guarantees have closed, reorganized under bankruptcy proceedings, or defaulted on loans. Profitability dropped significantly in 1986 due to the collapse of oil prices but rebounded in 1987 when crude oil prices increased, corn prices fell, and byproduct prices rose.

At the same time that political support for ethanol was growing, Federal tax incentives for the ethanol industry came under scrutiny as one way to reduce the Federal budget. There is growing debate over continuation of the 6-cent-per-gallon gasoline excise tax exemption. The exemption, scheduled to expire in 1993, was created during a period of relatively high crude oil prices and was designed to encourage production of nonpetroleum fuels. Continuing debate over the appropriate Federal role in ethanol production has created a climate of uncertainty for potential investors in the industry.

THE PROCESS TECHNOLOGY

The two main processing methods for ethanol production are dry and wet milling. In the dry-mill process, ground corn is slurried with water and cooked. Enzymes are added to convert starch to sugar, then yeast is added to ferment sugars, producing a mixture containing alcohol, water, and solids (suspended and dissolved). The alcohol/water mixture is then distilled and dehydrated to create fuel-grade ethanol. The solids remaining after distillation are dried to produce a byproduct and are sold as an animal feed supplement. Distillation reduces the water content to approximately 5 percent, and dehydration removes the remaining water.

The wet-mill process removes solids before converting starches to sugar and produces a greater variety of byproducts, a few of which have high market values. Early removal of solids yields a purer sugar-and-water mixture for fermentation. The ethanol wet-mill process is identical to the fructose-producing process through the starch-production phase. Combining ethanol and fructose production in a wet-mill plant has proven financially advantageous.

Fuel ethanol is produced using a well-established technology. The basic process of making alcohol using yeast to ferment the starch and sugars in fruits and grains has been the basis for beverage production for centuries. However, today's ethanol fuel production industry is barely 10 years old.

Production of fuel ethanol requires that close attention be paid to efficiency of operation compared with that of beverage ethanol. The initial challenge faced by fuel ethanol producers was to build facilities that were much larger than traditional ethanol facilities and operate them at much lower costs.

Ethanol producers have used well-known technologies from related industries to reduce ethanol production costs. For example, computer control over the entire process and continuous fermentation have been profitably adapted to ethanol production. Improving cogeneration (providing steam and electricity for a plant from a single boiler) and developing electric motors that cycle to fit the power load are processing refinements common to many industries. Ethanol producers have also found significant economic potential in a variety of plant outputs, including carbon dioxide, stillage, and waste heat. New techniques were developed for upgrading waste products to marketable commodities, increasing the value of traditionally marketed byproducts, and for recovering waste heat for plant use.

PRODUCTION COST DATA

Production costs are categorized as net feedstock costs (grain costs minus the value of byproducts), cash operating costs, and capital costs. Net feedstock costs were derived from published prices of corn and byproducts given unit corn requirements and byproduct output. Producers supplied data on cash operating costs through a third party to maintain confidentiality. Capital costs were developed from discussions with industry officials and from confidentially supplied cost data on specific engineering plans. We verified data through plant visits and followup conversations where necessary.

Eleven firms provided cash operating costs for their plants.2/ The data, as complete and comparable as possible given the diversity of plants, covered the bulk of production capacity. Operating cost data were supplied by the top six producers in the industry, who accounted for 77 percent of operating capacity in 1986. These plants had an annual production capacity of 30 million gallons or more. Data were also supplied by two midsized plants with annual capacities of 10-30 million gallons and three small (less than 10 million gallons per year) commercial producers.

Although the information represents the most current and complete accounting of industry production costs available, data limitations exist. To protect the anonymity of individual firms, detailed information is not supplied on individual pieces of equipment, such as those used for generating electricity as a byproduct, and on processes used, such as byproduct drying. Therefore, we cannot identify specific conditions that led to particularly low or high component costs.

The variety of existing plants complicates the task of conclusively attributing cost differences to such factors as scale, milling technology, feedstock, and fuel used. Extensive discussions with plant managers, separate from the formally supplied information, enabled us to assess cost savings associated with significant plant improvements.

Net Corn Costs

The net corn cost is the cost of corn per gallon of ethanol after the prices received for byproducts have been subtracted. The net corn cost was the most

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2/ Cost estimates were developed by W. Robert Schwandt, former Vice President of A.E. Staley's Ethanol Division.

important variable cost factor, ranging from nearly 79 cents per gallon of ethanol produced to less than 10 cents for a short period during early 1987 (table 1). Since 1980, corn prices have varied from $1.59 to $3.16 per bushel, having fallen for the most part until 1988. Byproduct values also varied but not nearly as much as corn prices. Byproduct prices have risen and corn prices have declined in recent years.

Cash Operating Costs

Cash operating costs of production (excluding feedstock costs) were less variable than the net cost of corn and were substantially lower than when the industry began. We obtained information on cash operating costs for energy, ingredients (enzymes, chemicals, yeasts, and miscellaneous material costs), personnel and maintenance, management and administration, and insurance and taxes. Among the large plants, total cash operating expenses were about 40-59 cents per gallon, compared with small and midsized plants with total cash operating expenses of 32-66 cents per gallon.

Energy costs for the large plants tended to be the largest cost component, averaging 11-24 cents per gallon, which was 36 percent of cash operating costs (table 2). Energy costs depend on whether the plant uses coal, gas, or oil, and whether it purchases or cogenerates its own electricity. Cogeneration using coal was the cheapest energy source. Where inexpensive high-sulfur coal was available, fluidized bed combustors were economical, allowing the plant to meet air quality standards while using cheaper coal.

The ingredients and personnel and maintenance categories were the next largest cash operating cost components, averaging 22 and 29 percent of cash operating costs. The other categories, management, administration, insurance, and taxes, averaged 9 and 5 percent of cash operating costs.

Much of the variability in cash operating costs is caused by the energy cost component. Even though local fuel prices and other conditions vary, a new plant should be able to operate with energy costs of 11-15 cents per gallon. The plant with the highest total cash operating costs had reasonably low energy costs but the highest personnel/maintenance and management/administration costs. Three plants had reasonably low costs in all categories.

Cash operating costs for the small and midsized plants varied more than for the larger plants (table 3). Cash operating costs for small and midsized plants, except one, tended to be 5-10 cents per gallon higher than for large plants. Both energy and personnel costs tended to be higher. Small plants were less able to take advantage of coal boiler cogeneration and economies of scale. Small producers indicated that plant capacity could probably be increased by 50 percent without adding personnel.

The management, administration, insurance, and tax cost category was 3-4 cents lower for the small plants. Some of these differences may be attributable to differences in accounting for management and general personnel, with the small and midsized plants allocating less of the payroll to management overhead.

One plant reported exceptionally low energy costs, achieving the lowest cash operating costs among all surveyed plants. The low energy costs can be attributed to feeding undried distillers' grains directly to cattle, an example of the cost competitiveness of small plants in special situations.

Table 1--Net corn costs of wet and dry milling

Year	Corn cost	Wet milling 1/			Dry milling 2/		
		Byproduct value as share of corn cost	Net corn cost		Byproduct value as share of corn cost	Net corn cost	
	Dollars/ bushel	Percent	Dollars/ bushel	Dollars/ gallon	Percent	Dollars/ bushel	Dollars/ gallon
1981	3.16	44.9	1.74	0.70	41.0	1.86	0.72
1982	2.48	55.8	1.10	.44	51.5	1.20	.46
1983	3.12	48.2	1.62	.65	44.6	1.73	.67
1984	3.11	44.0	1.74	.70	34.0	2.05	.79
1985	2.52	45.4	1.37	.55	33.8	1.67	.64
1986	1.95	59.3	.79	.32	54.7	.88	.34
1987	1.59	80.0	.32	.13	69.6	.48	.19
1988	2.36	64.5	.84	.34	58.2	.99	.38
1989 3/	2.62	56.3	1.14	.46	54.6	1.19	.46

1/ CO_2 recovery not included; ethanol yield is 2.5 gallons/bushel. 2/ Dry-mill byproducts are evaluated at 125 percent of value of corn gluten feed, and yield is assumed to be 18 pounds/bushel; ethanol yield is 2.6 gallons/bushel.
3/ January only.

Table 2--Operating costs, excluding net corn costs in 1987 for large plants

Cost item	Surveyed plant						
	1	2	3	4	5	6	Average
	Dollars per gallon of anhydrous ethanol						
Energy	0.115	0.159	0.136	0.239	0.160	0.209	0.169
Ingredients	.060	.111	.135	.070	.090	.147	.102
Personnel and maintenance	.140	.228	.097	.135	.140	.079	.137
Management, administration, insurance, and taxes	.082	.088	.043	.070	.065	.036	.064
Total cash operating cost	.397	.586	.411	.514	.455	.471	.472

Investment Cost per Annual Gallon of Installed Capacity

Reported levels of investment per gallon of installed capacity for existing facilities have ranged from below $1 to near $3. This range is misleading, however, because of the differences in construction and accounting among firms. Some firms originally overdesigned plant components but boosted production above original rated capacity with minimal additional investment. Other firms achieved low initial investment but had to increase investment levels after plant startup to meet planned capacity levels and improve plant efficiency.

Significant variations in investment costs depended on whether ethanol production was added to an existing wet mill, an idle industrial plant was converted to ethanol production, or a totally new facility was constructed. The Staley and Archer Daniels Midland companies successfully added ethanol capacity to operating wet mills. Pekin Energy modified an idle corn wet-mill plant, South Point Ethanol converted an idle chemical plant to ethanol production, and Shepherd Oil retooled an idle oil refinery. Few of the most successful existing plants were built as totally new facilities.

Construction of a new dry mill with an annual capacity of 40 million gallons, or a wet mill with an annual capacity of 100 million gallons, will cost $2-$2.50 per gallon of installed annual capacity (table 4). Fermenter/distiller additions to existing wet-mill sites cost about $1-$1.50 per gallon of installed annual capacity. The $1-$1.50 range represented the full additional capital cost of ethanol production for an operating corn-fructose production plant with cyclical excess capacity to grind corn and with little requirement to boost grind capacity to produce ethanol and corn sweetener products efficiently. The best of the idle industrial sites will require an acquisition and upgrade investment of about $1.75 per installed gallon.

Table 3--Operating costs excluding net corn costs in 1987 for small and midsized plants

Cost item	Surveyed plant and size: Small 1	Small 2	Medium 3	Medium 4	Medium 5	Average
	Dollars per gallon of anhydrous ethanol					
Energy	0.217	0.053	0.190	0.251	0.215	0.185
Ingredients	.091	.073	.065	.126	.059	.083
Personnel and maintenance	.160	.160	.180	.233	.197	.186
Management, administration, insurance, and taxes	.040	.035	.050	.048	.080	.051
Total cash operating cost	.508	.321	.485	.658	.551	.505

Capital Charges per Gallon Produced

Estimating ethanol production costs requires that capital charges be allocated to production across the lifetime of the producing investment. The capital charges depend on the cost, investment life, and the tax treatment of investment, interest rate on debt financing, desired return on equity, and the inflation rate.

The capital charges for added capacity ranged from 19 to 48 cents per gallon, based on tax rates established under the Tax Reform Act of 1986 (once the energy investment tax credit has been fully phased out) (table 4). The 19-cent investment charge per gallon corresponded to the lowest cost incremental capacity addition to existing wet mills and the 48-cent investment charge per gallon corresponded to a completely new plant. Previous tax laws treated investment much more favorably, with shorter tax lives, a 10-percent investment tax credit, and the energy tax credit. We estimated the capital charge per gallon of ethanol production per dollar of investment at 19 cents, compared with 16 cents under previous tax laws (table 4).

Total Production Costs

Total production costs vary considerably because of variability in net corn costs (fig. 1). We plotted approximate average industry costs for 1980-87. The calculations assume that corn and byproduct price variation is the only source of variability over time. The full cost of production from an efficient stand-alone plant has ranged from as low as 85 cents per gallon with the unusually high byproduct prices and low corn prices of early 1987 to the $1.40-$1.50 range

Table 4--Investment costs and capital charges on capacity addition

Capacity addition	Investment cost per annual gallon	Capital charge per gallon produced 1/
	Dollars	
Incremental addition to operating wet mill	1.00 - 1.50	0.19 - .29
Adaption of abandoned oil refinery distillation capacity or wet-mill capacity	1.75 - 2.00	.33 - .38
New plant	2.00 - 2.50	.38 - .48

1/ Capital charge of 19 cents per dollar invested computed as a capital rental rate based on the following assumptions: (1) Tax Reform Act of 1986 (8-year tax life for equipment, no investment tax credit or energy investment tax credit, 38-percent income tax rate); (2) Nominal, pretax equity return of 15 percent; (3) nominal interest on loan of 8.5 percent; (4) debt/equity equal to 78/22; (5) annual inflation rate of 4 percent; and (6) an actual asset life of 30 years.

during 1981, 1983, and 1984. An ethanol plant addition to an existing wet mill could achieve costs of as much as 20 cents per gallon lower due to capital cost savings.

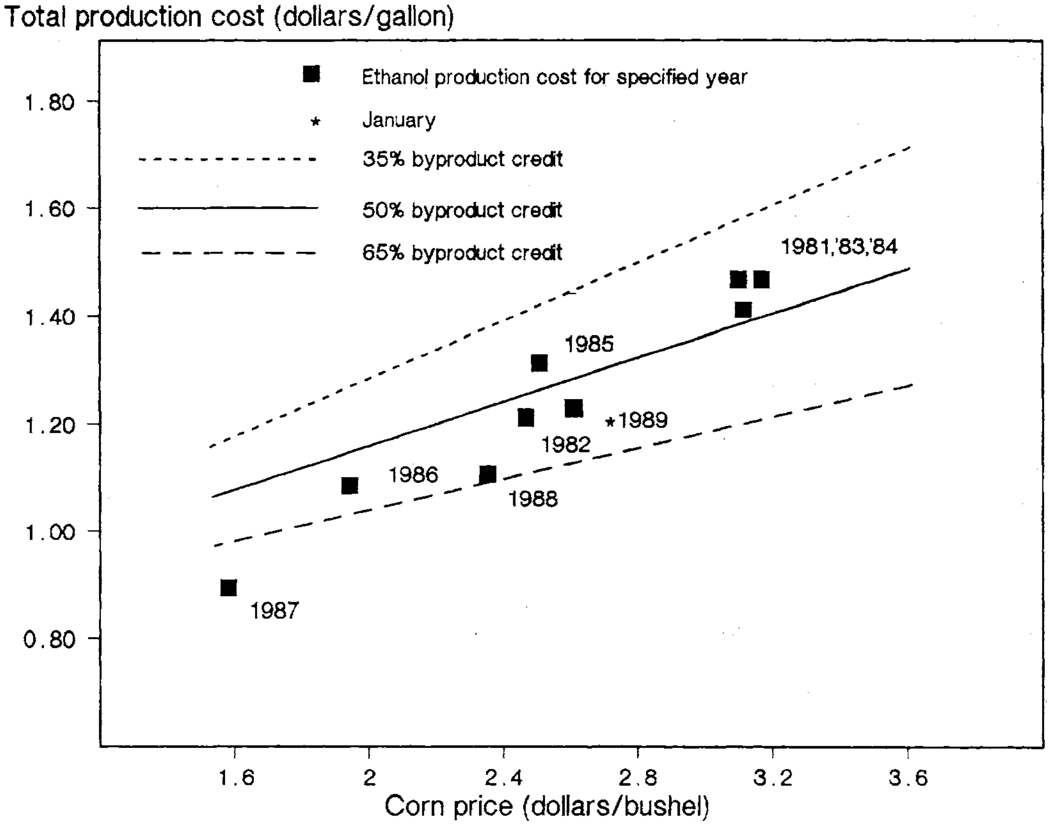
PRODUCTION COSTS: ADDITIONAL CONSIDERATIONS

Three additional production cost issues have implications for public policy. These are: economies of scale, the economics of wet- versus dry-mill technology, and the effects of Federal Government loan guarantee programs. Our survey design did not allow us to address directly and completely these questions due to requirements of confidentiality. Even detailed data would not support conclusions definitively attributing cost differences to milling technology or plant size, with only a handful of large plants divided between wet and dry mills.

Economies of Scale

The ethanol industry is unusually heterogeneous, with plants that vary by size, type of technology, source of financing, traditional grain-processing experience, and diversification. Just four plants accounted for nearly 50 percent of operating capacity in 1986. The eight largest plants, owned by the five largest ethanol-producing firms, constituted nearly 75 percent of operating capacity. Only 17 of approximately 50 ethanol plants had a capacity of at least 10 million gallons per year.

Figure 1--Total production costs: corn prices and byproduct credits



Our data indicated that operating costs may average 5-10 cents higher for small and midsized plants than for large plants. Although investment costs were generally similar among large and small plants per gallon of installed capacity, engineering designs have shown economies of scale in investment costs (9). Engineering design cost comparisons were typically made for comparable plant designs. Rather than suffer higher capital costs, many smaller plants may have reduced initial investment costs per gallon of installed capacity to levels comparable with large plants by altering plant design. Savings in initial investment, however, translated into higher operating costs because of lower energy efficiency, less computer control, lower yields, and higher labor requirements.

While investment costs appear similar among large and small plants, annualized capital charges, taking into account lower operating levels, were considerably higher for small plants. Capital charges increase 13 cents if the expected operation level drops from 100 percent to 75 percent of rated capacity, with an investment of $2 per gallon of capacity and under the assumptions in table 4. Given the poor operating performance of small plants, an assumption that they could operate at 75 percent of rated capacity over the lifetime of the plant may be optimistic.

Large plants consistently produced at or above rated capacity. Many midsized and small plants have not operated continuously because of difficulty in finding markets for ethanol or byproducts, difficulty in maintenance and repairs, and problems of fermenter contamination. A few had consistent operating records, but many have failed completely or have been shut down for extended periods of time. Even if the initial investment costs were equal among large and small plants, poorer operating performance of smaller plants can lead to higher capital charges per gallon.

Together, higher annualized capital charges and operating costs indicate that, on average, small plants produce ethanol at 18-23 cents per gallon over the costs achieved by large plants. The estimated average cost, however, conceals considerable variability. As a result, actual operating experience shows a wide range of overlap between small and large plants.

The overlap can be traced, in part, to three limited circumstances that provided cost advantages to some small producers, offsetting basic economies of scale in production. First, although the largest firms had complex grain procurement and product distribution systems enabling them to compete effectively in national and international markets, some small firms took advantage of limited, local feedstock supplies. Grain prices can be 20-30 cents per bushel lower away from the major transportation hubs, but the level of grain production in these areas may not support a large ethanol producer. Second, ethanol production from low-cost or no-cost wastes from fruit, potato, or cheese production and processing reduces feedstock costs. The size of such plants is limited by the amount of waste generated. Existing plants that took advantage of such fermentable waste were less than 5 million gallons per year. Third, major savings in energy costs can be achieved if the distillers' grains produced as a byproduct of ethanol production can be used locally without drying. Locating a plant near a feedlot is the most practicable approach to assuring a local use of distillers' grains. Combining a feedlot with a large dry mill has been considered in some facility plans, but the size of the required feedlot would be too large to be practical.

The role of midsized plants is more tenuous. Midsized plants may be at a significant cost disadvantage in relation to large plants. Most large-plant operators believed that their plants did not fully exhaust potential economies of scale. If they were to construct another plant, most operators, even those whose plants produced 60 million gallons a year, indicated that the new plant would be 20-30 million gallons per year larger. Midsized plants most likely represent the early phase of industry expansion when many companies explored the commercial viability of ethanol but wanted to limit the level of financial commitment or were limited by lenders due to the riskiness of the enterprise. While the midsized plants were too small to exhaust potential economies of scale, they frequently were too large to exploit effectively the special factors that can render some small plants competitive.

If the industry expands significantly, large plants will account for most of the capacity. Plant sizes of 100 million gallons per year or more will likely become common, compared with one plant above 100 million gallons per year that now exists. If more reliable small-scale production technology were available, small plants could proliferate, adding value to waste or byproduct streams from other industrial processes.

Economics of Dry- Versus Wet-Mill Technologies

Analysts disagree over whether wet-mill or dry-mill operations are the most profitable. For example, Keim (10) argued that wet mills had a 16- to 19-cent cost advantage over dry mills, even after correcting for capital cost overruns and startup troubles experienced by large dry mills. He found that wet mills had a 70- to 75-cent advantage over a small dry mill. Wet mills are initially more expensive to establish, but they are capable of producing many different, higher valued byproducts. Processing wet-mill byproducts, however, increases operating costs for energy, materials, and labor. Wet mills have had lower alcohol yields because starch left with the byproducts cannot be fermented. All of the starch produced in dry mills is available for fermentation, and the entire ground corn mash is fermented. The difference in yield is about 0.1 gallon per bushel.3/

Existing industry costs are a poor indicator of the relative economics of the two technologies. Dry mills should show a capital cost advantage because less byproduct investment is required. Because of the diverse conditions under which existing plants were constructed, however, cost comparisons of existing plants tend to show a capital cost advantage for wet mills.

Dry-mill technology has the potential to achieve greater cost savings as operating experience grows, but the relative economics depends on corn and byproduct prices. The costs over time from large-scale, dry-mill operations have led to speculation that a dry-mill ethanol plant built today might achieve only 10-percent lower capital costs than a comparable wet mill. One might expect the difference to be 25 percent because of necessary additions for byproduct processing in wet mills. Neither of the two technologies is clearly preferred under all sets of future prices, because the tradeoff between capital cost penalties and high-value byproduct credits depends on economic conditions.

3/ Saint Lawrence Reactors, Ltd. developed a process that strips all of the starch in the wet-mill process. The process has not had widespread commercial application in the United States.

Figure 2 summarizes the economic tradeoffs between wet-mill and dry-mill technologies based on capital cost differences and historic differences in net corn costs. Figure 2 assumes no corn syrup production by wet mills. The net additional return to wet mills due to higher valued byproducts had been as little as 1.5 cents per gallon and as much as 9.2 cents per gallon based on national average corn and byproduct prices. Some wet millers focused on producing unusually high-quality byproducts, obtaining prices above national price quotes. Dry milling tended to hold a cost advantage over wet milling. The capital costs of dry milling are, however, considerably more uncertain than those of wet milling. The potential capital cost advantages of dry-mill facilities have not yet been borne out by existing plants.

The relative economics of wet and dry mills also depends on the timeframe and overall level of industry expansion expected. Combining ethanol production with existing wet-mill/corn fructose production is likely to be profitable for a modest, near-term expansion of the industry. Most observers, however, see the fructose market as saturated. Thus, rapid and long-term expansion of the ethanol industry is likely to improve the competitiveness of dry mills.

Profitability and Financing of Plant Construction

Federal programs that have facilitated the financing of fuel ethanol plant construction have been divided between the U.S. Department of Agriculture (USDA) and the U.S. Department of Energy (DOE). USDA has generally assisted small ethanol facilities, while DOE has assisted larger facilities. Although USDA has guaranteed a larger number of loans, the value of USDA loan guarantees has been about half that of DOE (table 5). Of the 16 financed facilities, USDA has

Figure 2--Relative costs of dry-mill versus wet-mill technology

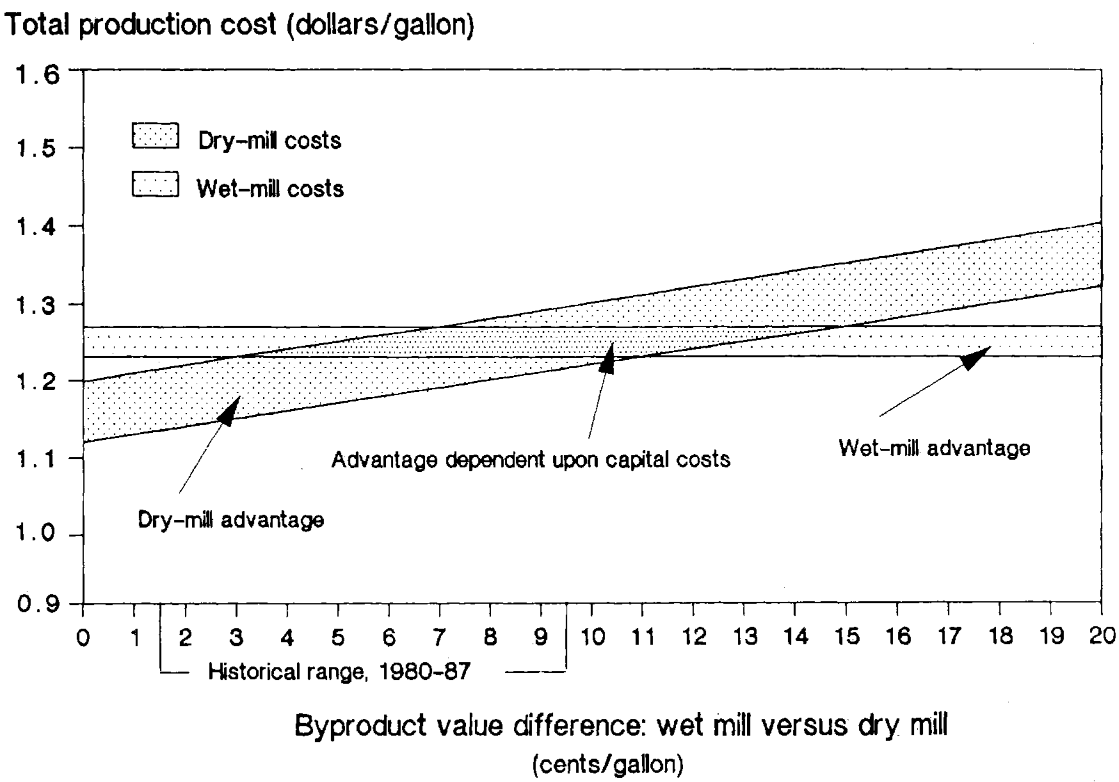


Table 5--Federal ethanol production loan guarantees (1988)

Company	Location	Loan amount	Rated plant capacity	Status
		Million dollars	Million gallons	
DOE loan guarantees:				
New Energy Co.1/	South Bend, IN	127.0	50.0	Operating, making payments
Tennol Inc.	Jasper, TN	65.5	25.0	Liquidated
Agrifuels Refining Corp.	New Iberia, LA	78.9	35.0	Defaulted on loan
Total		271.4	110.0	
DOE cooperative agreements: 2/				
Kentucky Ag. Energy Co.	Franklin, KY	9.8	21.0	Not operating
South Point Ethanol	South Point, OH	24.5	60.0	Operating
Total		34.3	81.0	
USDA loan guarantees:				
Clinton-Southeast JV	Douglas, GA	1.9	3.0	Bankrupt
Idaho Fuels	Boise, ID	.5	.4	Liquidated
Farm Fuel Production	Storm Lake, IA	3.8	2.3	Liquidated
Kentucky Ag. Energy Co.	Franklin, KY	35.2	21.0	Operating, making payments
Amer. Fuel Technologies	Federalsburg, MD	2.5	3.4	Loan repaid
ADC-1 Ltd.	Hastings, NE	20.0	10.0	Operating, making payments
Boucher Rural Products	Ravenna, NE	.3	.2	Liquidated
Alchem, Ltd.	Grafton, ND	8.4	4.0	Operating, making payments
Dawn Enterprises	Walhalla, ND	20.0	10.0	Loan closed
South Point Ethanol	South Point, OH	32.0	60.0	Operating, making payments
Carolina Alcohol	Kingstree, SC	.5	.5	Liquidated
Coburn Enterprises	Sherman, SD	.8	1.0	Liquidated
Sepco, Inc.	Scotland, SD	.8	1.0	Liquidated
Total		126.7	116.8	

1/ New Energy Co. also received a DOE feasibility study grant of $1.7 million. New Energy Co. is the only plant of 47 to receive a study grant and to be awarded a loan guarantee. Repayment of the grant is necessary only if the plant is eventually awarded a loan guarantee. 2/ DOE cooperative agreements are direct loans to facilities that have USDA loan guarantees. The repayment schedule does not begin until 10 years after plant startup and extends 10 years beyond the first payment.

assisted 13 for a total of $126 million of loan guarantees. DOE has provided $271 million in loan guarantees to three facilities. Two of the USDA-guaranteed facilities were partly funded by DOE for an additional $34.3 million through cooperative agreements. Plants guaranteed solely by USDA had a total rated capacity of 116.8 million gallons, and DOE-financed plants had a total rated capacity of 110 million gallons. The jointly financed plants had a rated capacity of 81 million gallons.

Federally financed plants constitute 25 percent of industry capacity. Federal loan guarantees helped construct two of the three largest dry mills and two of the eight largest plants in the industry. The Federal Government has been most involved with plants with capacities of 10-39 million gallons. More than 60 percent of these plants were federally guaranteed.

Many plants built under Federal loan guarantees have been unsuccessful. Of the 12 loans guaranteed by USDA's Farmers Home Administration (FmHA), only one loan has been fully paid off, and four plants are operating and making loan repayments. Of the three facilities constructed with DOE loan guarantees, one is operating and making payments on schedule.

Implications of the high Federal loan failure rate are unclear. The FmHA program was initially limited to small-scale production facilities. The benefits of the Federal loan guarantee have not sufficiently outweighed the burden of inducing producers, who eventually proved successful at producing and marketing ethanol, to take advantage of Government programs. Any loan guarantee program is likely to offer the largest advantage to small, new enterprises with unproven records who are unable to obtain private financing at competitive rates.

FUTURE TECHNOLOGICAL IMPROVEMENTS

Since 1979, significant advances in plant design and plant component designs have been made, and additional improvements are likely. We consider three production cost cases: a state-of-the-art plant, a near-term plant (about 3-5 years), and cost considerations in the long term (over 5 years). State-of-the-art technology makes use of the best elements of plants in operation, with an overall engineering design effectively integrating the components into an efficiently operating unit. Among near-term improvements, we have included technologies that have been demonstrated but not yet incorporated into a commercial plant. These technologies could be integrated into a plant built today. But, achieving hoped for cost improvements will likely involve some experimentation and minor changes at the commercial level. Long-term improvements are subject to uncertain commercial viability and will depend on changing market conditions. Although most ethanol-production facilities use enzymes to break down grain and starch feedstocks into sugars and use yeast to ferment the sugars, future plants may substitute bacteria for yeast, may use sensitive membranes to separate solubles from the alcohol/water mixture, and may immobilize yeast, enzymes, or bacteria for more efficient fermentation. Longer term improvements include using cellulosic materials for feedstocks and developing high-value chemical byproducts from alcohol production.

State-of-the-Art Technology

State-of-the-art plants, by definition, would use the most efficient components of currently operating plants. Discussions with plant operators and researchers provided information on the design features most likely to be incorporated into a state-of-the-art plant. A state-of-the-art plant would be able to produce 60 million gallons per year (dry mill) and 90-100 million gallons per year (wet mill). Continuous processing would be employed in the cooking, starch conversion, fermentation, and distillation phases of production. Yeast would be recycled. Processing control would be fully computerized. The plant would likely combine starch conversion and fermentation to gain higher yields. Large plants may choose onsite production of enzymes. Wet mills would separate fine fibers from the gluten meal and feed. Two alternatives to the standard dehydration technologies exist, corn grits (11) and the molecular sieve technology. Neither of these dehydration alternatives use benzene, labeled a carcinogen by the U.S. Environmental Protection Agency.

Further upgrading of byproducts to obtain higher market value may be a component of the plants. One alternative is production of human-consumption grade distillers grains. A significant barrier to upgrading animal feed supplement byproducts for human consumption is the development of markets for products rather than technological concerns (6). Another alternative, fusel oil, a liquid byproduct stream of alcohols produced during fermentation that is currently not utilized, can be separated into small amounts of alcohol products for markets that already exist. These alcohols can be used in the production of high-value products like perfumes. The cost of upgrading these byproducts generally approximates their value, making the impact on ethanol's competitiveness minimal. The potential markets are also small, in many cases allowing only a few ethanol producers to find a profitable niche in upgrading certain byproducts.

Perhaps the most significant design feature of a state-of-the-art plant involves the full integration of the powerplant with waste energy use. The most efficient plant today bypasses cogeneration and uses direct steam drive to replace large electric motors.

A reduction in net corn costs resulting from state-of-the-art technology would be extremely sensitive to corn and byproduct prices. For example, a 4-percent improvement in yield for wet mills using technologies that are able to separate all the starch from the fiber (a yield increase from 2.5 to 2.6 gallons per bushel) would reduce the net corn cost by less than one-half cent, when corn prices are low and when byproduct prices are high, as was the case in spring 1987. When corn prices are relatively high, $2.50 per bushel, and cost recovery from byproduct sales is low, the savings per gallon for the same yield increase would rise to more than 1.5 cents.

We compare the average operating costs experienced by existing plants and engineering design costs for a planned plant incorporating state-of-the-art technology to check the reduction in production costs expected from employing state-of-the-art technology (table 6).4/ The comparison does not include the cost of corn. Operating costs of 47 cents per gallon of ethanol for average existing technology could be reduced to 38 cents per gallon with state-of-the-art technology. That is, the state-of-the-art plant could achieve an estimated 19-

4/ W. Robert Schwandt furnished estimates of design costs for a planned ethanol-producing facility using state-of-the-art technology.

percent reduction in operating costs, unevenly distributed among three cost categories. The greatest absolute savings, 6 cents per gallon, results from reductions in energy costs. Of the remaining categories, the costs of management, administration, insurance, and taxes could be reduced more easily than costs of ingredients, personnel, and maintenance.

Experience gained from constructing and operating existing plants will help to reduce annual capital costs of plants built in the future. Past plant costs have suffered from overbuilding and the need to replace or upgrade plant components that failed to meet expected performance. Annual capital charges in the state-of-the-art plant, estimated at 40 cents per gallon, assume that some site-related costs could be saved through use of an existing industrial site. A completely new facility requiring complete site development, including such items as railroad sidings, electrical transmission, and sewer and waste treatment, incurs a capital charge of 47 cents.

Potential Technological Improvements in the Near Term

Three new technologies have the potential to reduce production costs over the next 3-5 years. These applications include replacing yeast with the *Zymomonas mobilis* bacteria, using a special membrane to separate out solubles, and immobilizing enzymes and yeasts (or the *Z. mobilis* bacteria) in the wet-mill process. These technologies are experimental and are not proven at full-scale production levels.

The potential advantages of *Z. mobilis* bacteria are greater temperature tolerance and higher alcohol yields compared to yeast (2, 4). Membrane separation of solubles allows removal of approximately 40 percent of the water prior to boiling, greatly reducing the energy needed (17). Current research aims to reduce the tendency for the membranes to become clogged with the solubles.

Immobilizing yeasts and enzymes involves passing the starch or sugar solution, the clarified substrate, through a medium containing the enzyme, yeast, or bacteria. This procedure allows improved control of fermentation and maximizes

Table 6--Average and state-of-the-art operating costs, excluding net corn costs

Cost category	Current average 1/	State of the art 2/
	Cents	
Energy	17	11
Ingredients, personnel, and maintenance	24	24
Management, administration, insurance, and taxes	6	3
Total	47	38

1/ Unweighted average of large plants from industry survey. 2/ Engineering estimate for a specific plant site.

the use of the yeast or bacteria and enzymes. The standard practice is to use yeast and enzymes rather than the state-of-the-art practice of recycling yeast. Immobilization is an improvement over recycling because by holding the yeast in place the chances of fermenter contamination are reduced. Because immobilization requires a clear liquid substrate, it is applicable only to wet mills.

Continued small gains can also be expected through improvements in process control and waste heat use. Without predicting the specific source of cost savings, we have estimated that the state-of-the-art plant of 3-5 years in the future may obtain an additional 5-cent savings in operating costs per gallon. That is, a 10-percent reduction over today's state-of-the-art plant can be achieved without substantial changes in capital costs.

Potential Technological Improvements in the Long Term

Long-term payoffs to ethanol research and development cannot be examined in the narrow context of the ethanol-production facility itself. Other factors need to be considered in an analysis of the improvements required to allow the industry to grow beyond using grain: potential reductions in the costs of ethanol made with other grains, sugar, and potatoes; biological conversion technologies capable of using woody-plant feedstocks; and the development of, and markets for, byproducts from both new and existing technologies (8).

Technologies that may provide payoffs in the longer term include alternative crops, such as Jerusalem artichokes, sugar beets, fodder beets, sweet sorghum, and grains other than corn (1). Use of these crops for ethanol does not present technological hurdles. Should corn prices rise, these alternative crops may prove to be cheaper because some can be grown in diverse soils and in climates not suitable for corn production. Bioengineering and traditional plant-breeding technologies that increase per acre yields or increase starch and sugar contents of corn and other crops also offer the potential for lowering the production costs through reductions in feedstock costs.

Processes used to break down various types of cellulosic biomass materials into sugars that can then be fermented is an active research area (3, 11, 14, 16). Ethanol eventually could be produced from woody plants and a wide range of organic waste. Examples of cellulosic feedstocks include alfalfa, corn stover, bagasse, and wood. Direct cost competitiveness of these technologies would be difficult to achieve if grain prices remain low. However, the byproducts derived from these technologies would be considerably different from existing ethanol byproducts. Ethanol could become a complementary output, with demand for the high-valued chemicals produced along with ethanol driving the production process (15).

The best current cost estimates for producing alcohol and complementary products from cellulose range from $1-$1.20 per gallon (12). This estimate includes CO_2 and the energy value of unconverted cellulose as coproduct credits. Although direct comparisons to a corn-processing plant are difficult, costs for a grain plant at current corn prices can be placed at 60-90 cents per gallon. The large difference in production costs could decline if experimental cellulose conversion technologies show significant improvements while petroleum prices rise.

ETHANOL IN THE FUTURE

Current industry plans include only modest capacity expansion at existing sites, despite a relatively high return to ethanol production in 1987 and 1988. Subdued interest in expansion has been attributed to the expiration of the motor fuel excise tax exemption in 1993 combined with projections of only modest increases in world petroleum prices.

Should production expand significantly, using existing corn wet mills and adapting idle industrial capacity are likely to provide the bulk of expansion. Abandoned corn wet mills in Morrisville, PA, and Montezuma, NY, built in the 1970's, are near the Northeast gasoline-refining market. Twenty-four oil refineries in the Midwest, with a distillation capacity of 17 billion gallons per year, were abandoned during 1981-84. Current U.S. ethanol production capacity, in contrast, is nearly 1 billion gallons per year.

The number of abandoned facilities suitable for ethanol production is large, but only the best sites among those available will have an economic advantage over new facilities. The design of the adapted facility may constrain the use of improved technology or location of components of the plant, increasing operating costs. The site may be poorly located in relation to either corn or ethanol markets. The least costly approach for using some sites may be to raze the entire physical structure, keeping only the rail siding or roadway access. An advantage to using an existing industrial site may be the speed with which approval for construction could be granted by local government.

Under suitable economic conditions, 1 billion gallons of ethanol capacity would be available by adding to existing wet mills that do not have ethanol-production capacity and by expanding existing ethanol-production facilities. With corn at $1.50 per bushel, the full cost of ethanol production before subsidies would be roughly $1 per gallon (at 50-percent byproduct cost recovery). Ethanol costs would be $1.30 per gallon, with corn at $2.50 per bushel. Adapting the best of abandoned industrial sites could easily add another 1-2 billion gallons of capacity at ethanol-production costs of $1.15-$1.40, depending on corn prices. New ethanol plants can be built with production costs ranging from $1.20 to $1.45 per gallon, depending on corn prices. Such new plants are likely to be limited to geographic areas of strategic marketing interests where other capacity does not exist.

Comparing the cost of ethanol with that of gasoline and other blending agents is difficult because of the complicated and interrelated patterns of petroleum and ethanol production and distribution, environmental regulation, and Government incentives. Ethanol's competitive position depends on the distribution system configuration, the use of ethanol as either an octane enhancer or a fuel extender, volatility restrictions, age of the motor vehicle stock, and State and local subsidies. Figure 3 reduces the question to a simple comparison between grain and crude oil prices, capturing the additional uncertainty of the future status of the Federal subsidy for ethanol.

We assume that a new state-of-the-art plant will produce ethanol with byproduct recovery of 50 percent of the cost of corn. We assume ethanol will compete on a direct cost per gallon basis with gasoline, reflecting a middle position between decreasing the value of ethanol on the basis of its lower Btu level and increasing its value on the basis of its higher octane value.

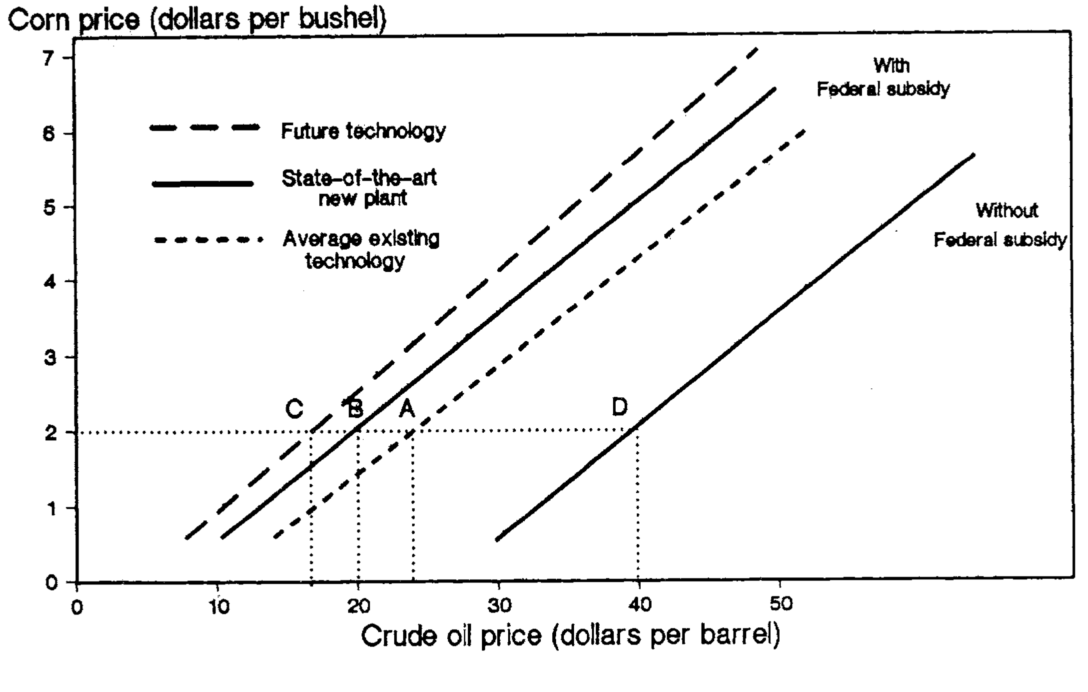
State-of-the-art technology represents an improvement over the average existing technology and has, therefore, enhanced the competitiveness of ethanol. With $2-per-bushel corn and the existing Federal subsidy, ethanol produced when using average existing technology is competitive with crude oil at $24 per barrel (point A), compared with $20 per barrel with state-of-the-art technology (point B). Further technological improvements within the next few years could make ethanol competitive at $18 per barrel of crude oil (point C). If state-of-the-art technology is used but the subsidy is discontinued, crude oil prices would have to rise to at least $40 per barrel (point D) for ethanol to be competitive. Without the subsidy and with existing technology, ethanol cannot be competitive with petroleum when petroleum prices are below $25 per barrel, unless byproduct credit exceeds the cost of corn.

CONCLUSIONS

The ethanol industry has grown from 20 million gallons in 1979 to 750 million gallons in 1986. Many small plants, including those receiving Federal loan guarantees, have closed, reorganized under bankruptcy proceedings, or defaulted, particularly in 1986 when oil prices fell dramatically. Since 1980, ethanol production costs have averaged $1.40-$1.50 per gallon, yet considerable variability among firms has existed and costs have varied over time as corn prices have changed.

A variety of evidence supports existence of economies of scale in the industry. Our data indicate that costs for small plants are 18-23 cents per gallon above costs for large plants, but the cost ranges of small and large plants overlap considerably. Local grain markets and locating a plant with a feedlot, for example, can make small plants competitive. Wet- and dry-milling costs are similar for stand-alone plants. Relative prices for byproducts are likely to determine which process will be cheaper in the future.

Figure 3--Ethanol break-even curves: technology and Federal subsidy



Reductions in ethanol production costs due to improved technology will occur, but reductions that would offset the loss of the Federal fuel excise tax exemption are unlikely. A state-of-the-art plant built today can achieve a 9-cent-per-gallon savings over average industry costs. Some firms approach state-of-the-art cost levels today. State-of-the-art plants of 3-5 years in the future could achieve an additional 5-cent savings in operating costs per gallon in the 1990's.

Converting cellulose and processing other renewable resources into ethanol and chemicals will remain a major challenge to agriculture. How soon the advances will occur depends on research and development in producing, processing, and fermenting cellulosic materials in addition to the development of processes that transform cellulosics into marketable products.

Although conditions in 1987 were relatively favorable for the ethanol industry, plans for expansion were modest due to pending expiration of the Federal fuel excise tax exemption for ethanol fuels. Under favorable conditions for expansion, as much as 1 billion gallons of capacity could be added for about half the cost of new plants through additions to existing ethanol facilities and operating wet mills. Another 1-2 billion gallons could be added by adapting abandoned industrial oil refineries and wet mills at 10-25 percent less than the cost of a new plant.

A reasonable likelihood that favorable conditions would continue to exist over the next 10-15 years is needed for the industry to expand significantly. Prospects of only moderate increases in the price of crude oil well into the 1990's and little change in the variability of net corn costs means that industry expansion depends largely on extension of the Federal excise tax, which is scheduled to expire in 1993. For ethanol to be competitive in the 1990's without the Federal subsidy, crude oil prices would have to rise to at least $40 per barrel.

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