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FUEL ALCOHOL FROM GRAIN:
Energy and dollar balances of small ethanol distilleries and their economies of size and scale

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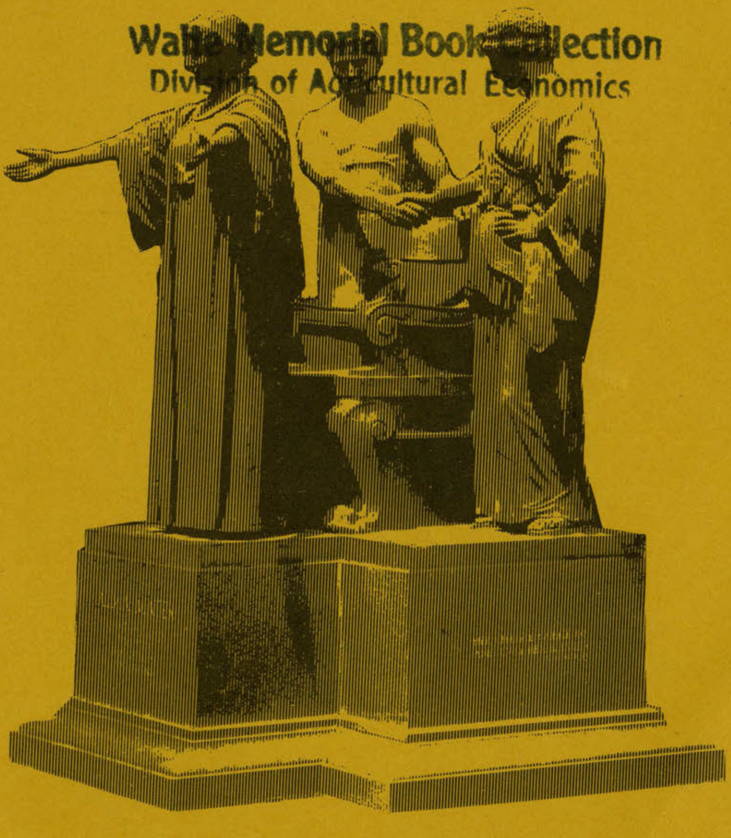

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Abstract

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Abstract.

We have calculated energy and economic balance for three sizes of ethanol-for-grain plants:

1) Single-farm size (10,000 gallons a year)
2) Farm-consortium size (250,000 gallons a year)
3) Industrial size gasohol plant (2.5 million gallons a year).

Energy results are based on actual measurements during operation. Economic balances are also based on empirical materials requirements, but prices for these requirements are treated generically (e.g., we use an average price of grain, even though at least one plant studied is currently purchasing surplus seed grain at a low price).

Use of energy (direct energy plus the "energy cost of energy") decreases with increasing plant size, varying between 89 thousand and 36 thousand Btu per gallon of ethanol. Inclusion of indirect energy does not reverse this conclusion.

There are also some economies of size in money terms, but these are variously offset by the price advantage which farm level operations have both in acquiring grain and in utilizing feed residue. Further complications arise from labor costs which tend to be more flexible on small than on large plants.

1. Rationale and approach.

A study of fuel alcohol production needs no general justification at this time. The magnitude of the energy problem, and especially of the investment needs that will have to be filled in the medium term of ten to twenty years ahead makes necessary that we know as much as possible about alternative paths of energy development.

Burgeoning literature about alcohol fuels from biomass already contains huge amounts of information from a variety of sources. Owing to the short time during which fuel alcohol has been a serious alternative to other new or modified sources of liquid fuel in the United States, most studies to date reflect either industrial operations for which fuel alcohol is a component in a multi-product scheme or those where the technology was designed to produce beverage-grade alcohol, or else they draw on engineering blueprints and other "anticipation" material. None of these sources comes close to portraying what happens in a two-product (fuel and feed) industry operating in a variety of plant sizes ranging from single-farm stills to factory scale operations. The specifics of this study will be outlined to show its place in the broader framework of ongoing research.

Our study aims at limited but well defined objectives to be reached by observing, as closely as possible, three actually operating distilleries at various size levels. Of necessity, the case material is as yet very limited and should be greatly enlarged as a research resources will permit. The following main points will be pursued:

a) measurement of actual use of direct energy in recently started distilleries, to establish empirically valid parameters for direct fuel consumption in grain alcohol production;

b) applying the techniques of energy analysis to establish parameters for energy used indirectly (both by the energy industries and by other input producing industries, including crop farming) for grain alcohol production;

c) applying generally valid market prices to the bills of goods used in distilleries to obtain comparable cost estimates for grain alcohol production;

c) applying generally valid market prices to the bills of goods used in distilleries to obtain comparable cost estimates for grain alcohol production;

d) comparison of the results under a) - c) to obtain information of comparable energy and dollar costs as these may be affected by economies or diseconomies of scale and size.

The last part of the analysis should contribute to an advance judgement of the advantages and drawbacks of small-scale versus larger size production, and also give indications of the significance of capacity utilization. This will show some of the possibilities that may exist in developing alcohol distilleries as a decentralized industry, contributing to the economic strength and diversification of rural areas.

We do not overloook the likelihood that fuel alcohol from grain may be a passing phase in fuel development, eventually to be overtaken by other feedstocks. Maybe at length methanol from cellulose feedstocks will be preferred over ethanol from starchy ones. However that may turn out, ethanol from grain is what we have coming on now in substantial scope. Our pilot effort to collect empirical data about this line of development should prepare the way for an eventually more complete overview of the total potentials for liquid fuels from biomass.

The following three case studies are based on actually operating distilleries, all of them inteded as prototypes for eventual production of numerous identical (or closely similar) establishments; for the first two, a number of duplicates are already in place or under construction. On each site, direct use of energy was established by reading of fuel gauges and electricity meters during periods when the distilleries were operating to capacity. Data were also obtained on quantities of feedstocks used and products obtained during the time periods covered by the energy measurements.

Some indirect energy was computed from the direct energy quantities (the so-called "energy cost of energy"). We have not calculated all indirect energy, but have verified that the difference in indirect energy between the different operations is significantly less than the difference in direct energy.

For cost analysis, prices of feestock corn and feed byproducts were borrowed from current agricultural statistics (Agricultural Prices, USDA), various issues . Both sets of prices were differentiated according to size of distillery, in the ways explained in Appendix 2. Prices of enzymes and yeast are those charged by several commercial suppliers, those of natural gas and electricity were obtained from Illinois Power Company in Champaign, Illinois, by telephone and relate to small industrial customers, while the price of LP gas paid by farmers is cited from Agricultural Prices (USDA), Oct. 31, 1980. Labor on farm-level and farm-consortium distilleries was for the most part set at the Illinois Farm Business records current estimate of farm operators' self-employed labor for 1980, at $7.50 per hour. (Information supplied by R.A. Hinton). For the industrial gasohol distillery, labor costs were computed from data published by the Bureau of Labor Statistics.

Cost of capital was obtained from suppliers of whole distilleries and checked in part from price quotations of various suppliers of parts. Cost of interest on fixed capital was computed, assuming stable value of money, as shown in Appendix 2.

In the cost analyses, no attempt was made to explore the actual costs in the plants studied. affected as those are by incidentals. Rather, we wanted to establish normal costs, independent of what individual ingenuity or hazards might accomplish in a few cases.

2. A single-farm distillery: 10,000 to 15,000 gallons a year.

The distillery investigated in this category has three tanks each equipped for the complete process of cooking, enzyme treatment and fermentation, and a single distillation column serving all three tanks. The cooking - fermentation cycle takes up to 72 hours, distillation 7-8 hours. Thus, distillation could be all in daytime, assuming the tanks are working on suitably staggered schedules.

Cooking, fermentation, and distillation here all occur in the same tank; this type of distillery is therefore often called a "pot" boiler. The unit is heated by a natural gas burner situated beneath each of the tanks. Cooling is accomplished by circulating water through copper coils that run around the inside of each tank.

During distillation the fermented beer is simply boiled, allowing an alcohol-water vapor to pass through a packed 4-inch column. The single distillation column is jacketed by copper coils through which water is circulated at a rate sufficient to maintain the top of the column at about 173^{0}F. The flow rate is adjusted automatically by a temperature sensitive valve, allowing for unsupervised operation.

The distilled vapors are condensed in a second, shorter column. The flow of the condensing fluid is determined only by the water faucet, and therefore is not contolled by any feedback.

Direct energy inputs to the on-site conversion are natural gas for cooking and distillation, and electricity for operation of the agitator. The unit studied here has no pumps, and therefore electricity consumption is quite low. To reduce cooking time and energy, the hot condensing fluid is drained into one of the three tanks and reused in the next batch. Currently there is no recovery of the heat in the mash remaining after distillation.

After distillation is completed, the mash is filtered through a screen. This eliminates energy inputs for drying but also leaves a very wet byproduct. The feed output is therefore a wet version of DDG without solubles, dry weight of about 12 pounds per bushel of corn.

Each batch processes 16 bushels of corn. In an observed run, 39 gallons of 180 proof product were produced, for a yield of 2.19 gallons EtOH per bushel. Energy inputs for this run (see Appendix 1) were 2670 cubic feet of natural gas and 4.8 kwh of electricity. For each gallon of ethanol, these inputs are 76.1 cubic feet natural gas and 0.14 kwh electricity.

The byproduct is DDG without solubles. At the farm level, this justifies a credit of 60 percent of the price of corn, as shown in Appendix 2.

The manufacturer's prospectus specifies use of liquefying and saccharifying enzymes per bushel of feedstock corn. Yeast is not specified in quantity, nor are accessory supplies such as lime. Labor is specified in such a way that more intensive operation will require proportionately more labor.

Capital costs of three tanks (fully equipped) and the distillation column is given as $18,500. Including the building (which in this case can be quite simple) and the materials for plumbing and wiring connected with installation, total capital cost can be approximated at $25,000.

Capacity of the distillery is advertised as 10,000 gallons of product a year. This is a lower bound. Assuming about 335 days of functioning, thus 335 batches, we obtain at least (39 x 335) 13,100 gallons a year. If the cooking-to-fermentation cycle can be shortened to 60 hours instead of 72, we would obtain 402 batches instead of 335; presumably, distillation could be stretched, using long days some parts of the year, and with 2.5 gallons per bushel, which is more than obtained so far, total EtOH output would come to 15,700 gallons a year. An upper bound, under optimal conditions, would be about 15,000 gallons. Taking some farmers' thumb estimate that it takes 15 gallons of alcohol (180 proof) to farm an acre in corn or soybeans, the production range of 10,000 to 15,000 gallons of EtOH would supply a farm in the range of 750 to 1100 acres of cropped acreage, or two-four smaller farms acting as a consortium.

Using these indications, and the cost data mentioned in the introduction and in appendixes 2 and 3, we may draw the following balance sheet, relating alternatively to 10,000 to 15,000 gallowns of EtOH output.

Table 2 -1. Dollar balances of single-farm distillery. Dollars and cents per gallon of EtOH.

	For 10,000 gallons	For 15,000 gallons
Feedstock: Corn at $3.20/bu, for 2.2 gal/bu, $1.45/gal less feed credit of 12 lb, DDG without solubles, @60% of the corn, ≈ 87¢		
Net feedstock cost	.58	.58[a]
Enzymes, yeast, chemicals, 60 ¢/bu	.27	.27[a]
Natural gas, 76.1 cu. ft. @.32¢, electricity, .14 kwh @ 2.3¢	.25	.25
Labor, 600 - 900 hours @ $7.50	.45	.45
Capital, $25,000, 8 years at 2% real interest, $3400/year	.34	.23
Miscellaneous costs	.06	.06
Total costs per gallon EtOh	1.95	1.84
Sub-total: Total cost except labor	1.50	1.39

[a] In case higher capacity utilization means higher alcohol yield per bushel of feedstock, these items become somewhat lower.

Note: Feedstock, materials and energy are treated as proportional to volume of output.

Assuming the output to be used on the farm where produced, no price of fuel alcohol is needed. Instead, we cite the price of diesel fuel, which is at present about $1/gallon, paid by farmers. (Agricultural Prices, USDA recent issues). Because of estimated fuel requirement of 1½ gal. ethanol per 1 gal diesel, the cost of ethanol now greatly exceeds that of diesel fuel. Even without counting the farmers' own labor in this connection, the alcohol fuel from this distillery costs him approximately twice the current price of fuel.

If it bears out that ethyl alcohol in farm machines has its highest fuel value at 180 proof, then all cost figures in the above are reduced by one-tenth.

3. <u>A farm-consortium distillery: ¼ million to 1 million gallons a year.</u>

The prototype studied in this category is modular, in units of ¼ million gallons of annual capacity which can be built in entities of one to four units. Two unit (and four unit) entities have an advantage because the anticipated labor requirement is the same for two units as for one.

For each unit, the "package equipment" offered for sale at $272,100 includes the following equipment:

1 - 2,000 gallon cone bottom, black iron saccharification unit with hydraulic driven agitator and liquid pump. Mounted on hydraulic load cell scale with dial. Contains hydraulic and pneumatic valve system. Tank - 90" x 72".

1 - 2,000 gallon stainless steel yeast tank. Air agitated with cone bottom. 72" x 150".

2 - 15" stainless steel distillation columns and condenser with hydraulics and pneumatic valve system mounted on mild steel frame. Designed to produce 33 gallons of 190 proof alcohol per hour. 54" x 80" x 204".

1 - Air cooled 75 ton water cooling tower.

4 - 7,600 gallon mild steel fermenters. Covered, cone bottom, hydraulically agitated, equipped with cooling coils. 144" x 168".

1 - 7,600 gallon mild steel water storage tank. Insulated, with cone bottom. 144" x 168".

2 - 12,000 gallon mild steel storage tanks with fittings. UL approved. 132" x 204".

1 - SWECO solids separator designed to reduce moisture level in by-product.

1 - ph buffering system consisting of 1-96" x 192" tank with accessories, piping and pump.

1 - 45 gallon per minute hydraulic system adequate to power - agitation on fermenters and cooker, auger in corn, if needed, and main product pump.

1 - Electronic, digital, scanning temperature sensor capable of 32 scanning locations, and recorder to record same on paper.

1 - Complete laboratory package consisting of: mash tester designed to test alcohol content; hydrometer; graduate; thermometer; funnel; screen; hematocytometer; test tape; hand refractometer; 2-graduated cylinders; and 4-beakers.

1 - Complete plumbing package with all pipes, valves and fittings needed to complete the assembly and installation of this plant. [All primary valves on saccharification unit are pneumatic operated, also the fill and withdrawal on each fermenter is also pneumatic operated.] Primary valves are remote controlled from the saccharification unit or the distillation columns.

For building and installation (including pipes, wiring, and plumbing and electricity work), there applies an additional estimated $100,000 to be added to the package cost for two units; presumably, half applies to the one unit (the estimate for building is so much per square foot). Thus the total investment cost per unit come to $322,000. Cooker, yeast tank and distillation columns are specified as made of stainless steel, fermentation tanks as black iron or mild steel. Lifetime of most of the equipment can be set at 10 years, but there would be considerable salvage value, especially in stainless steel componets for which lifetime is given as indefinite. Presumably, the unit could after 10 years be re-fitted with new tanks etc., at less cost than the original investment. Lifetime of building is uncertain; probably it would still be serviceable after 10 years.

A unit of this size typically has three columns: stripper rectifier, and condenser. The mash is pumped into the top of the first column as steam is pumped in from the bottom to "strip" the alcohol from the beer. This water-alcohol mixture is then passed into the rectifying column and distilled there to a much higher proof. Finally, the vapors are condensed in a water jacketed column.

Both cooking and fermenation are batch operations; the former in a small, heavily insulated cooker and the latter in one of four large fermentation tanks. Under normal operating conditions the fermentations are staggered so that the distillation columns can operate at a constant rate, 24 hours a day.

In this operation, opportunities exist for energy savings through heat recovery. The distillery studied here includes heat exchangers on the condenser column and on water leaving the rectifying column. Fermented mash at 90^0F was passed through these heat exchangers and preheated up to 150^0F before entering the first column. Additional use of heat exchangers could be used to recover heat from the cooked mash when it is cooled for fermentation, as at the Schroder distillery in Colorado (Jantzen and McKinnon, 1980).

The residue after distillation is separated with a high-speed centrifuge. Solids are removed at about 60-65^0 moisture; liquids are separated and stored in a large, heavily insulated holding tank. A large portion of this water is recycled for cooking, reducing both water and energy demands. Build-up of salt, however, eventually limits the recycling and necessitates dumping a portion of the water.

Energy inputs for this operation are propane as boiler fuel and electricity for motors and pumps. Measurements were made and normalized to one output "batch" of 595 gallons of EtOH ethanol . Assuming an input of 16,000 lbs. at normal moisture levels, this is a yield of 2.08 gallons of EtOH per bushel. To convert this corn to alcohol, 107 gallons of propane were used for cooking, and 196 gallons in the distillation process. In addition 923 kwh of electricity were required to operate the pumps and motors (details on the measurements are given in Appendix 1). Inputs are equal to 0.51 gallons propane (energy equivalent to 45 ft $^{3/}$ natural gas) and 1.55 kwh electricity for each gallon of ethanol.

As a farm-consortium distillery, this entity may capture the trading margins in corn and feed residue, as indicated in Appendix 2.

For most of the labor specified, the estimated salary level is in line with the Illinois farm business record assumption about the worth of a farm operator's self-employed labor in 1980, or $7.50 per hour. Only the manager, and intermittent help from plumbers and electricians, would come in higher wage classes.

From these indications, costs per gallon of EtOH would come as shown in the following table.

Table 3 -1. Dollar balances of farm-consortium distillery. Dollars and cents per gallon of EtOH.

	for ¼ million gallon capacity	for ½ million gallon capacity
Feedstock: Corn at $3.20/bu, @ 2.1 gal/bu, $1.52/gal, less feed credit @ 69% of the corn for (DDGS) $1.05, net feedstock cost.	.47	.47
Enzymes, yeast, chemicals	.15	.15
Energy: Liquid petroleum (LP) gas, .51 gal/gal EtOH @ 63¢/gal LP gas	.32	.32
Electricity, 1.55 kwh/gal EtOH, @ 2.3¢/kwh	.04	.04
Labor: 6 man years plus extras, @ $7.50/hour, at 2000 hours per man-year and 10 percent extra time.	.40	.20
Capital: $322,000 at 10 years and 2% real rate of interest, $35,000/year, per unit of ¼ gallon annual capacity	.14	.14
Miscellaneous costs	.06	.06
Total cost per gallon EtOH	1.58	1.38
Sub-total: Total cost, less labor cost	1.18	1.18

As before, if machines use 1½ gallon of 180 proof alcohol for each gallon of diesel fuel, all costs are reduced by 10 percent for comparison with diesel fuel.

4. A small industrial gasohol distillery: 2-1/2 million to 10 million gallons a year.

The particular case studied here is an operating distillery of 2-1/2 million gallons of ethanol annual capacity, designed by the ACR Process Corporation, Urbana, IL., and using the Chambers technique of producing a mixture of ethanol and gasoline (gasoline being a process input) with gasohol as the eventual output. The plant is modulár in the sense that up to four identical sets might be combined, bringing capacity as high as 10 million gallons a year. Some economies of scale might be obtained in this way, in the use of management and office overhead costs, possibly also in the use of the sewage treatment plant (which is one-tenth of the investment cost); essentially such returns to scale will be a matter of higher profit because the owner-director's time (which is not budgeted)can be stretched over more output.

The conversion processes used in this gasohol plant are actually quite similar to those at the farmer-consortium level. However, the scale of the operation justifies an improvement in the sophistication of certain components such as

1) A computer control system to automatically regulate most of the plant's operation.
2) Continuous cooking of the corn feedstocks.
3) Better drying of the residuals.
4) Improvements in energy-savings technologies.

Increases in efficiency also produce a close interaction between different stages of the operation. Energy inputs for drying, for example, may also be inputs for distillation. Under steady state conditions, the plant is best treated as a black-box: a certain amount of feedstocks enter the plant, and a certain amount of products leave as output. Ideally, these measurements would be over a large enough period of time to simulate steady-state. In this study we could only make measurements over a short time period (about 28 hours). However, based on the constant production we are confident that our measurements closely approximate steady-state situations.

Direct energy inputs for this operation are natural gas, for boilers and drying, and electricity for pumps and motors. We were unable to break down the quantities to learn, for example, the natural gas inputs for drying the DDG.

Fermentation of the mash is, as in the smaller distilleries, a batch process. (One larger distillery we visited, but did not study, was planning on converting to continuous fermentation.) The beer is then passed into a holding tank and from there through the distillation columns. An additional anhydrous column is required after the rectifier to remove all but a small portion (0.05%) of the water.

The residue is collected at the rectifying column, and therefore is not contaminated by the gasoline used in the anhydrous column. The residue is pumped through a separator to remove much of the liquids. The solids from the separator are pressed to remove more of the water, then augered into a gas-fired drier. Under normal circumstances, the liquids flow through an evaporator which converts them into a syrup. This syrup is poured onto the residue before it enters the drier, producing a byproduct known as distillers dried grains and solubles (DDGS).

While we were at the plant, the evaporator was not operating. This will lower our measured energy inputs, although not by the amount necessary to run the evaporator separately. The evaporator is fueled by steam from the boiler, but this steam is then fed into the distillation columns. Shutting the evaporator simply diverts the steam directly to the columns.

We were told that the net amount of extra gas needed to operate the dryer was on the order of 10,000 Btu per gallon, but we made no measurements of this ourselves. Our calculations have therefore assumed that the byproduct is distillers dried grains without solubles.

The alcohol distilled at this plant is very nearly anhydrous alcohol (water content was typically about 0.05% or less) but the actual product coming out of the column is a blend of alcohol and gasoline. (Typical ranges of alcohol/gasoline ratio were 5%-15% gasoline, 95%-85% alcohol.) Strictly speaking then, the columns do not produce anhydrous alcohol or gasohol as normally defined (90% gasoline) but rather an alcohol/gasoline blend. After distillation additional gasoline can be added to bring the gasoline content up to desired levels.

During a steady operating period of 24 hours, energy inputs were 121,000 ft^3 of natural gas and 8170 kwh of electricity, and corn input was 164,000 lb., or 2920 bushels. Output was 6785 gallons of EtOH for a yield of 2.32 gallons EtOH per bushel. The energy inputs per gallon of EtOH are 1.20 kwh electricity and 17.8 ft^3 of natural gas.

In computing the costs, some items were related to unit of feedstock, others to estimated annual plant capacity. The price of corn feedstock at $3.20 at the farm gate in November 1980, was augmented by 10% for marketing margin, to $3.52. At 2.3. gallons of EtOH per bushel, gross feedstock cost comes to $1.52 per gallon. With only DDG (and solubles discarded), and with a 35% of the cost of the corn, or 53¢ per gallon, leaving net feedstock cost at 99¢ per gallon of EtOH.

Cost of yeast, enzymes and chemicals were computed from technical data obtained from the plant. Energy expenses are those measured, as described above.

Labor costs were calculated on the estimated 24 man-years, 2 of which in managerial ranks and the rest operatives, repair people, and office personnel. Wages for the 22 workers were computed from the earnings in industries labeled "Miscellaneous chemical products" (Bureau of Labor Statistics, Employment and Earnings, Vol. 27, No 9, 1980), raised by 33% which is the typical proportion between earnings and wages according to other Bureau of Labor Statistics data. For the two supervisory persons, salaries were computed from 1977 data (Handbook of Labor Statistics 1978, Table 99), for Chief Accountant and Director of Personnel, lowest category for 1977, raised to 1980 levels by the index of wages and earnings in the meantime.

Depreciation of captial is complicated because of varying life spans of investment items. Mild steel tanks are supposed to last only seven years; the column, and some other items made of stainless steel, will last at least three times as long. The planned sewage treatment plant (one-tenth of the 5 million dollars) must also have a long life span. Had it been possible to estimate the cost of refitting the factory with a new set of the short-lived items, we could have figured two future re-fittings, giving the plant a 21 year life span, with a higher total investment cost. Detail is lacking, however, and instead we assume that one round of re-fitting will be well within the value margin of the long-lived items (their salvage value after 14 years is assumed to exceed the cost of the second set of mild-steel tanks etc.). Accordingly, the $5 million were depreciated over 14 years, which should still leave substantial, but unspecifiable, salvage value over and above the cost of one re-fitting - meaning that the $5 million more than covers the net capital cost for 14 years of operation.

Results are shown in Table 4-1.

Table 4-1. Dollar balance of small industrial gasohol plant. Dollars and cents per gallon of EtOH.

	For 2.5 million gallons
Feedstock: Corn at $3.52 per bushel; at 2.3 gallons EtOH per bushel, or $1.53 per gallon of EtOH; less feed credit, 35% or 54¢ per gallon, thus net feedstock cost	.99
Enzymes, yeast, chemicals	.16
Energy: Natural gas, 17.8 cu. ft./gal @ .32¢/cu. ft.	.06
Electricity, 1.2 kwh @ 2.3¢	.03
Labor, 2 x 2 managers and 22 workers at wages in chemical industry	.22
Captial: $5 million, over 14 years at 2% real rate of interest, $450,00/year	.18
Miscellaneous costs	.06
Total cost per gallon of EtOH	1.70

Unlike the small plants, it has no meaning here to compute costs net of labor cost. The director's time is not accounted for as he is a risk taker and expects profits rather than a salary; he would stand to gain considerably from adding more modules (up to 4).

5. Comparative Energy Balances

Energy analysis is controversial, and rejected by many economists. These claim that prices will adequately reflect energy realities. However, since ethanol/gasohol already receives significant incentives, the market has already been tampered with. Therefore, even if one believes that a free market will transmit the energetic realities through prices, it should not be expected here. In addition, there is an interaction between the net energy question and the effective incentive to a subsidized energy supply technology. Being close to the net energy limit (when "energy in equals energy out") can multiply the subsidy per unit actually delivered to the rest of the economy. Further, knowledge of requirements allows estimation of sensitivity to energy price changes.

We already know (Chambers, et.al. 1979) in some detail the generalized ethanol-from-grain energy picture, which is roughly as follows. To produce one gallon of ethanol from corn requires :

Agricultural input	$50-70 \times 10^3$ Btu
Process energy in distillation	$40-80 \times 10^3$ Btu (includes back linkage)
Capital equipment	$5-10 \times 10^3$ Btu
	$95-160 \times 10^3$ Btu

In this work we are interested in process energy and how it varies from design to design for ethanol/gasohol operations. The figure of 40 kBtu/gal is claimed for ACR process, [Chambers, et. al., 1979] which produces gasohol, and that of 80 is from some of the older ethanol operations which were originally beverage ethanol producing. The ACR figure of 40 kBtu/gal is about the lowest [for a dried grain product] claimed.

The enthalpy of combustion of 1 gallon of EtOH is about 80×10^3 Btu. When output is corrected for energy credits for feed byproduct and for miles-per-gallon relative to pure gasoline, it compares well with energy inputs near the low end of the range quoted [$\sim$ 95 kBtu], [Chambers et.al.

1979]. If the energy balance is done in terms of only liquid fuel, or inputs substitutible for them, the energy inputs are significantly less than for total energy. In any case, the process energy is of order 1/2 of the total and hence significant.

Because most energy information was either empirical but based on old, beverage-oriented technology, or theoretical, we wanted to obtain current empirical data on process energies. Based on the way the market was evolving and also on claims of, e.g., ACR, we aimed to look at 3 types of plants:

1. A single farm size operation producing approximately 180 proof EtOH.
2. A corsortium size operation producing approximately 180-190 proof EtOH.
3. A larger size operation producing gasohol (90% gasoline, 10% EtOH).

Table 5-1 lists in more detail the attributes of these.

An implicit question in the choice of sizes is whether there are energy economies of scale in EtOH production, as one might suspect on engineering and economic grounds. Also, from a total energy standpoint, we are sensitive to the possibility that an apparent economy of scale for direct energy might be cancelled by a diseconomy of indirect energy.

A brief discussion of the data-taking at the three operations follows:

A. SMALL, SINGLE FARM OPERATION (39 gal. of 180 proof EtOH/day)
We took data during two day-long runs in May and June, 1980, on a unit now in production for commercial sale. The unit we measured was in place at the manufacturer's plant. We had seen it in February when it was obviously not running well, but by May significant improvements had been made and (for distillation) it ran without attention.

Natural gas measurements were made from an in-house meter. We measured electrical consumption with our own watt-hour meter. Both proof and alcohol production measurements were also made by us during operation.

The results are:

Per gallon of EtOh:	Natural Gas (ft^3)	Electricity
Cooking	8.0 ± 4%	0.020 ± 2%
Distilling	68.1 ± 5%	0.12 ± 2%

Yield 2.19 ± 5% gal EtOH/bu

For details on uncertainty estimates, see Appendix 4.

B. FARMER CONSORTIUM OPERATION (625 gal of 190 proof EtOH/day)

We took data over a three day period on a comercially available unit. A few adjustments were necessary in our analysis to account for some output we felt was not indicative of normal operating conditions. This particular unit used propane as a boiler fuel, measured with an in-house LP flowmeter. Electricity was measured with a utility owned watt-hour meter. The quantity of alcohol produced was measured from two separate meters. Proof readings were made at regular intervals by the operator. Yield calculations are based on the corn distilled while we were at the plants; the operators supplied us with the data on corn input.

The results are

Per gallon of EtOH	Propane (gal)	Electricity (kWh
Cooking	0.18 ± 8%	1.6 ± 4%
Distilling	0.33 ± 6%	

Yield 2.08 ± 7% gal EtOH/bu

C. GASOHOL PLANT (7000 gal. of 200 proof EtOH/day)

The largest scale operation studied here is a gasohol plant producing

2.5 million gallons of anhydrous alcohol per year. (The actual product leaving the columns is a mixture of alcohol and gasoline). If all of this product were blended at the plant at at 90% gasoline/10% alcohol ratio, this would represent a capacity of 25 million gallons of gasohol per year.

Data were collected during a two-day period of steady and good operating conditions. Natural gas inputs for the boilers and drier were mearsured from a utility meter on the gas line supplying the plant. Electrical inputs were also measured directly from a utility meter. We relied on the operator's measurements for quantity of alcohol actually produced (measured as total output for eight hour intervals). Yield calculations are based on the corn cooked while we were at the plant; the operators later supplied the data on output from these cooks. The results are

Per gallon of EtOH

	Natural gas (ft^3)	Electricity
Cooking	17.8 ± 9%	1.20 ± 3%
Distilling		

Yield 2.32 ± 5% gal EtOH/bu

Results for the 3 operations are summarized in Table 5-1. Figure 5-1 shows the direct energy inputs, with the following conversion factors:

Natural Gas 1035 Btu/ft^3 x (1.10)* = 1139 Btu/ft^3

Propane 91600 Btu/gal x (1.20)* = 109920 Btu/gal

Electricity 3413 Btu/kwh x (3.79)* = 12935 Btu/kwh

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* The factors in parentheses are the energy cost of energy and reflect power plant efficiency, refinery losses, and other material and handling costs which require energy themselves.

Source: [Herendeen and Bullard, 1974].

Fig. 5-1, which plots energy/gal vs. gal/yr, points to an economy of size,* since the direct energy cost per gallon of EtOH has more than halved with a 17-fold increase of production capacity.

Before promoting those results, however, we must varify that indirect energy effects (besides the energy cost of energy, which we have already considered) do not change the basic conclusion from Fig. 5-1. As indicated at the beginning of this section, the agricultural inputs are rather large, while the energy to produce capital inputs to the plant seem rather minor. But we must check to be sure.

To evaluate indirect energy requirements, we turn to the economic data. As in previous work, we assume that the energy cost of labor is zero.

A word on discounting and depreciating: while there is now some limited support for introducing time discounting into energy analysis we refrain from doing so here. We will use an undiscounted, straight line depreciation scheme in which

$$\frac{\text{capital energy requirements}}{\text{gallon}} = \frac{\text{capital cost converted to energy units}}{\text{number of gallons produced in operation's lifetime}}$$

We can work directly from the economic data in Sections 2,3, and 4, by noting that the undiscounted straight-line depreciated cost per gallon is related to the (discounted) capital recovery payments as follows:

$$\frac{\text{Undiscounted cost per gallon}}{\text{Discounted cost per gallon}} = \frac{1}{N} \Big/ \frac{r\,(1+r)^N}{(1+r)^N - 1}$$

where r = interest rate per year and N = number of years

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* Size may not be the only factor. But this is an empirical study. If bigger plants do better, pragmatically speaking it isn't relevant for us whether that is due to better technology or "pure" size effects.

For r = 2%, this ratio is

N (years)	Ratio
5	0.9427
8	0.9157
10	0.8983
14	0.8647
20	0.8176
30	0.7465

Using this ratio and the data from Sections 2,3, and 4, we find that the undiscounted capital costs are (1980 dollars)

Single-farm operation	\$0.21-0.31/gal EtOH	(8 years)
Farm consortium	\$0.13/gal EtOH	(10 years)
Gasohol operation	\$0.16/gal EtOH	(14 years)

The corresponding energy is obtained by multiplying these figures times the energy intensities, or disaggregating and then using disaggregated energy intensities. To estimate appropriate energy intensities, we use those from [Wall Chart, 1975] halved to account for the roughly 100% inflation from 1967 to 1980. This yields an energy intensity of 37×10^3 Btu/\$ (1980).* Using this figure yields energies thus:

Single farm operation	$8\text{-}11 \times 10^3$ Btu/gal EtOH
Farm consortium operation	5×10^3 Btu/gal EtOH
Gasohol operation	6×10^3 Btu/gal EtOH

These energies are small, but not negligible, compared with those in Fig. 5-1. But note that their (possible) inequality will only enhance the inequality in the figure; the farm-size operation has the greatest capital energy.

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*Energy intensities from [Wall Chart, 1975] all in Btu/\$ (1967): New construction, 70×10^3; plumbing and heating equipment, 96×10^3; machine shop products, 55×10^3; an unweighted average is 74×10^3.

The same question must be asked about enzymes, yeast, etc., which are potentially energy intensive materials. The per gallon cost is \$0.27 for the farm-size operation, \$0.15 for the consortium size, and \$0.16 for the larger gasohol operation. Once again, the farm size uses more than the others.

Estimating the energy intensity of enzymes, etc. is difficult.* From the [Wall Chart, 1975] we have these intensities

Chemicals	245×10^3 Btu/\$ (1967)
Drugs & Toilet preparations	65×10^3 Btu/\$ (1967)

Even from a more disaggregated source [Bullard and Herendeen, 1974] there is a wide range. It is not likely that the intensity is at the high end of the range since that presumably reflects industrial inorganic chemicals. We therefore choose 150×10^3 Btu/\$ (1967), which we correct to 75×10^3 Btu/\$(1980). This yields energies:

Single farm operation	20×10^3 Btu/gal.
Farm consortium	11×10^3 Btu/gal.
Gasohol operation	12×10^3 Btu/gal.

Other sources of unequal indirect energies include different yields (gallon/bu) implying different agricultural energies per gallon, and the fact that the larger operation by necessity must pay a higher ("retail") price for corn and receive a lower ("wholesale") price for distillers grain byproduct. The latter two are a result of distance from grower to the operation, and both imply transportation energy consequences. In addition, the first two interact because changed yield implies changed corn requirement per gallon.

To illustrate the interaction, consider two ethanol operations:

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* The inclusion of \$0.06 miscellaneous for all operations will have no effect on ordering.

1: pays price p_b (\$/bu) for corn

has yield y (gallons EtOH/bu)

2: pays price $p_b + \Delta p_b$

has yield $y + \Delta y$

We will later assume that Δp_b is all for transportation and/or trade margins.

Define p_g = grain price per gallon.

$$p_{g2} = \frac{p_b + \Delta p_b}{y + \Delta y}$$

$$p_{g1} = \frac{p_b}{y}$$

$$\Delta p_g \equiv p_{g2} - p_{g1} = \frac{p_b + \Delta p_b}{y + \Delta y} - \frac{p_b}{y}$$

$$= \frac{(\Delta p_b)y - (\Delta y)p_b}{y(y + \Delta y)}$$

$$\Delta p_g = \left(\frac{\frac{\Delta p_b}{p_b} - \frac{\Delta y}{y}}{1 + \frac{\Delta y}{y}} \right) \frac{p_b}{y} \qquad (5\text{-}1)$$

Δp_g reduces to $\frac{\Delta p_b}{y}$ when $\Delta y = 0$, as expected.

Here (cf Tables 2-1, 3-1, and 4-1), $\frac{\Delta p_b}{p_b} \simeq 0.10$ and

$$\frac{\Delta y}{y} \simeq 0.10,$$

so that the effect of the yield change is as significant as that of the increased grain price. Further, speaking of indirect energy per gallon,

$$\Delta E = E_2 - E_1 = \Delta p_g \; \varepsilon_t + \frac{(-\Delta y)}{y(y + \Delta y)} \varepsilon_b \qquad (5\text{-}2)$$

where ϵ_t is the energy intensity of transportation (Btu/\$)

ϵ_b is the energy intensity of agricultural production (Btu/bu)

From Tables 2-1, 3-1, 4-1, we have these data: considering the gasohol operation as the base case (p_b = \$3.52/bu, y = 2.3 gal/bu)

Farmer consortium	$\Delta p_b = \$-0.32$/bu
	$\Delta y = -0.2$ gal/bu
Single farm	$\Delta p_b = \$-0.32$/bu
	$y = -0.1$ gal/bu

which yields

	Δp_g (\$/gal)	$\frac{-\Delta y}{y(y + \Delta y)}$ (bu/gal)
Farmer consortium	-0.0066	+0.0414
Single farm	-0.0759	+0.0197

Therefore, relative to the gasohol operation, the energy requirements for both the farmers consortium and single farm operation are reduced because of lower grain price and increased because of poorer fermentation yields.

The energy intensity of wholesale and retail trade is estimated to be 18000 Btu/\$(1980); while the corresponding figures for rail and truck transport are 39000 and 23000. The appropriate intensity is probably towards the high end of this range; we assume it to be 30 thousand Btu/\$.

$\epsilon_b \cong 180$ thousand Btu/bu [Chambers, et al, 1979]

which gives (in 10^3 Btu/gallon EtOH)

	Farmer consortium	Single farm
ΔE	+7	+1

The farmer consortium requires more energy than the gasohol operation due to the effect of reduced yield. The single farm operation uses only slightly more because the yield reduction is almost overcome by the effect of lower grain price. But given the obvious sensitivity to the yield and the fact that it apparently can easily vary by 10%, the whole effect is probably washed out by experimental uncertainty.

So far we have covered the effect of grain price and fermentation yield. To account for the different price received for dried grains, we note from Section 4 that the gasohol operation is prevented from selling dried grains at the "retail" price because it must be shipped a long distance to the consumer. The energy implication of the retail markup not collected should be added to the indirect energy requirements of the gasohol plant. This markup is assumed to be 35% of wholesale or \$0.53 x 0.35 = \$0.19 per gallon of EtOH. Again using an intensity of 30 x 10^3 Btu/\$(1980), we obtain an energy consequence of 6 x 10^3 Btu/gal.

The consequences of all these potential indirect energy differences are summarized in Table 5-2. The differences in general are relatively small(at most 8 x 10^3 Btu/gal) compared with the differences in direct energy. But additionally, there is some cancellation of the differences. For example, compared with the gasohol operation, the single farm operation has a higher energy requirement for enzymes, etc. (because it apparently uses more), but a lower energy requirement associated with the sale of its dried grains. When all differences are summed, the total difference is small (7 x 10^3 Btu/gal) and indicates more energy for the single farm operation.

Therefore the effect of all the anticipated differences in indirect

Table 5-1

Comparison of the Three Operations; Energy Requirements.

Figures in parentheses are energies, including "energy cost of energy"

	SINGLE FARM	CO-OP SIZED	LARGE GASOHOL PLANT
Description of Product	Hydrous ethanol	Hydrous ethanol	Mixture of anhydrous ethanol and gasoline
Output (Gal. EtOH/day)	35	600	6785
Proof of Product	∿180	∿190	200 (not including gasoline; EtOH/gasoline ratio can vary from 6 to 19
Yield (Gal. EtOH/bu)	2.14 ± 5%	2.08 ± 4%	2.32
Fuel type	Natural Gas	Propane	Natural gas
Use per gal. EtOH:			
Cooking	8.0 ± 6% ft^3 (9100 Btu)	0.18 ± 13% gal. (19800 Btu)	17.8 ft^3 (20300 Btu)
Distilling	68.1 ± 6% ft^3 (77600 Btu)	0.33 ± 6% gal. (36300 Btu)	
Electricity use per gal. EtOH:			
Cooking	0.020 ± 3% kWh (260 Btu)	1.55 ± 4% kWh (20000 Btu)	1.20 (15500 Btu)
Distilling	0.120 ± 3% kWh (1550 Btu)		
Total Energy Use per gal EtOH	83,500 ± 4% Btu	76,800 ± 4% Btu	35,800 ± 5% Btu
Column Diameter	4"	15"	42"
COMMENTS:	The above production for 8 hours distillation per day. "Pot boiler" with single condensing distillation column only. Feed byproduct not dried or centrifuged. Little attempt at insulating tanks, etc. Some recycling of hot water.	Intended to run continuously. Conventional distillation (stripper-rectifier-condenser) Feed byproduct centrifuged to 60% water content Extensive insulation. Fairly extensive recycling of hot water.	Runs continuously. Anhydrous distillation, but product contains gasoline. Intended for gasohol market Solid byproduct dried in separate drier. Evaporator normally used to reduce liquids from stillage, but not in operation here. Extensive use of heat recovery systems.

TABLE 5-2.

Estimated differences in indirect energy for the different size operations. In each case the gasohol operation is taken as the base case.

	Change in energy (10^3 Btu per gallon EtOH	
Cause	Farmer Consortium	Single Farm
Difference in capital expenditures	-1	+4
Difference in cost of enzymes, yeast, etc.	-1	+8
Difference in price paid for grain and difference in fermentation yield	+7	+1
Difference in price obtained for dried grains	-6	-6
SUM OF DIFFERENCES	-1	+7

energy will not change the conclusions about energy use based on direct energy only.

In Fig. 5-1, we include the result for the Schroder plant in Compo, Colorado (Jantzen and McKinnon, 1980). This plant is comparable to the farm-consortium sized plant we have studied, but appears to use 54% less direct energy per gallon. The alleged reason for this is better heat recovery; at this point we cannot verify this explanation. A recent personal communication with one of the authors [Thomas McKinnon, 19 November 1980], indicates that the researchers support these results and see no reason to run the experiment again on the suspicion of bad data.

It is also fair to point out that the plant we studied was operated by inexperienced personnel; because of expansion and sales the more experienced workers were at other installations. Operation by experienced people is expected to reduce energy requirements, but we have no estimate of how much.

6. Comparative dollar balances.

Comparsion of dollar costs reveals moderate differences in the total cost per gallon of EtOH produced. There are more interesting differences in the details. Table 6-1 summarizes the results shown in Tables 2-1, 3-1 and 4-1.

Table 6-1: Cost per gallons of EtOH, three plants, each at its lowest capacity. Dollars and cents per gallon.

	Single-farm plant, 10,000 gallons	Farm-consortium plant, ¼ million gallons	Industrial gas plant, 2½ mill gallons
Net feedstock cost	.58	.47	.99
Enzymes, etc.	.27	.15	.16
Fuel and electricity	.25	.36	.09
Labor	.45	.40	.22
Capital	.34	.14	.18
Miscellaneous	.06	.06	.06
Total cost	1.95	1.58	1.70
Sub-total, cost excl. labor cost	1.50	1.18	(Not relevant)

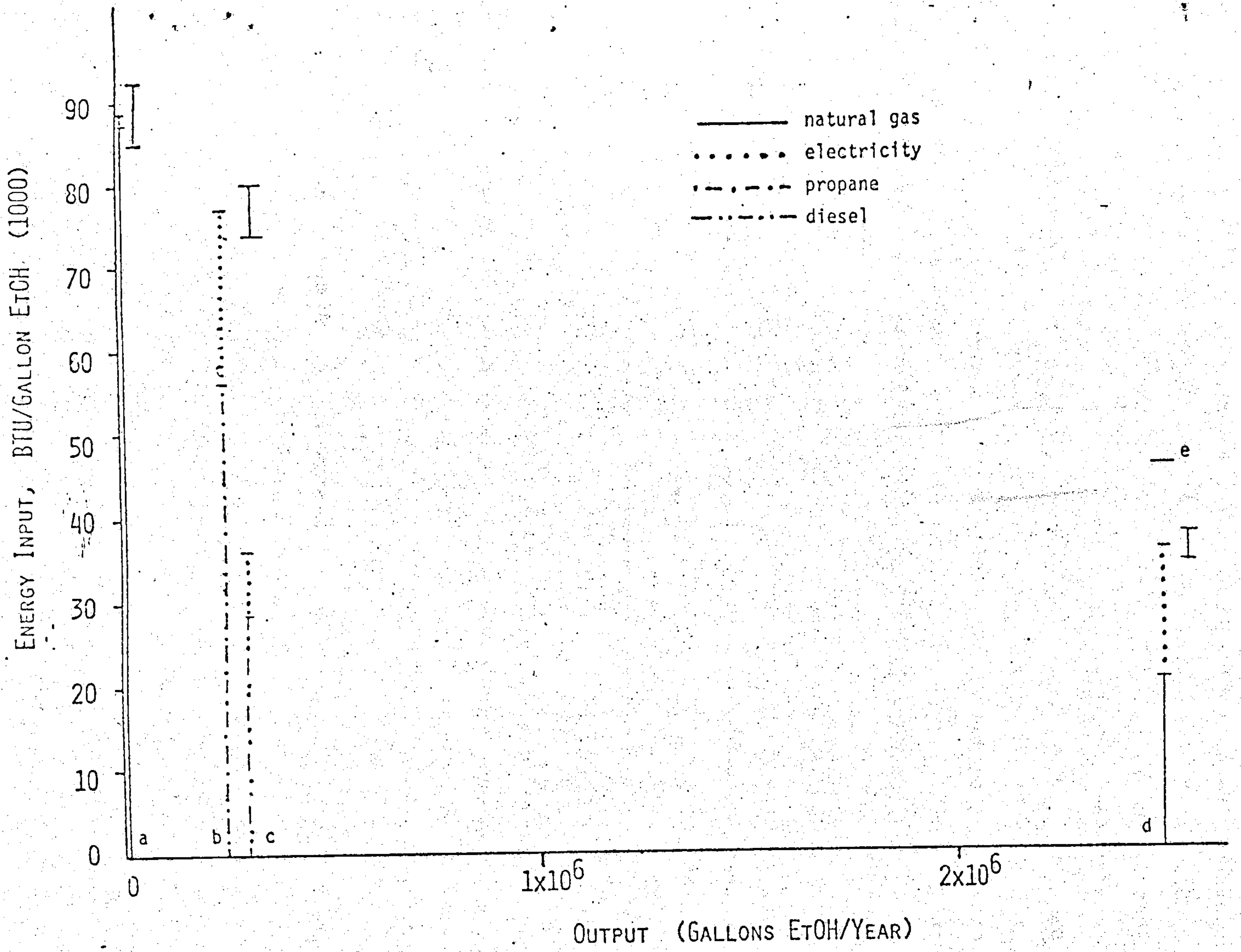

Fig. 5-1. Direct Energy Inputs for Various Alcohol Operations

Agricultural and indirect energy inputs are not included except the "back linkages" for the energy cost of energy. Shown is the energy required to produce one gallon of EtOH, though the actual product may be a mixture of alcohol and water or gasoline. Error bars are to the right of each input.

(a) Single Farm Distillery (86,700 ± 4% Btu). (The small upper portion of the bar is electricity.).
(b) Farmer Consortium Distillery (76,800 ± 4%).
(c) Schroder Operation, as studied in (Jantzen and McKinnon, 1980) (35,800 ± 5%). We have calculated and included a factor for the energy cost of energy. Their report contains no uncertainty analysis.
(d) Gasohol Plant (35,800 ± 5% Btu). The line at "e" represents the manufacturers estimate of the energy input if the evaporator were running.

The differences between total dollar costs are easily below the variations in management success that can be expected, not to mention uncertainties in the computations themselves. Note that the farm-consortium plant has higher cost of fuel than the others because it uses propane. At 63¢ a gallon (October 1980) propane costs 57¢ per 100,000 Btu, while natural gas at .32¢ per cubic foot comes to 36 cents per 100,000 Btu. With natural gas, the farm-consortium plant would show a cost per gallon of EtOH 14¢ lower than in tables (3-1 and 6-1).

The subtotals for cost minus labor in the farm-level distilleries are not meant to suggest that farmers are prepared to work for zero wage. Rather, they express the latitude of acceptable loss, given that the farmers' labor bill is not a cash charge. In practice, farmers are known to work on their own account with labor-income expectations varying according to season and type of work. Thus, their accepted cost will often be less than total cost, but usually more than the sub-total excluding labor.

The cost figures have in any event different meaning for industrial plants and farm-level plants. On the face of it, none of them is competitive with either gasoline or diesel fuel at current prices. As a practical matter, the gasohol factory may very well make a profit, even without having recourse to exceptionally good buys on some of its inputs. This could be the result, directly, of the tax incentives now in effect on gasohol, and other public support (the State of Illinois has mandated use of gasohol in its vehicles). The rationale for such public incentive and support seems to be mainly in saving foreign exchange (import substitution). There is also a variant of the infant-industry argument: current alcohol development may be necessary as a precursor to more economic biomass fuels industry later. Another, more solid rationale may be in the still controversial question of fuel efficiency. To settle this, we need more road tests, and also more precise data on the octane effect and how it may be affect refinery operation (using less heat to finish gasoline at lower octane value).

The farm-level distilleries do not aim at the gasohol market, nor could they, in general, given the proof (alcohol percentage) of their product. To enter the gasohol market, they would have to sell through large commercial distilleries at a discount for the water content of their product. Rather, the farm-level distilleries aim at supplying the farms themselves with propulsion fuel for farm machines and trucks, replacing diesel fuel with 180 proof alcohol - or, sometimes, combining alternate use of 100 proof alcohol with diesel fuel in the "aquahol" application of a diesel engine. In such use, ethyl alcohol is not now competitive with diesel fuel on the basis of price alone, nor is it likely to be so in the near future. The advantage to farmers, real or merely perceived, is twofold: security of supply against interruptions, and eventual market power (price support) whenever sufficiently many farmers build and operate distilleries to have an effect on the grain markets. Distilleries need not remove very many percent of the grain supply before this leads to upward pressure on grain prices - the generally low price elasticity of demand for food assures us of that.

7. Summary and outlook.

Energy balance comes out best in the gasohol (ACR) plant and worst in the smallest farm-level distillery. Including indirect energy in capital goods, materials and the trade margins (on feedstock grain and feed residue) changes these conclusions but slightly.

Because we lack data from large plants using conventional distillation technology, we are unable to say how far the gasohol plant's superior energy balance depends on size of the plant and how much on the ACR technology. The advantage of the larger over the smaller farm-level plant's points in any event to some economy of size, through less heat loss from the surfaces of tanks, and other features of better heat recovery. The point about comparing ACR technology with other technology need not be explored in the present inquiry, because it appears that the ACR technology is not applicable to small plants.

This comparison of energy balance in three plants is based on the use, in all three plants, of high-grade fuels. The outlook on energy efficiency may change considerably if and when the various plants switch to other fuels. The gasohol plant may switch to coal which may be cheaper than gas but likely to bring higher operational and maintenance costs.

The small, farm-level plants also have options of local fuels which are not available to a large plant, or are available to it only at higher cost: stover, scrub wood, and methane from anaerobic digestion (of manure, crop refuse, or distillery residue in case of silage feedstock). In such combinations, small-scale plants may come to compare favorably with the large ones in terms of draining on fuels which are scarce in the national economy.

The near equality in cost of production between the smaller and larger plants is not all that can be discussed. Smaller plants are more flexible, not only in their labor regime and the use of local fuels. There may also emerge an interesting difference in relation to the grain markets. Large plants, because they are less flexible and more likely to try to operate at full capacity, are also more likely to have an adverse effect on grain markets: by claiming a more or less constant share in the graincrop, they would increase the variability of supply for normal uses, which would be left with the whole of variation due to weather. Small plants, operated by farmers, can easier respond to higher grain prices by varying their operation. High grain prices are the farmers' profit anyway, so a loss on alcohol distillery account may be offset by higher profits on grain. After alcohol distilleries have grown to some sizeable volume (if that ever happens), one of the effects will be to affect the price of grain - upward. This effect means the large plants could be in some way self defeating, while the farm level plants can not lose. To the extent farm-consortium size plants are bought by non-farm groups, their retaining of the farm-level advantages will depend on how close ties they maintain with local farmers both as suppliers of grain feedstock and as buyers of feed residue.

Eventual switch to other starchy feedstocks, such as silage, will also be more feasible on farm-level plants. How transportation-sensitive the large plant is, came forth in the higher net feedstock cost even when the feedstock is grain, to the point of balancing the advantages of size in capital, energy, and labor. Silage, if it turns out to be a desirable substitute for grain, is of course even more transportation sensitive, as are local fuels such as stover.

little confusion allocating energy inputs to different portions of the production. Our measurements on the farm-sized distillery were made during two separate visits, encompassing a full cycle for one batch* During the first day, fermented beer from a previous batch was distilled. In the process, water was preheated in the condensing column and fed into a second tank. After distillation was complete, 16 bushels of ground corn were poured into the second tank, and cooking was begun. We did not measure the corn input ourselves, but we are confident it is accurate with ±5%.

Natural gas burners are used to supply energy for cooking and distillation. The quantity of natural gas used was measured directly from a Singer AL-175 meter installed on site. We were unable to personally calibrate this meter, though manufacturer tolerances are typically on the order of ±1/4% for a properly operating meter under constant climate conditions. Temperature variations, and therefore volume variations, can be expected to produce the largest error margins. Meters are typically calibrated at 60°F; our measurements were made at an air temperature of about 80°F (though, admittedly, we don't know if the gas was also at this temperature). These temperature fluctuations could produce an error of about 4%.

Consumption of electricity was measured with our own watt-hour meter. According to our calibration this meter is accurate to within ±1%. The meter was placed in series with the agitator motor, and remained there for the distillation process. The motor consumed

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*We took distillation data for two batches. Since one batch was in an uninsulated tank, and the other in an insulated one, we use cooking and distillation data for the insulated one only. The insulation consisted of 3-1/2" fiberglass applied rather casually, but the distillation energy for the insulated tank was bout 6% lower.

APPENDIX 1

MEASUREMENT OF ENERGY INPUTS

This appendix will describe the processes used to measure energy inputs for the three distilleries. We will note any irregulatiries or special circumstances that may lead to misleading interpretations. Finally, a brief discussion will be given on the magnitude of errors.

Concern about energy inputs to alcohol distilleries is a recent development, and coincides with the increasing interest in the potential of alcohol as a liquid fuel. The technologies for energy efficient distillation are new and often just one step above the experimental level. The major concern of the operators of the distilleries we visited was simply getting their units operating properly. Complete optimization of energy inputs cannot and should not be expected until the distilleries are satisfied they are consistently producing a good product. For example, one distillery had the potential to reduce energy at the cooking stage, but this decrease in energy consumption came at the cost of increased complexity in operation. Understandably, there was little interest in complicating the operation until all of its problems are solved. These figures for energy inputs therefore may not be the lowest achievable, but do represent the current state of technology.

A. FARM-LEVEL DISTILLERY

The production processes of a farm-level distillery are simple enough that they can be directly observed and measured. Cooking, fermentation and distillation are all batch operations, and there is electricity at a constant rate (measured in kWh/hr). Although we did not have the meter installed during cooking, we can determine the electrical demand from the operating time for the motor during the period. We did not measure the energy input to run the motor during fermentation. (Whenever the heat from fermentation exceeds a certain level, cold water is fed through cooling coils and the agitator is turned on.) However, this comprises only a small portion of the fermentation time, and running time of the motor is very small in comparison with cooking and distillation times. We also did not measure electrical inputs for lighting (one bulb) or the control panel, considering both to be very small.

Cooking inputs for 16 bushels of corn was measured to be 280 cubic feet of natural gas. The motor was in operation for 2.5 hours; based on a measured consumption rate of 0.28 kWh/hr, this is an electrical consumption of 0.7 kWh for cooking.

Four days later we returned to measure energy inputs for distillation. (The plant was closed on Sunday, the third day, so we had to wait an additional day). Heating of the beer was begun at 5:30 A.M., and it took about 4-3/4 hours before product began to be distilled. Energy requirements for this startup was 800 cubic feet natural gas and 1.3 kWh electricity (4.75 hr. x 0.28 kWh/hr).

Output was measured on a gallon-by-gallon basis with a calibrated gallon container. The proof of each gallon was measured, as well as the time it took for distillation. Electricity and gas consumption rates were noted throughout the distillation process, and were found to be relatively constant. In particular, electricity consumption was steady and led to demand during distillation of 2.9 kWh in a 10.3 hours time period, or 0.28 kWh/hour.

The boiler was fired until 39 gallons of 180 proof product had been distilled. Energy inputs for this distillation, measured directly from the meters,were 2390 cubic feet natural gas and 9.1 kWh electricity.

Total energy inputs for the 39 gallon batch therefore were 280 cubic fe ural gas for cooking, 2390 cubic feet for distillation,and 4.8 kwh electricit These inputs are equivalent to an input for each gallon of ethanol of 8.0 cubic feet natural gas for cooking, 68.1 cubic feet for distillation and 0.14 kWh electricity. The alcohol yield was (39 gallons)X(0.9)/(16 busl or 2.19 gallons EtOH/bushel.

On the following graphs we have shown three interesting production relationships for the pot-boiler still. Since distillation in this still involves simply boiling the beer, there clearly are diminishing returns as the alcohol content of the remaining mash decreases. These diminishing returns affect the time and energy required to produce additional gallons of ethanol, especially near the end of the batch. The important question for the operator is when do these increases in energy and time exceed the value of the alcohol produced?

Figure A1-1 shows a graph of cumulative production of ethanol during distillation as a function of time. The zero-point in time is defined as the time at which the first product dribbled out of the columns. Note that the rate of production was fairly constant for about the first five hours, but then output began to level off.

The additional energy required just for the distillation of each individual gallon of EtOH is shown in figure A1-2 (back linkages, or the energy cost of energy, are included) In the beginning, energy inputs were low and a bit eratic (perhaps due to non-equilibrium temperatures in the columns, or general start-up irregularities). As more ethanol was distilled energy inputs rapidly increased, and eventually exceeded

150,000 BTU for the final gallon.

However, these graphs show only distillation energy inputs, and therefore do not include the direct energy requirements for cooking. Before any distillation can begin, a considerable input is required to cook the mash (prior to fermentation) and, after fermentation, to preheat the mash to boiling. This energy can be considered a "fixed" input which must be divided among the output. As more gallons are distilled, the average input per gallon due to this fixed share decreases.

The total energy inputs therefore consist of two factors: 1) a "fixed" input, whose magnitude is inversely proportional to the number of gallons produced, and 2) a "marginal" input, whose magnitude increases rapidly with number of gallons produced. Figure A1-3 shows the interaction of these factors. The curves represent cumulative averages; for example, at the end of 20 gallons the average fixed energy embodied in the alcohol is 62,500 BTU/gallon, the average "marginal" energy (from only distillation) is 32,500 BTU/gallon, and the net average energy input is 95,000 BTU/gallon. At 30 gallons production the average inputs for distillation equal the average inputs from the "fixed factors," an the effect of diminishing returns is large enough to offset the declining average fixed inputs. Total average energy input per gallon, therefore, increases.

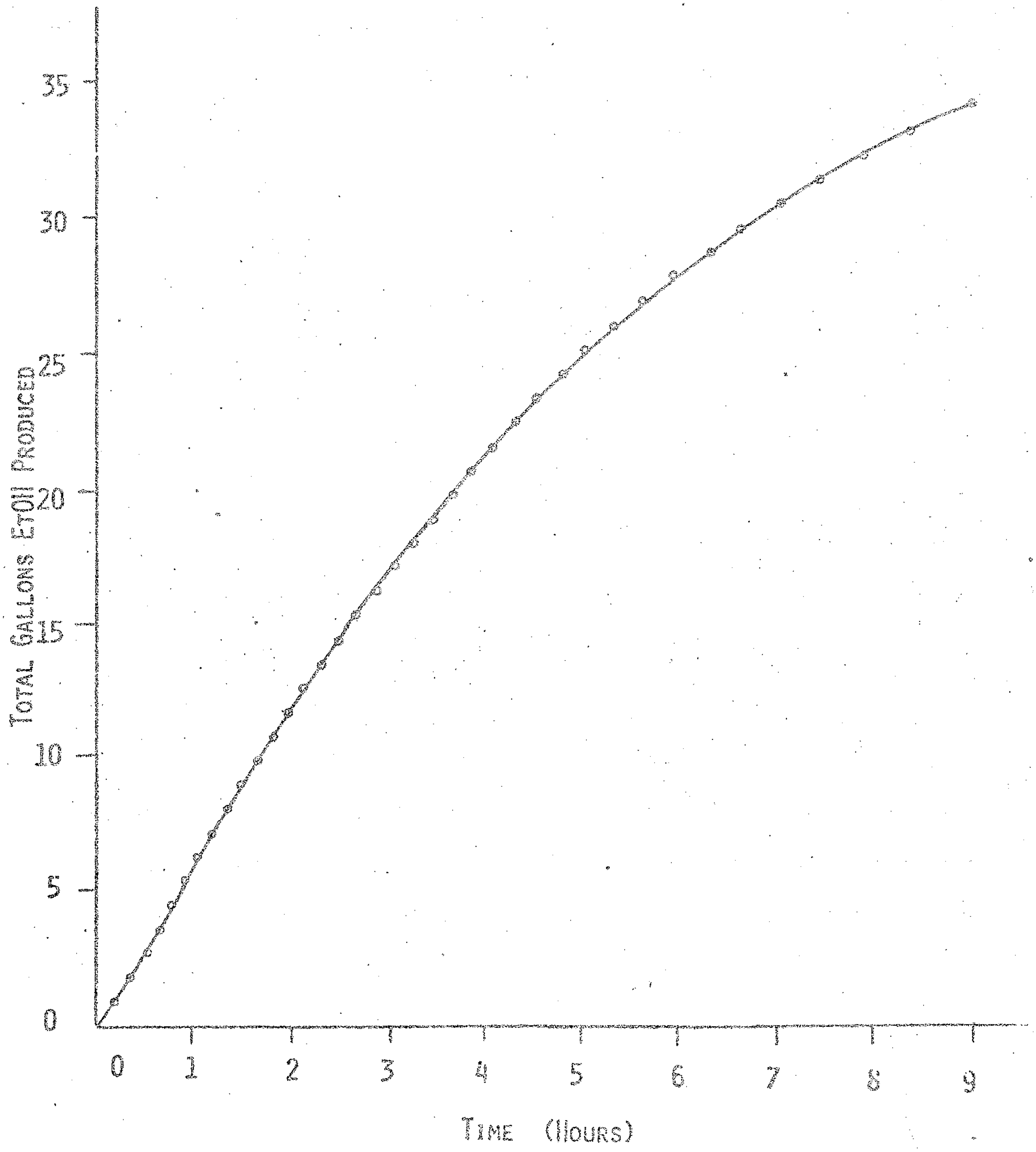

Fig. AI-1. Single Farm Distillery,
Production of EtOH as a Function of Time.

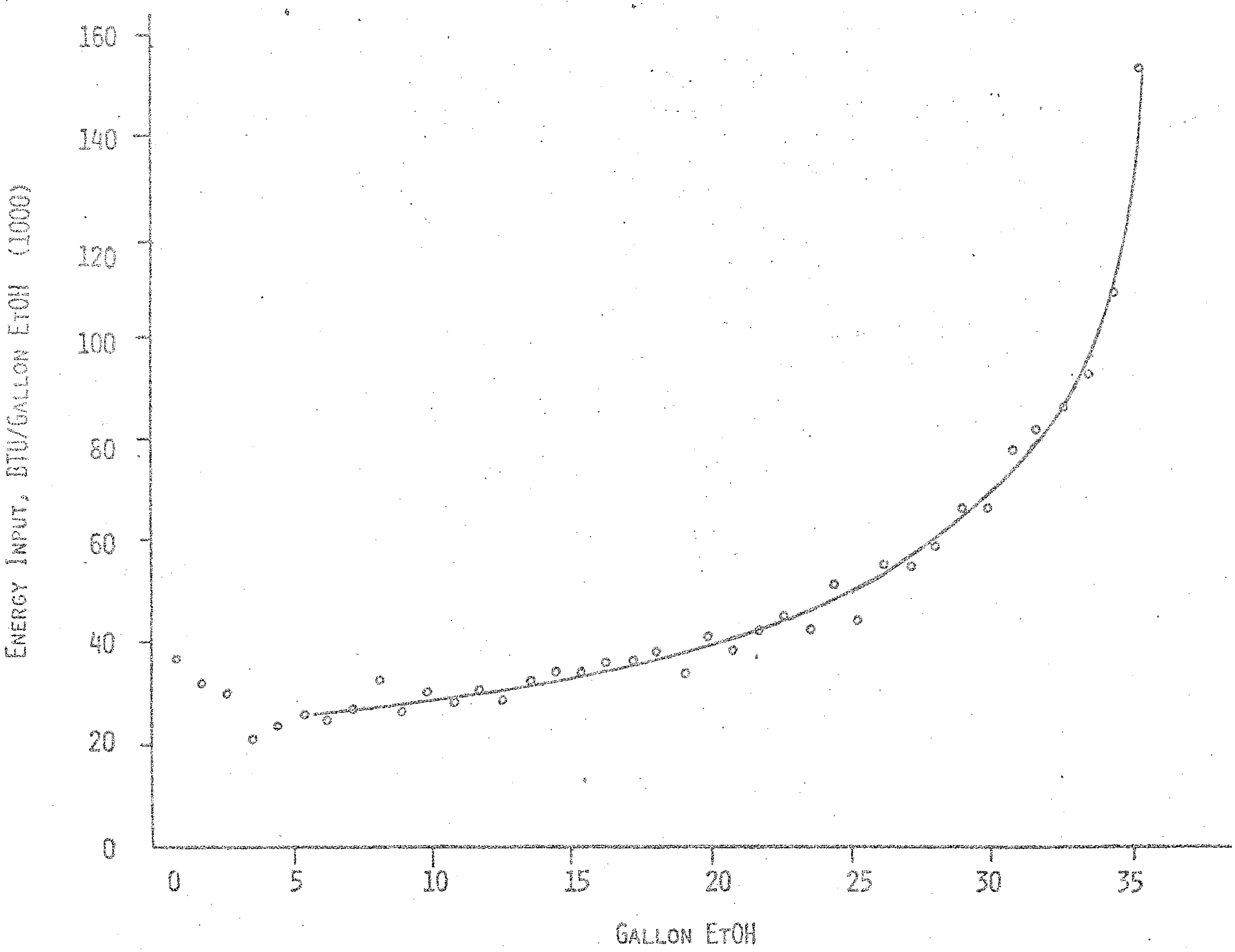

Fig. A1-2. Single Farm Distillery - Additional Direct Energy Inputs to Distill Each Additional Gallon of EtOH (including the energy cost of energy).

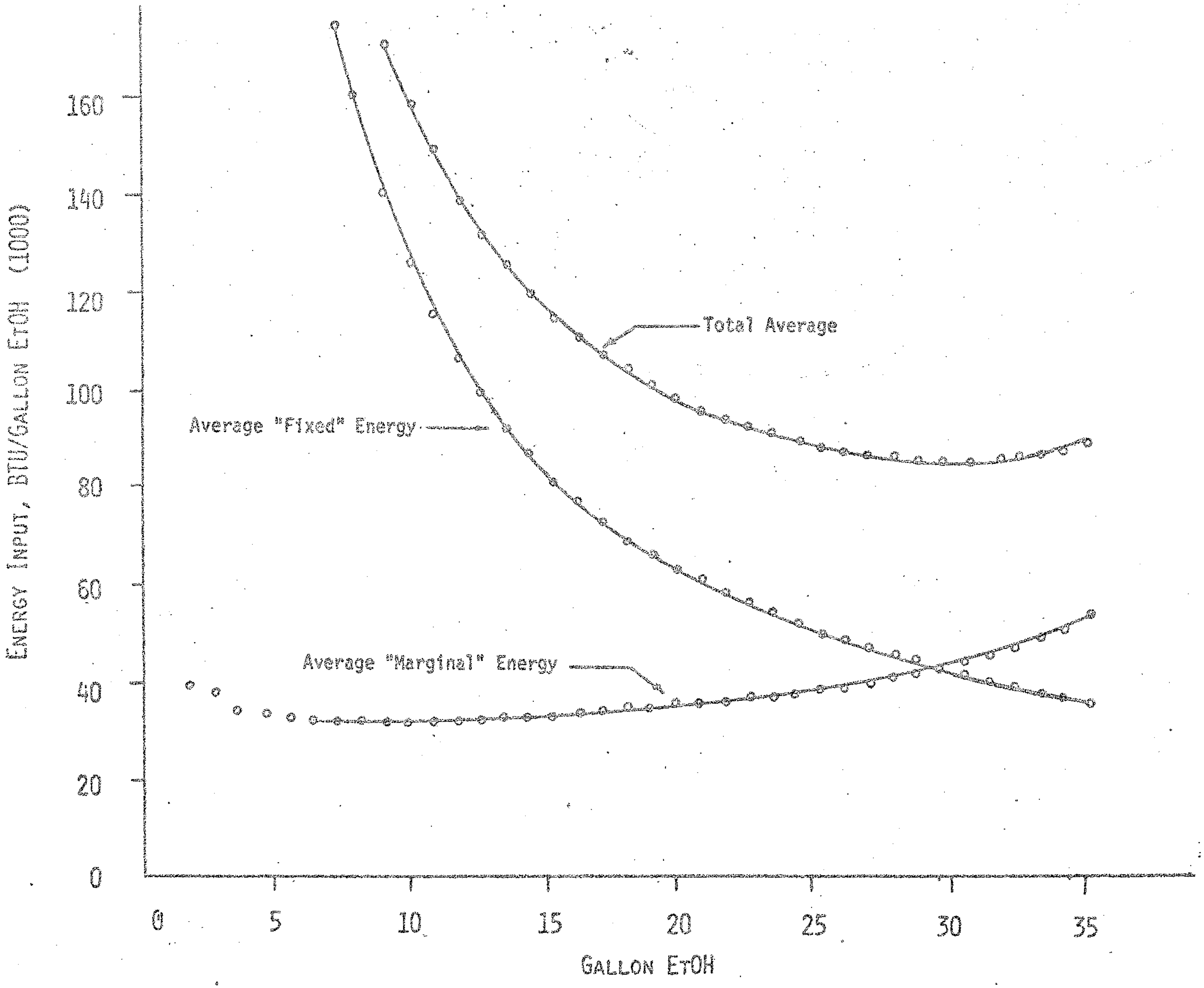

Fig. A1-3. Single Farm Distillery, Average Direct Energy Input
for EtOH [illegible]

B. CONSORTIUM-SIZED DISTILLERY

The consortium-sized distillery represents a facility whose scale of output is approximately 1/4 million to 1 million gallons product per year. The unit would be expected to run 24 hours a day, producing alcohol at a maximum of about 190 proof. The distillery we studied used propane as a boiler-fuel for cooking and distilling, and electricity for pump and motor operation. Separate boilers were used for distillation and cooking, and these boilers were metered separately. There was, however, no opportunity to disaggregate electrical demands, as the entire distillery (including office space) was monitored by just one meter.

Propane inputs were measured with an on-site Rockwell L-P propane flow meter. The propane flows through the meter in gaseous form though the calibration is scaled to read liquid gallons. According to manufacturer specifications, under constant climate conditions (60°F 1/4 lb. pressure) this meter is accurate to within ±1/4%. Temperature variations will again affect these readings, although we can only approximate the magnitude. Readings were made at an air temperature of about 80°F, so an error of ±4% is not unlikely.

Product was measured with two separate meters: 1) a "Gasboy" flowmeter and 2) a float in the storage tanks that measured changes in the level of the liquid. This scale is calibrated so that a one-inch increase in height corresponds to a 710.9 gallons. We found that there was a 7%-10% difference between these two meters, the flowmeter being consistently lower. With the data we have we cannot conclude that one meter is more accurate than the other, so we have averaged the readings.

Proof of the product was measured about once every hour. It seldom dropped below 190, and at times reached as high as 193 (temperature corrected). We will base our calculations on a 190 proof product.

Our measurements were made during two visits over a three-day operating period. The total time over which we collected data was 52 hours. However, after 38.5 hours of operation, the operators began to distill a large tank of beer with only 7.5% alcohol. (Under normal circumstances, the beer should have an alcohol content of 9-10%.) Although low yields like this should certainly be an occasional consequence of operation, we felt that analysis based on irregularly low yields could lead to misleading results. Calculations for corn input and alcohol output were therefore based on this shorter but more consistent 38.5 hour distillation period.

Measurements taken throughout the visit indicated that propane for distillation was burned at the constant rate of 8.6 gallons per hour. This rate was maintained even during the distillation of the lower concentration alcohol. We relied on this consumption rate for our calculations of energy input. Although this is a slight approximation, it allowed us to interpolate energy consumption for time periods during which we have better data on other inputs.

The fermentation product of 27,011 pounds of corn were distilled from 8:00 A.M. on the first day until 10:30 P.M. on the second day. We calculated that, during this 38.5 hour period, (38.5) (8.6) = 331.1 gallons of propane were burned. The amount of product produced, as measured by the Gasboy was 1011.7 gallons. The float on the storage tanks showed a change in product levels of 1'6-5/8" ± 4%, indicating a production of $(1'6\text{-}5/8'')(710.9\ \frac{\text{gallons}}{\text{ft}}) = 1103.4$ gal. The average of these two meters is 1058 gallons product.

Cooking is done in batch operations, so we measured energy consumed for each "cook" of 4000 pounds corn. The total propane consumption for seven of these cooks was measured at 195.2 gallons propane. However, one particular cook was irregular in that the cooling coils were inadverently turned on during the cook. This particular cook took 34 gallons propane. We feel that this additional energy should be subtracted, as it represents an abnormal input that may lead to misleading results.

If we let x = average consumption per cook, then $195.2 - (34-x) = 7x$ or $x = 26.9$ gallons per cook of 4000 pounds .

Consumption of electricity was measured at intervals of about 30 minutes. Based on these measurements as well as measurements during the entire visit, we concluded that consumption of electricity at the plant could be approximated as a constant rate of 40.5 kwh/hr. During the 38.5 hour measurement period the total electrical consumption was then (38.5)(40.5) = 1559 kWh.

These inputs can be scaled to energy per gallon, as well as energy per 16,000 pound corn "batch," (16,000 pounds is chosen as it represents the standard input to one of the large fermentation tanks). Since each of the "cooks" we measured cooked 4,000 pounds of corn, the energy required for 16,000 pounds is (4)(26.9) = 108 gallons of propane. The distillation p can be expected to consume (16,000/27,011)(331.1) = 196 gallons propane for a 16,000 pound batch. Finally, electrical consumption can be scaled down in a similar fashion, so that the consumption for 16,000 pounds is (16,000/27,011)(1,559) = 923 kWh.

Based on an input of 27,011 pound corn (482 bushels) and an output of 1,058 gallons of 190 proof product, the yield is (1,058 gallons) (0.95)/482 bushels = 2.08 gallons EtOH/bushel. The output from a 16,000 pound corn input would be 594 gallons EtOH. Energy inputs normalized to each gallon are, therefore; 0.18 gallons propane for cooking, 0.33 gallons propane for distrillation, and 1.6 kWh electricity for each gallon of EtOH.

C. A GASOHOL PLANT

The gasohol plant we visited had approximately ten times the capacity of the consortium sized unit, and 100 times the capacity of the farm-sized unit. As can be expected, the complexity of the operation increases considerably with these increases in scale. Although the processes themselves (e.g. cooking, adding of enzymes, etc.) are straight forward and similar to the smaller units, the interaction of the system as a whole is difficult to study. We therefore treat the gasohol plant as a "black box" and from a quantitative standpoint, concern ourselves only with the plant's input and output. Flows within the plant can be qualitatively discussed, but here we do not measure them.

It should be emphasized again that the distillation process itself does not produce gasohol, but rather a blend of about 90% alcohol and 10% gasoline. Blending can be done afterwards to adjust the gasoline content. Figures for capacity reflect the total amount of alcohol produced.

Data were collected on a two day visit to the plant, comprising a total period of 28 hours. The plant was operating smoothly and continuously during this interval. Since cooking as well as distillation were continuous processes, we measured energy inpurs as a function of time (i.e. energy consumption per time). We could then measure alcohol output over time, and from this calculate the energy required per unit of alcohol or bushel of corn.

Only two meters were used to monitor the plant, a Singer natural gas meter and a Sangamon electric meter. Both of these were owned by the utility, and measured energy to the entire plant (including offices). Natural gas was consumed in two boilers that supply steam for the plant, and also in a separate burner used for drying the by-product. We were unable to measure how much gas is used by just the burner, though the plant owner stated it was approximately 10,000 BTU/gallon EtOH. This figure, when added to our final result for energy consumption per gallon of EtOH (31,000BTU without back linkages, 36,000 BTU with back linkages) agrees closely with ACR's claim of 40,000 BTU/gallon EtOH for operation including the evaporator.

During our stay we measured about once every thirty minutes the cumulative consumption of natural gas and electricity. Our measurements showed that under normal operating circumstances, the consumption rate for these two fuels was nearly constant over time. We found that natural gas was burned at a rate of 5,050 cubic feet per hour, or 121,000 cubic feet per day. Electricity consumption was measured to be 340 kWh/hr, or 8,170 kWh/day.

Corn was fed continously through a mill and into the cooker. The flow rate of corn is determined by the auger speed on the feed handling system. Measurements were taken within the plant every hour to independently monitor the corn input. About 80% of these measurements indicated a feed rate of 120 pounds per minute. Occasionally, however, it jumped to slightly over 130 pounds/minute.

Cooking was controlled so that corn was fed into the cookers if and only if they were in operation. A clock was used to measure the number of hours per eight-hour shift that the cooker is on, which in turn gave the amount of corn input for the same time interval. Typically, the cooker ran on a nearly continuous basis (while we were there, it ran 22 3/4 out of 24 hours). However, three days prior to our visit the cooker was off for hours at a time, and consequently the total corn input was reduced below normal levels. To obtain proper figures for yields we contacted the operators three days after our visit to determine output from the corn inputs we observed.

The total corn converted in one day, assuming 22 3/4 hours of cooking and a feed rate of 120 pounds per minute (7,200 pounds per hour) was (22 3/4)(7,200) = 164,000 pounds per day, or 2,930 bushels per day. The amount of anhydrous alcohol produced from this corn was 6,785 gallons measured by the operators. Alcohol yield, therefore, was 6,785 gallons/2,930 bushels or 2.32 gallons per bushel.

Based on these figures we can directly calculate the energy required to process one gallon. The amount of natural gas is 121,000 ft^3/6,785 gallons or 17.8 ft^3/gallon. Electrical demand is 8,170 kWh/6,785 gallons or 1.20 kWh/gallon.

Appendix 2 Coproduct credits.

The substantial feed byproduct from ethanol distilleries using grain as feedstock necessitates discussion of three related issues: conventional market value of DDG ("distillers' dried grains"); the feed value of the coproducts; and the energy credit for the coproduct, based on energy used to produce the nearest substitute, which is soybean meal.

a) Conventional market value of DDG. Distillers' dried grains, DDG, is a recognized item in agricultural statistics, with wholesale price quoted month by month and year by year. We first want to compare these prices with those of soybean meal, a roughly comparable, high-protein feedstuff. Using annual data from 1964 through 1977 [Agricultural Statistics 1979, p.60, Table 81], and comparing them with prices of soybean meal with 44% protein, we obtain soy/DDG price ratios varying from 1.166 (1964) to 2.245 (1972), averaging 1.41 for the 14 years; eliminating the exceptional ratio of 1972, we obtain 1.34 for the other 13 years. Accepting 1.35 as a round value, we conclude that the market treats DDG as equivalent of 74 percent of the 44 percent soybean meal, or as (.74 X .44 =) 33 percent protein. The same result is obtained from more recent monthly data[Feed Situation, 1977-80].

Next we should compare DDG prices with those of corn, to establish the chargeoff for coproduct value. This comparison will come out different for farm-level and larger distilleries. For farm-level distilleries, the relevant price of corn is that paid to farmers in the area. In case the distillery owners use the coproduct feed themselves, or sell it to nearby farmers without any commercial intermediaries, the relevant price of DDG is also not the wholesale price but the price paid by farmers.

For corn, the USDA suggests a trade margin of 10 percent: when farmers are paid $3.20 a bushel, industrial distillers would have to pay $ 3.52.

There do not seem to be published any prices-paid-by-farmers for DDG, but those for soybean meal reveal a traders' margin of 35 percent. Thus, for the farm-level distillery, the wholesale price for DDG plus 35 percent comes to the same as the wholesale price for soybean meal, which then is the economic value of DDG at this level.

Data for the years 1964-77 indicate an average price ratio DDG wholesale price/corn farm price of 1.46, while recent years and months consistently hover around 1.70. Accepting these as representing three more years, we obtain a ratio of 1.50 as average of 17 years. For farm-scale distilleries, we would then add 35 percent for the traders' margin to obtain farm value (price paid by farmers), and arrive at just over twice the farm-gate (paid <u>to</u> farmers) price for corn. Thirty percent of the volume of corn should then be credited with 60 percent of the price of corn. For industrial distilleries, the figure is lower. The price paid for corn being higher, the wholesale price of DDG becomes only (150:110=) 1.37 times that of corn, and no further margin applies, since the large distillery must sell on the wholesale market ; they can not reach individual farmers directly.

At present, the recent DDG: corn price ratio of 1.70 should be used; that certainly seems adequate for 1980. Then the value of feed residue on the farm-level distillery rises to 2.3 times that of corn, or 69 percent for the 30 percent residue. The large distillery's selling price could go to 1.55 times that of the corn, that is 47 percent of the price for each bushel (for its 30 percent residue), or 35 percent of solubles are not recovered.

b) <u>Feed value of DDG</u> is more complicated because of the varied results that obtain in applying different feed mixtures and in feeding different kinds of animals.*

Distillers' feed residue (from corn or sorghum) has its greatest value as feed supplement to cattle, especially dairy cows. To some extent, such supplement value is enhanced in distillery residue through the chemistry of yeast fermentation. The protein in the distillery residue is thus not merely the protein that existed in the feedstock grain. The animal scientist makes the distinction between DDG (without solubles) and DDGS (which includes the dried solubles - about one-fourth of the residue, by weight). The former appears to have higher feed value, pound for pound, than the latter, but is of course of lesser weight, from each unit of grain feedstock. Recovery of the solubles appears to work some impairment of the feed value of the protein in the total residue. The difference in feed value between the DDG and the DDGS (from a given unit of feedstock grain) is thus less than the difference in poundage.

This difference is not reflected in recorded wholesale prices; the statistics know only one category of DDG (which is mostly DDGS). In comparing feed rations, DDGS appears to have the feed value, compared to soy meal, that would correspond to the difference in wholesale price. DDG (without solubles), even though sold at the same wholesale price, comes out as 20 percent cheaper (for the feed value delivered) than soymeal. Hence, a farm-level distillery operator who produces DDG (without solubles, to save energy) and gets it used on the same or on a nearby farm, in the optimal feed mixture, could well place a higher value (per pound) on DDG (without solubles), than would follow from the wholesale price ratio; the price tag on DDG (without solubles) could be raised by 25 percent. This

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* The following is based on[Larry L. Berger, 1980].

comes close to justifying, for instance, the feed credit used in the report on the Schroeder distillery in Colorado. [Jantzen and McKinnon, 1980]. But also justifies a 60% byproduct credit on the singe-farm distillery.

Whether this advantage could be obtained also in large distilleries, may be worth investigating. Since the increased value of DDGS over DDG without solubles (per unit of feedstock grain) is modest (in the range of 10 to 15 percent), it may not be worth the added energy use in the recovery process.

Wet stillage as energy feed for ruminants has less economic value but also takes less energy to secure. Specialized uses (e.g., dried solubles in swine rations) may have other potentials, as yet not well explored.

c) <u>Energy credit</u> for distillery residue can not be computed on the basis of what fraction of the feedstock grain, or of its economic value, is recovered in the distillery feeds. Rather it should be based on the energy needed to produce DDG:s nearest substitute, which is soybean meal.

Soybeans require less energy in production than corn, largely because of the difference in nitrogen fertilizer. Because of lower yields per acre, the difference in energy requirement per bushel is less than per acre. In the central Midwest, we may reckon with energy inputs of about 90,000 Btu per bushel of soybeans (1500 per pound, at 60 pounds per bushel), against about 120,000 Btu per bushel of corn (at 56 pounds per bushel).

To distribute the energy used for soybean production between the oil and the meal, we need to consider the weight proportions of these two products (per unit of bean processed) and the price proportions between them. The physical oil/meal proportion comes to 18.5:81.5 (of the products obtained; a few percent of the bean weight is lost in processing). The higher price of oil (per pound) raises the value proportion of soy milling to 40:60. Hence the share of meal in value is about 74 percent of its share in weight (60/81.5 = .736), and the energy charge for a pound of meal is about 1100 Btu/lb.

This energy charge will be applicable to distillers' feeds according to how many pounds of soybean meal they replace. 12 pounds of DDG (without solubles) replace about as many pounds of soy meal, hence this would create an energy credit for byproduct of 13,000 Btu/bushel of grain feedstock. 17 pounds of DDGS would replace (17 X .8 =) 13.6 pounds of soy meal, and cause an energy credit of about 15,000 Btu/bushel of grain feedstock.

These energy credits are basically the same for small and large distilleries. They are proportionately far smaller than the corresponding dollar credits for product value. The charge, that substituting distillers' feeds for soybean meal will lead to more energy intensive crop farming, still stands.

Appendix 3. Interest charges on fixed capital.

Cost of capital is influenced by the rate of interest, which may vary within very wide limits, as recent experience has shown. High current interest rates act as a deterrent against investment, especially for those who have to borrow the funds or some large part of them. In current account there should also be interest charges on inventory (carryover), which could also deter expansion in periods of high current interest rates, even expansion which only aims at using existing capacity in full. Inventories in alcohol distilleries are hard to capture, especially on the small ones where they merge with farm inventories.

For capital charges over the lifespan of the installation, an entirely different approach to interest charges must be discussed.

Current-term interest rates in times of inflation are "high" only because they have to be paid in the short term, before the borrower has had time to cash in on any of the capital-gains consequences of inflation. In time of inflation, it is profitable to be in debt, provided one can handle the cash flow. Over the years, most of the interest charges are compensated by the falling real value of the debt. Conversely, if current terms are preferred over the constant ones, the book value of fixed assets would go up, the more so the higher the rate of inflation and the rate of interest. Since it is impossible to estimate, ever so tentatively, what future rates of inflation and inflation-induced interest rates will be, the only feasible method is to assume that the value of the dollar, and the prices of capital goods, remain stable from now on, and apply an interest charge that would be reasonable under those conditions. Such rates are, under modern and normal conditions, rather low. How low can be explored from the statistics of recent decades. Appendix Table 2:1 shows some representative data.

The moving five-year averages show that at no time since 1950, has the real rate of return to money reached 2½ percent for any extended period. In recent years, annual rates have varied erratically, being occasionally negative. In most of the seventies, moving averages were below 1 percent. The sixties had higher rates, but the fifties were as erratic as the seventies, with moving averages below 1 percent in the late fifties and negative in the early part of the decade, as also happened in many years before that.

Appendix Table 2-1 United States: Current rates of interest, rates of inflation, and real rate of interest

a) 1950-70

Year	Prime rate, 4-6 months	Implicit price deflator, GNP, percent change	Real rate of interest	Same, in five-year moving average
1950	1.45	1.39	.06	
1951	2.16	6.73	-4.28	
1952	2.33	2.22	.11	- .48
1953	2.52	.91	1.60	- .35
1954	1.58	1.47	.11	.49
1955	2.18	1.45	.72	.49
1956	3.31	3.41	-.07	.15
1957	3.81	3.72	.09	.60
1958	2.46	2.56	-.08	.88
1959	3.97	1.60	2.33	1.23
1960	3.85	1.67	2.14	1.63
1961	2.97	1.26	1.69	2.09
1962	3.26	1.15	2.09	2.11
1963	3.55	1.32	2.20	2.16
1964	3.97	1.49	2.44	2.38
1965	4.38	1.93	2.40	2.32
1966	5.55	2.71	2.77	2.25
1967	5.10	3.24	1.80	2.33
1968	5.90	4.00	1.83	2.28
1969	7.83	4.82	2.87	
1970	7.72	5.46	2.14	

b) 1970-79

Year	Prime rate charged by banks			
1970	7.91	5.4	2.4	
1971	5.72	5.1	.6	
1972	5.25	4.1	1.1	1.44
1973	8.03	5.8	2.1	.6
1974	10.81	9.7	1.0	.8
1975	7.86	9.6	-1.6	.8
1976	6.84	5.2	1.6	.5
1977	6.83	5.9	.9	.4
1978	8.11	7.4	.66	
1979	11.04	10.8	.22	

Sources: a) Historical Statistics of the United States, Colonial Times to 1970. Part 1, p. 224, Table F 1-5 and Part 2, p. 1002, Table X444-445, Washington, DC 1976

b) Statistical Abstract 1979; col. 2, 1979, from Survey of Current Business, July 1980, p. 18, Table 19; col. 1 1978 and 1979 from same source, August 1980, pp 5-15.

APPENDIX 4.

ESTIMATES OF UNCERTAINTY IN ENERGY REQUIREMENTS.

We carry out an elementary analysis here, in which we measure, guess, or obtain from manufacturers uncertainties in the various quantities. Total uncertainty is then calculated on the assumption that the various uncertainties are independent, and small, so that a power series approximation can be used. If the desired quantities, energy use per gallon of EtOH, is a function of many inputs, i.e.,

$$E = f\cdot(X_1, X_2, X_3, ----)$$

We assume

$$\frac{\Delta E}{E} = \sqrt{\left(\frac{\partial f}{\partial X_1} \quad \Delta X_1\right)^2 + \left(\frac{\partial f}{\partial X_2} \quad \Delta X_2\right)^2 + --- \left(\frac{\partial f}{\partial X_3} \quad \Delta_{X_2}\right)^2}$$

Further, if $f(X\ , X\ , --- X_n)$ is only a product or quotient of the X ---- X_n (e.g., $f = X_1 X_2/X_3$),

$$\frac{\Delta E}{E} = \sqrt{\left(\frac{\Delta X_1}{X_1}\right)^2 + \left(\frac{\Delta X_2}{X_2}\right)^2 + \left(\frac{\Delta X_n}{X_n}\right)^2}$$

The quantities we deal with are related as products or quotients, so the latter equation is appropriate.

Besides the uncertainty from measurement errors and equipment calibration, there is the overall uncertainty from the variability in yearly output. For example, we already mentioned that the output of the farm size operation could be from 10 to 15 thousand gallons per year. Since this variation affects only the per-gallon capital costs, depending on the particular operation, the effect on energy cost is relatively samll.

It does affect labor costs, but these are assumed to have zero energy intensity. Returning to the single-farm operation, we see a variation of per gallon capital cost (undiscounted) of $0.21 (15 thousand gallons EtOH/year) to $0.31 (10 thousand gallons EtOH/year), which we have already included in the discussion in Section 5; it results in a variation of 3 thousand Btu/gallon EtOH.

We do not know the uncertainty in the yearly output for the larger operations. One argument says it is relatively low because a stoppage is expensive, mainly because the labor costs are essentially fixed. The only energy change is from capital expenditures. Again, using figures from Section 5, we find that a 30% reduction in yearly output will increase per-gallon energy requirements by 2 thousand Btu (consortium sized) and 3 thousand Btu (gasohol operation).

These uncertainties are in the indirect per-gallon energy requirement. Since this report stresses the direct requirements, we do not pursue this source of uncertainty further.

Uncertainties in direct energy requirements are calculated below.

A. FARM-SIZE OPERATION - UNCERTAINTY

Variable	Estimated % Uncertainty	Comments
1. Volume of product (gal)	± 1	Measured with calibrated bucket
2. Proof	± 1	Temperature dependent
3. Corn (bu)	± 5	Estimated
4. Gas (ft^3)	± 1	Meter instrumental inaccuracy

A. SINGLE-FARM OPERATION - UNCERTAINTY (continued)

Variable	Estimated % Uncertainty	Comments
5. Gas (ft^3)	±4	Volume change of gas with temperature
6. Gas (ft^3)	±3	Uncertainty in deciding whe process is considered compl
7. Electricity	± 1	Meter instrumental inaccura

Step		Pertinent Uncertainties	% Uncertainty-Units ($=\sqrt{\Sigma(\ )^2}$)
Cooking	Gas	1, 2, 4, 5,	4.4 ft^3/gal EtOH
	Electricity	1, 2, 7	1.7 kWh/gal EtOH
Distillation	Gas	1, 2, 4, 5, 6	5.3 ft^3/gal EtOH
	Electricity	1, 2, 7	1.7 kWh/gal EtOH
Yield		1, 2, 3	5.2 gal EtOH/bu

B. FARM-CONSORTIUM OPERATION - UNCERTAINTY

Variable	Estimated % Uncertainty	Comments
1. Volume of product	±4	Uncalibrated meter and ta
2. Proof	±1	Temperature dependent
3. Corn	±5	Estimated
4. Gas	±1	Meter instrumental inaccu
5. Gas	±4	Volume change of gas with temperature
6. Gas	±5	Uncertainty in waste heat recovery
7. Electricity	±1	Meter instrumental inaccu

B. COOP-SIZE OPERATION - UNCERTAINTY (continued)

Variable		Pertinent Uncertainties	% Uncertainty-Units ($=\sqrt{\Sigma\ (\ )^2}$
Cooking	Gas	1, 2, 4, 5, 6	7.7 ft^3/gal EtOH
	Electricity	1, 2, 7	4.2 kWh/gal EtOH
Distillation	Gas	1, 2, 4, 5,	5.8 ft^3/gal EtOH
	Electricity	1, 2, 7	4.2 kwh/gal EtOH
Yield		1, 2, 3	6.5 gal EtOH/bu

C. GASOHOL PLANT - UNCERTAINTY

Variable	Estimated % Uncertainty	Comment
1. Volume of product	±1	Measured by operators
2. Proof	±0.5	
3. Corn	±5	Based on observed varia
4. Gas	±1	Meter instrumental accu
5. Gas	±4	Volume change
6. Electricity	±1	Meter instrumental inaccu

Step		Pertinent Uncertainties	% Uncertainty-Units ($=\sqrt{\Sigma\ (\ )^2}$
Cooking	Gas	1, 2, 4, 5,	4.3 ft^3/gal EtOH
	Electricity	1, 2, 6	1.5 KWh/gal EtOH
Distillation	Gas	1, 2, 4, 5	4.3 ft^3/gal EtOH
	Electricity	1, 2, 6	1.5 kWh/gal EtOH
Yield		1, 2, 3	5.1 gal EtOH/bu

Total energy input is the sum of the individual energy requirements for cooking, distilling and electricity. The error in this sum $\Delta E/E$, will not be the square root of the sum of the uncertainties squared, (as it was when we were dealing with products or quotients), but rather the square root of the sum of the weighted uncertainties squared. That is:

$$\frac{\Delta E}{E} = \sqrt{\left(\frac{f_1}{f}\cdot\frac{\Delta X_1}{X_1}\right)^2 + \left(\frac{f_2}{f}\cdot\frac{\Delta X_2}{X}\right)^2 + \left(\frac{f_n}{f}\cdot\frac{\Delta X_n}{X_n}\right)^2}$$

where f_i/f equals the fractional input to the total "f" from the component "f_i".

We next calculate these errors for the three different distilleries:

Single-Farm Distillery

The measured energy inputs and uncertainties per gallon EtOH are:

Natural Gas: Cooking- $(8\ ft^3)(1139\ BTU\ ft^3)$ = 9112 BTU ± 4%

Distilling - $(68.1\ ft^3)(1139\ BTU/ft^3)$ = 77566 BTU ± 5%

Electricity: Cooking- (0.02 kWh)(12935 BTU/kWh) = 259 BTU ± 2%

Distilling - (0.12 kWh)(12935 BTU/kWh) = 1552 BTU ± 2%

The total direct input, including energy cost of energy and excluding byprodu credits is, then 88489 BTU/gal EtOH.

Weighted and total uncertainties are calculated as follows:

Item	Fractional input $\left(\frac{f_i}{f}\right)$	Uncertainty $\left(\frac{\Delta X_i}{X_i}\right)$	Fractional Uncertainty $\left(\frac{f_i}{f}\right)$
Natural Gas:			
Cooking	0.10	4%	0.41
Distilling	0.88	5%	4.38
Electricity:			
Cooking	0.003	2%	0.01
Distilling	0.017	2%	0.03

$$\sqrt{\sum\left(\frac{f_i}{f}\cdot\frac{\Delta X_i}{X_i}\right)^2} = 4.4\%$$

Farmer Consortium

Propane: Cooking - (0.18 gal)(109920 BTU/gal) = 19,786 BTU ± 8%

Distilling - (0.33 gal)(109920 BTU/gal) = 36,274 BTU ± 6%

Electricity: Total- (1.60 kWh)(12935 BTU/kWh) = 20,696 BTU ± 4%

Total direct input = 76,756 BTU/gal EtOH.

Weighted and total uncertainties are:

Item	Fractional input $\left(\frac{f_i}{f}\right)$	Uncertainty $\left(\frac{\Delta X_i}{X_i}\right)$	Fractional uncertainty $\left(\frac{f_i}{f}\right)($
Propane:			
Cooking	0.26	8%	2.06
Distilling	0.47	6%	2.83
Electricity	0.27	4%	1.08

$$\sqrt{\sum\left(\frac{f_i}{f}\cdot\frac{\Delta X_i}{X}\right)^2} = 3.7\%$$

Gasohol Plant

Natural Gas: $(17.8\ ft^3)(1139\ BTU/ft^3)$ = 20.274 BTU ± 9%

Electricity (1.20 kWh) 12935 BTU/Kwh) = 15522 BTU ± 3%

Total direct input = 35796 BTU

Weighted and total uncertainties are:

Item	Fractional input $\left(\frac{f_i}{f}\right)$	Uncertainty $\left(\frac{\Delta X_i}{X_i}\right)$	Fractional uncertainty $\left(\frac{f_i}{f}\right)($
Natural Gas	0.57	9%	5.10
Electricity	0.43	3%	1.30

$$\sqrt{\sum\left(\frac{f_i}{f}\cdot\frac{X_i}{X_i}\right)^2} = 5.3\%$$

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