Chapter 17

Economic Fundamentals of Ethanol Production from Lignocellulosic Biomass

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Information on the production potential for ethanol from lignocellulosic resources is summarized, and the benefits for reducing carbon dioxide accumulation are discussed. The fundamentals of ethanol production are examined in terms of the primary features influencing cost: feedstock cost, feedstock composition, product yield, energy use, and other operating costs. These costs are compared to the revenues that can be realized for fuel ethanol and co-product electricity, and the margin left to cover annualized capital costs is determined. Then the allowable capital cost for the plant is calculated, and analogies are made with existing technology for ethanol production from corn. From this analysis, it is shown that ethanol from cellulosic biomass can be a cost-competitive fuel.

urrently, petroleum provides the largest single source of energy in the United ates (40%), transportation fuels are almost totally derived from petroleum (about %), and about two thirds of the petroleum used in the United States is for nsportation. Because about half the oil used in the United States is imported, we strategically vulnerable to disruptions in our supply of transportation fuels. In dition, at a cost of about $40 billion annually for oil imports, the largest fraction our trade deficit is contributed by petroleum imports, and we are susceptible to nificant economic dislocations if oil prices increase dramatically, as has occurred the past *(1-2)*.

Transportation fuels are substantial contributors to urban air pollution *(3-6)*. out two-thirds of the carbon monoxide pollution in our cities is due to the nsportation sector. In addition, approximately one-third of the ozone-forming npounds that cause smog in our cities is due to transportation. Because nsportation fuels are derived from fossil sources and constitute a significant fraction energy used in the United States, it is not surprising that about one-third of the bon dioxide accumulation in the United States is due to the transportation sector.

Of course, carbon dioxide is a major greenhouse gas that could contribute to global climate change *(7)*.

Ethanol is a diverse, high-performance transportation fuel that has the potential to be produced on a large scale from plentiful sources of lignocellulosic biomass. Successful commercialization of this technology would substantially decrease or even eliminate our dependence on imported oil, thereby reducing the strategic vulnerability of the United States transportation sector, lowering the trade deficit dramatically, and creating substantial employment *(1)*. In addition, ethanol production from lignocellulosic biomass can reduce the accumulation of carbon dioxide by 90% or more, substantially decreasing the contribution to global climate change *(8)*. Technology for producing ethanol from biomass has been improved dramatically over the past decade or more so that ethanol could be competitive now in the United States for existing markets *(9-12)*, and opportunities have been identified to further reduce the cost of ethanol production to be competitive as a neat fuel with gasoline. Yet many still question the benefits of ethanol from lignocellulosic biomass and its potential to be economically competitive.

In this chapter, the current status of ethanol use to improve air quality will be reviewed to provide an update of the growing demand for this fuel. Then the technology will be briefly reviewed to acquaint the reader with the production of ethanol from lignocellulosic biomass and the impact on carbon dioxide buildup. Against this background, the economics of biomass ethanol production will be examined from a fundamental perspective and through comparison to the existing corn ethanol industry to demonstrate that ethanol could be made from lignocellulosic biomass at competitive prices. The goal of this approach is to clearly demonstrate the growing market for and benefits of ethanol production from biomass and establish in an unambiguous manner that ethanol can be made at competitive prices for advanced technology in well engineering processes.

Ethanol Use

Urban air pollution is due to evaporative and tailpipe vehicle emissions. Evaporative emissions occur during vehicle refueling and operation, as fuel components evaporate into the atmosphere. These emissions include various volatile hydrocarbons that cause ozone formation and smog. In addition, several components — such as benzene that constitute evaporative emissions — can be toxic. Tailpipe emissions, on the other hand, are emitted from the exhaust system of vehicles. Problematic examples include oxides of nitrogen, carbon monoxide, partial combustion products, and unburned hydrocarbons, which result from incomplete fuel combustion as well as high engine temperatures. These components contribute to carbon monoxide accumulation in cities as well as to ozone formation and smog.

Ethanol can be used in several ways as a fuel to help address air pollution. First, ethanol can be directly blended with gasoline as in the 10% mixtures now typically used in the United States (E10) or 22% blends used in Brazil (E22). Direct blends of ethanol with gasoline serve to extend gasoline by reducing the amount of gasoline required while boosting octane, thereby reducing the need for toxic octane ıosters. Ethanol also provides oxygen for the fuel to promote more complete ·mbustion. However, the vapor pressure of the resulting mixture increases when hanol is directly blended with gasoline at low levels, causing concerns about ·aporative emissions *(13-14)*.

Ethanol can also be reacted with isobutylene or other olefins to form ethers such ethyl tertiary butyl ether (ETBE). When blended with gasoline, ETBE provides the me benefits as direct ethanol blends in terms of extending the gasoline supply, ıosting octane, and providing oxygen. Additionally, ETBE actually reduces vapor essure when mixed with gasoline. Thus, ozone formation and smog decrease with ΓBE blends.

Finally, ethanol can be used as "pure" fuel in the form of hydrous ethanol ıntaining 95% ethanol and 5% water (as in Brazil) or with small amounts of gasoline promote cold starting. Mixtures of 95% ethanol with 5% gasoline are denoted as)5, while 85% ethanol with 15% gasoline is designated as E85 *(15)*. Neat ethanol el has a high octane, a high heat of vaporization, and other favorable properties that sult in higher efficiency operation than gasoline for properly optimized engines. As result, a 20%–30% increase in efficiency relative to gasoline is possible *(1)*. Neat hanol also has low toxicity, low vapor pressure, and low photochemical reactivity, ducing the potential for smog formation and other environmental impacts. In the nger term, pure ethanol is more readily adaptable than gasoline to fuel cell ıplications. Fuel cells can achieve far higher efficiencies than internal combustion ıgines, while realizing tremendous advantages in reducing air pollution *(16)*.

To improve urban air quality, oxygenated gasoline has been required in 39 ırbon monoxide non-attainment areas in the United States since 1993. This fuel must ıntain 2.7% oxygen during the winter months. This requirement includes a waiver r the higher vapor pressure that results when ethanol is blended with gasoline, ·cause ethanol reduces carbon monoxide emissions that are of concern in the winter onths, while smog formation associated with higher vapor pressure is not a serious oblem during this period. Reformulated gasoline (RFG) will be required beginning 1995 in nine ozone non-attainment areas within the United States. RFG must ıntain at least 2% oxygen year-round, but no vapor pressure waiver is provided for ıanol at this time. In addition, RFG must have a reduced aromatic content, especially benzene *(6)*.

In December 1993, the U.S. Environmental Protection Agency (EPA) proposed ıew rule that will require 30% of oxygenates in RFG to be derived from renewable urces, and the EPA enacted a phased in approach in June 1994 requiring 15% of ygenates in RFG be from renewable sources in 1995, and 30% thereafter. Ethanol, th production now at about 3.8 billion L (1 billion gal) per year, is expected to be the imary fuel affected. The renewable oxygenate standard (ROS) was adopted to reduce l imports and carbon dioxide accumulation, and create domestic employment. owever, some controversy surrounds the requirement for renewable oxygenates in FG. First, the increase in gasoline vapor pressure when ethanol is blended with soline is of concern. Some controversy also surrounds the amount of carbon dioxide at accumulates when ethanol is produced from corn, as is now the practice in the United States. In addition, opponents question the use of existing tax incentives ($0.14/L ethanol, $0.54/gal federal) to encourage corn ethanol use.

The ROS would allow direct ethanol blends to count toward the renewable oxygenate requirement from September 16 to April 30 to reduce carbon monoxide and unburned hydrocarbon emissions. However, from May 1 to September 15, only ethanol in ETBE would count toward the standard. In this way, ETBE would reduce tailpipe emissions of carbon monoxide and unburned hydrocarbons, while reducing evaporative emissions that lead to smog formation during the summer months when smog formation is an issue. To date, implementation of the ROS has been held up by legal challenges.

Other approaches are also potentially viable for reducing smog formation for blends. First, the vapor pressure of the gasoline blending stock could be reduced to compensate for the increased vapor pressure for a low-level ethanol blend. In addition, the higher vapor pressure is due to non-ideal behavior, and ethanol has a far lower vapor pressure than gasoline; thus, as the amount of ethanol is increased beyond about 22%, the vapor pressure of the gasoline-ethanol mixture actually is reduced from that of the gasoline to which ethanol is added. As mentioned previously, ETBE blends reduce vapor pressure while mixtures of ETBE and ethanol could achieve vapor pressures equal to that of the gasoline blending stock. Thus, the higher vapor pressure exhibited for 10% blends is not an inherent limitation of ethanol.

Ethanol Production from Lignocellulosic Biomass

Currently, more than 11 billion L (3 billion gal) of ethanol are produced annually from cane sugar in Brazil, but sugar is too expensive in the United States to achieve economical conversion to ethanol. In the United States over 3.8 billion L (1 billion gal) of ethanol is produced annually from starch crops, mostly corn. However, the cost to produce ethanol from corn is still higher than to produce gasoline, and federal and state tax incentives are used to compensate for the higher price.

In addition to producing ethanol from starch and sugar crops, ethanol can be made from lignocellulosic biomass. Examples of existing sources of lignocellulosic biomass include agricultural and forestry residues, a major fraction of municipal solid waste (MSW), wastepaper, and various industrial wastestreams. Future sources of lignocellulosic biomass could be herbaceous (grasses) and woody crops grown to support ethanol production.

Figure 1 illustrates the process for enzymatic conversion of lignocellulosic biomass to ethanol. First the biomass is pretreated to reduce its size and open up the structure to facilitate conversion of this naturally resistant material into ethanol. Often the hemicellulose fraction (which comprises about 20% to 40% of the material) is broken down to form its component sugars such as xylose during a pretreatment step; these sugars are subsequently fermented to ethanol. Left behind is a solid residue of cellulose and lignin, a small portion of which is fed to a cellulase enzyme production step. These enzymes are then added to the bulk of the solid cellulose-containing material to break down the cellulose into glucose (hydrolysis), and an appropriate organism ferments the glucose into ethanol. Following conversion of the sugars from

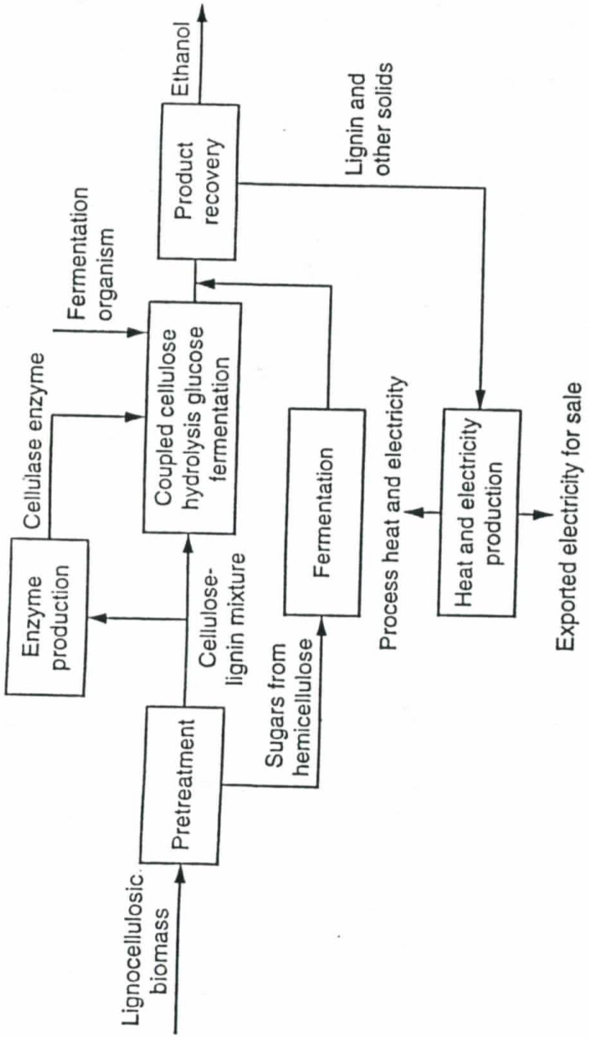

Figure 1. Processing lignocellulosic biomass to ethanol.

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the cellulose and hemicellulose fractions into ethanol, the fermentation broth is sent to a purification step where ethanol is recovered for use as a fuel. The solid residue left following purification contains primarily the lignin fraction, representing about 15% to 20% of the original biomass substrate, that can be burned to provide the heat and electricity to power the entire conversion process as well as excess electricity that can be exported for sale *(11-12)*.

Because lignin can fuel the conversion process, and because low levels of fossil energy inputs are required to grow biomass, most carbon dioxide released during production and utilization of ethanol from lignocellulosic biomass is recaptured to grow new biomass to replace that harvested for ethanol production, and little if any net carbon dioxide accumulates. The result is a 90% or greater reduction in carbon dioxide accumulation compared to use of RFG *(8)*.

Economic Fundamentals

Lignocellulosic biomass provides a low-cost, abundant, domestic resource that could produce enough ethanol to displace a substantial fraction, if not all, gasoline used in the United States. However, the cost of conversion to ethanol has historically been too high because of the recalcitrant nature of lignocellulosic materials. Over the past 14 years, substantial progress has been made in reducing the cost of ethanol production from lignocellulosic biomass from about \$0.95/L (\$3.60/gal) in 1980 *(9-10)* to \$0.32/L (\$1.22/gal) (11), and it can be competitive now, particularly for niche markets that use low-cost feedstocks or other cost-saving measures. Furthermore, additional opportunities have been identified to advance the technology so that ethanol produced from lignocellulosic biomass can compete with gasoline without special tax considerations.

Although detailed process designs and economic evaluations have been employed to estimate the cost of ethanol from biomass for current technology and identify targets for continued cost reductions, such studies are highly dependent on the process design chosen, and different studies estimate different ethanol production costs. However, consideration of fundamental economic principles can show that it is possible to achieve ethanol production at competitive costs. In this section, a simplified analysis will illustrate the economic merits of ethanol production from biomass and its excellent potential to be cost competitive in the open market.

Feedstock costs. The amount of ethanol derived from a given weight of biomass is a critical factor in establishing the economics of ethanol production, since the ethanol yield determines the potential revenue stream for the process and biomass represents a major cost element. The cellulose fraction is hydrolyzed to glucose and fermented to ethanol as shown in the following stoichiometric equation:

$$n(C_6H_{10}O_5) + n\,H_2O \underset{\text{enzyme}}{\rightarrow} n\,C_6H_{12}O_6 \underset{\text{yeast}}{\rightarrow} 2nC_2H_5OH + 2n\,CO_2 \qquad (1)$$

milarly, the hemicellulosic fraction is hydrolyzed to xylose and other sugars for rmentation to ethanol according to the following relationship:

$$3n(C_5H_8O_4) + 3n\,H_2O \xrightarrow[\text{acid}]{} 3n\,C_5H_{10}O_5 \xrightarrow[\text{yeast}]{} 5nC_2H_5OH + 5n\,CO_2 \qquad (2)$$

or the purposes of this analysis, the ratio of cellulose to hemicellulose is assumed to : 2:1 and 80% of the remaining material is assumed to be lignin. These ratios are ised on studies by others *(12)*, but the ratio of cellulose to hemicellulose is not critical the analysis, since the weight yield is only slightly higher for hemicellulose than for llulose. On the other hand, as we will see, the amount of lignin affects the amount excess heat or electricity that can be sold, but this effect is not expected to greatly iange the results of the analysis presented here.

The volumetric ethanol yield is calculated from the overall carbohydrate action (cellulose and hemicellulose), the ratio of these components, the stoichiometry r conversion to ethanol, and the fractional yield of ethanol obtained from the irbohydrates, as shown in equation *(3)*.

$$Y = 1260xC[0.568f_c + 0.581(1-f_c)] \qquad (3)$$

which Y is the volumetric ethanol yield in liters/tonne, x is the weight fraction of the edstock carbohydrates (cellulose and hemicellulose) converted to ethanol, C is the eight fraction of carbohydrates in the feedstock, f_c is the fraction of the feedstock rbohydrates that are cellulose, and $(1-f_c)$ is the fraction of the feedstock rbohydrates that are hemicellulose. This relationship is illustrated in Figure 2 in rms of the volume of ethanol produced per weight of feedstock as a function of the iction of the carbohydrates converted to ethanol for varying carbohydrate content, :., total cellulose and hemicellulose in the feedstocks. This figure clearly shows how amatically the volumetric ethanol yield changes with the fraction of carbohydrate ntained in the feedstock and its conversion to ethanol.

From an economic perspective, the key parameter is the cost of the feedstock r a given volume of ethanol produced. This value can be determined by dividing the edstock costs per unit weight by the volumetric ethanol yield as:

$$\frac{\text{Feedstock cost}}{\text{Volume ethanol}} = \frac{\text{Feedstock cost/weight of feedstock}}{\text{Ethanol volume/weight of feedstock}} \qquad (4)$$

ice again, we can vary the carbohydrate content and percentage yield to determine eir influence on the feedstock cost per volume of ethanol produced. Figure 3 shows e result for a feedstock costing $37/tonne ($34/ton). Figure 4 then compares the edstock cost per volume for a feedstock containing 70% carbohydrates as a function the yield to ethanol for feedstocks costing $37/tonne and $46/tonne ($42/ton). As pected, the volumetric feedstock costs are directly proportional to the cost of the edstock and greatly influenced by the carbohydrate content and ethanol yield from rbohydrates.

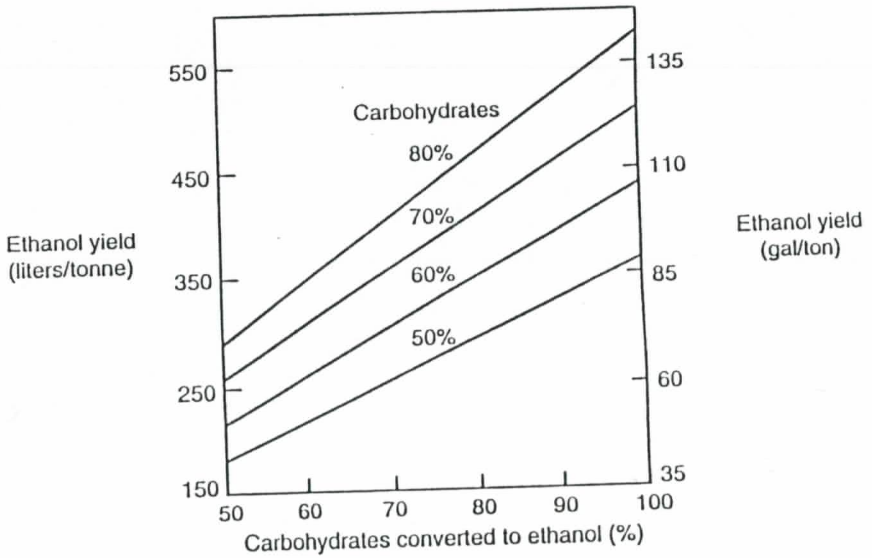


Figure 2. Volumetric ethanol yield per weight of feedstock as a function of the percentage of the total carbohydrates converted to ethanol (yield) and the carbohydrate content of the feedstock.

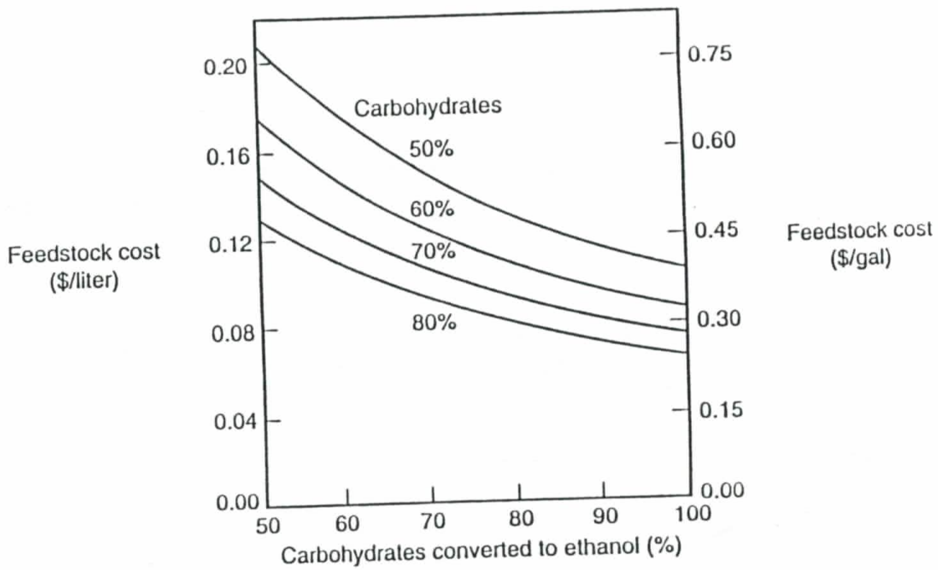
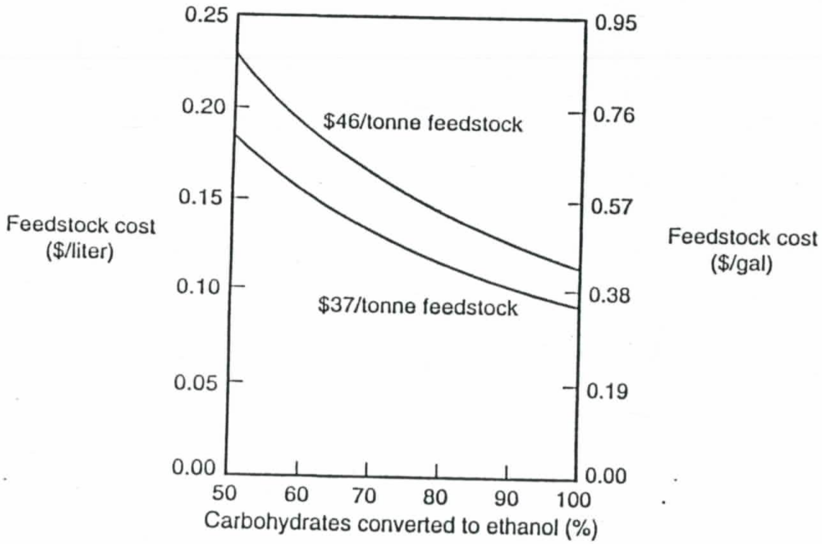
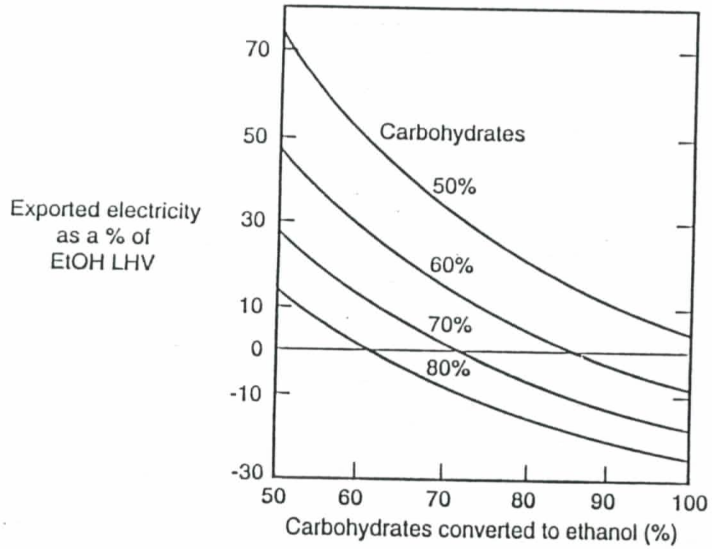


Figure 3. Volumetric feedstock cost for ethanol production as a function of the percentage of the total carbohydrates converted to ethanol for varying carbohydrate content and a feedstock costing $37/tonne ($34/ton).



igure 4. Comparison of the volumetric feedstock cost as a function of the ercentage of the total carbohydrates converted to ethanol for varying feedstock osts and a feedstock containing 70% carbohydrates.



gure 5. Estimated electricity available for export expressed as a percentage of the wer heating value (LHV) of ethanol for a plant requiring 22 MJ/L of ethanol oduced (80,000 Btu/gal) for process heat and electricity requirements. Exported ectricity is estimated for varying feedstock carbohydrate content as a function of

Process revenues. Two products are assumed to be manufactured for revenue generation from the ethanol process: ethanol and excess exportable electricity. As described previously, all materials not converted to ethanol are assumed to be burned to produce heat and electricity. The solid material that is burned following ethanol recovery is assumed for the purposes of this analysis to contain 50% moisture. Furthermore, it is assumed that the process requires either 22 MJ/L (80,000 BTU/gal) of ethanol produced or 11 MJ/L (40,000 BTU/gal) for process heat and electricity; the 11 MJ/L figure is typical of efficient modern corn ethanol plants. It is further assumed that the electricity is produced with a 33% efficiency and surplus electricity is sold.

Figure 5 shows the amount of excess electricity exported as a percentage of the lower heating value of the ethanol produced as a function of the material's carbohydrate content and the percentage of that carbohydrate converted to ethanol for a process requiring 22 MJ/L (80,000 BTU/gal) of ethanol produced. Shown in Figure 6 is similar information for a process that requires 11 MJ/L (40,000 BTU/gal) of process heat and electricity. From these figures, substantial amounts of electricity can be exported for a process with energy requirements similar to those of a modern corn ethanol plant, while little if any electricity export is possible for a less efficient plant. In fact, the less efficient plant benefits from a lower carbohydrate content so that more lignin is available to produce heat and electricity for the process.

For the purposes of this analysis, it is assumed that ethanol is sold at $0.18/L ($0.67/gal) and electricity is sold at $0.03/kWh. As shown in Figure 7, the ethanol selling price of $0.18/L for conventional gasoline corresponds to an oil cost of $25/bbl for ethanol achieving a range of 80% that of gasoline based on its superior properties that result in higher efficiency use.

The revenue can be determined from these unit prices for electricity and ethanol. Figure 8 shows the revenues per volume of ethanol produced for either ethanol alone or ethanol plus electricity sales for a feedstock costing $37/tonne ($34/ton) and a 70% carbohydrate content. Also shown is the feedstock cost per volume of ethanol produced as a function of the percentage of the carbohydrates converted to ethanol. The margin between the feedstock cost and the revenue from sale of ethanol or ethanol plus electricity is available to recover the remaining costs and realize a return on investment for the ethanol conversion process. From this figure, it can be seen that coproduct revenues in the form of electricity are very important for low ethanol yields from biomass, and become predictably less important as the yield improves. Furthermore, it can be seen that a significant margin is available to cover other costs of production (COP) and realize a return on capital.

For commodity products, the feedstock cost often represents 80% to 90% of the overall COP. From this, we could estimate the COP from the feedstock cost based on a factored cost estimate. For the purposes of this analysis, the feedstock cost is assumed to represent two-thirds of the overall production cost because a solid substrate is used in the conversion process, generally with higher conversion costs. Figure 8 presents the factored COP for a 70% carbohydrate feedstock costing $37/tonne ($34/ton) as a function of the fractional conversion of the carbohydrates to ethanol. As mentioned earlier, also shown are the revenues from the sale of ethanol or of ethanol plus electricity as well as the feedstock cost. Based on this analysis, the cost of ethanol

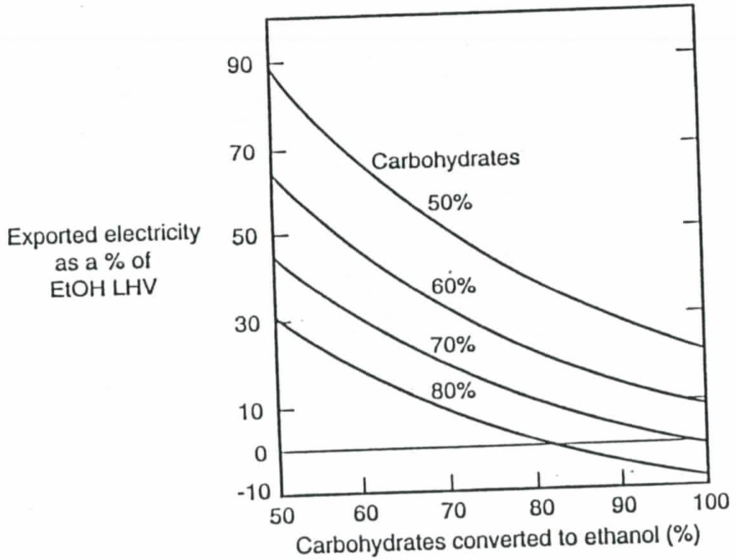


Figure 6. Estimated electricity available for export expressed as a percentage of the lower heating value (LHV) of ethanol for a plant requiring 11 MJ/L of ethanol produced (40,000 Btu/gal) for process heat and electricity. Exported electricity is estimated as a function of ethanol yield from carbohydrates.

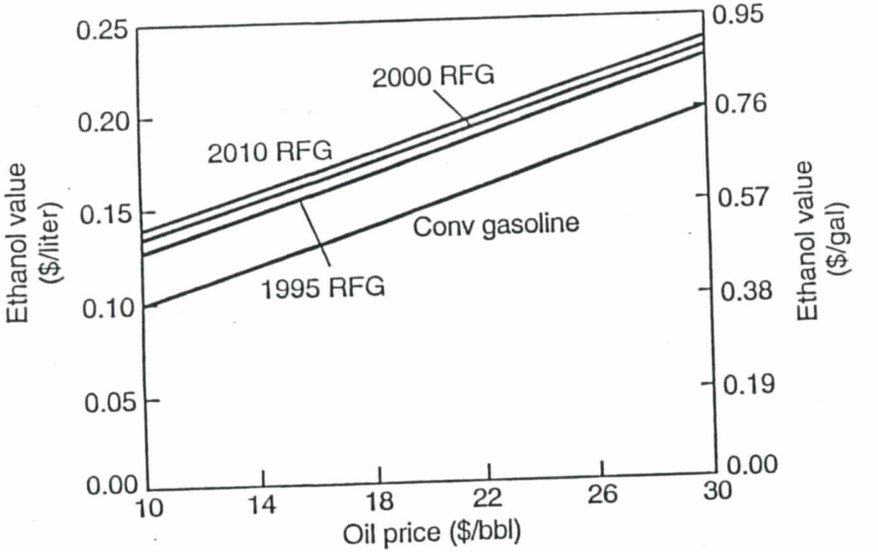


Figure 7. The value of ethanol as a neat fuel in competition with gasoline as a function of petroleum price for conventional gasoline and RFG designed to meet 1995, 2000, and 2010 EPA requirements.

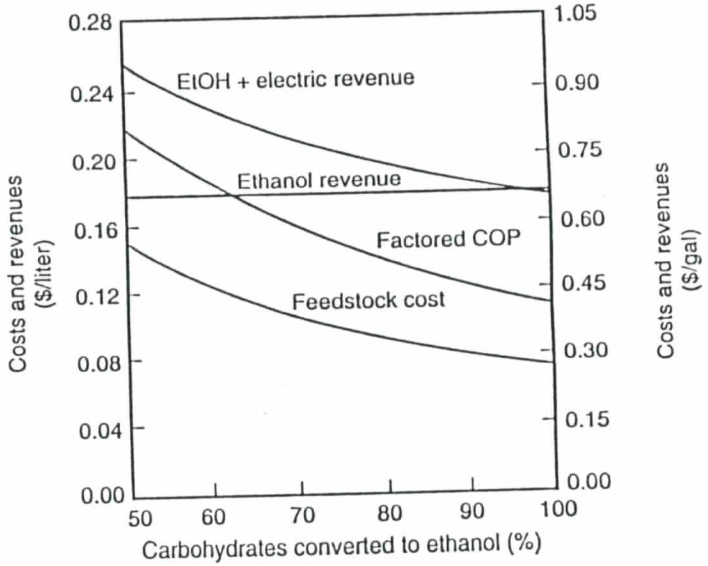


Figure 8. Feedstock cost, ethanol revenue alone, and combined ethanol and exported electricity revenue as a function of the percentage of carbohydrates converted to ethanol for a feedstock containing 70% cellulose and hemicellulose and costing $37/tonne ($34/ton). Also shown is the factored COP estimate based on feedstock cost alone.

production is projected to be significantly lower than the revenues derived from ethanol or ethanol plus electricity, particularly at high ethanol yields. Although simplistic, the analysis shows that production of ethanol (even though it is a low value product) could be economical for lignocellulosic materials if produced at the low processing costs typical of commodity products. Efficient, well-engineered, high-yield technology is needed to achieve this goal.

Unavoidable cost of production estimate. This analysis can be taken a step further by estimating costs felt to be unavoidable for ethanol production and determining the margin left to cover remaining costs that could be reduced through R&D. Table I summarizes the typical cost elements considered in estimating the required selling price for a product to cover all such costs as well as achieve a reasonable return on investment. These elements include the cost of feedstock as determined previously as well as costs for nutrients and other chemicals used in processing. In addition, labor costs for plant operation as well as associated direct overhead and general plant overhead expenses must be calculated. Similarly, maintenance costs and general plant overhead related to maintenance are estimated. Insurance and property tax expenses are included as well. Finally, the annualized cost of capital is calculated.

For the unavoidable cost analysis, feedstock costs are calculated as a function of yield and carbohydrate content, as discussed previously. Labor costs are determined for a 1745 tonne/d (1920 ton/d) ethanol plant that is assumed to require a total of eight operators at $29,800/yr each, an operating foreman at $34,000/yr, and an operating supervisor at $40,000/yr. These estimates are believed to be the minimum crew required to successfully operate a plant based upon operation of larger scale plants (on the order of 940 million L/yr or 250 million gal/yr) for corn ethanol production. The minimum costs possible for chemicals and nutrients is assumed as 3% of that for the feedstock. Current costs are projected to be higher than this, but as new pretreatment approaches and nutrient requirements and reuse are better defined, it may be possible to approach this level. Other costs are estimated by standard methods *(11-12)*. Maintenance costs are determined as 3% of the total fixed investment. Direct overhead is then calculated as 45% of the labor and supervision, while general plant overhead is calculated as 65% of labor and maintenance costs.

Table I Cost elements used to estimate selling price

- Feedstock
- Chemicals and nutrients
- Utilities
- Labor/Supervision
- Maintenance
- Direct overhead
- General overhead
- Insurance, property taxes
- Annual capital charge

The estimated minimum cost of nutrients and chemicals, operating labor, and direct and general plant overhead can be added to the feedstock costs as shown in Figure 9. The margin between the sum of all these costs and the revenue from either ethanol sales or ethanol plus electricity sales is available to cover the cost associated with capital recovery, including return on capital. As before, these costs are determined per volume of ethanol produced as a function of the ethanol yield from the carbohydrates for a 70% carbohydrate feedstock costing $37/tonne ($34/ton).

Allowable fixed capital investment. Having determined the minimum unavoidable costs for ethanol production, we can now determine the maximum capital investment that can be justified for this plant. Typically, the purchased capital cost is first estimated based on material and energy balances. Then the total installed capital cost is determined as a multiple of the purchased capital cost. In this case, the multiplier is taken as 2.85 based on other estimates *(12)*; although this value may seem low compared to chemical processes, it has proven reasonable for solid biomass such as corn when suspended in water at low temperatures and pressures. The fixed capital investment is calculated as 2% over the total installed capital cost. Finally, the total fixed investment is the sum of the start-up cost plus fixed capital investment, calculated as 5% above the fixed capital investment. These calculations are summarized in Table II *(11-12)*.

The capital cost can be annualized by multiplying the total capital investment by some factor, in this case 0.2 *(12)*. This factor is determined according to standard methods from the parameters in Table II. The plant is constructed over a three-year period, with 30% of the plant completed in the first year, 50% in the second year, and 20% in the third year. Furthermore, the plant is assumed to operate for 15 years with capacity at 60% of nameplate in the first year, 80% in the second year, and 100% thereafter. Straight-line depreciation is over a five-year period for equipment inside the battery limits and over a 15-year period for equipment outside the battery limits. Income tax is 37%, and no sales expenses are included in this calculation *(12)*. Typically, corn ethanol plants are built more rapidly and achieve full (and often over) capacity in less time.

Table II Factors applied to estimate total fixed investment and annualized capital cost

- Total capital outlay for ethanol plant
  - Purchased capital cost (PCC)
  - Total installed capital cost (TIC) = 2.85 • PCC
  - Fixed capital investment (FCI) = 1.02 • TIC
  - Startup costs + FCI = Total Fixed Investment (TFI) = 1.05• FCI
- Capital cost annualized by multiplying the total capital investment by 0.20 to account for:
  - 3 years of construction with 30% 1st year, 50% 2nd year, 20% 3rd year
  - 15 years of operation

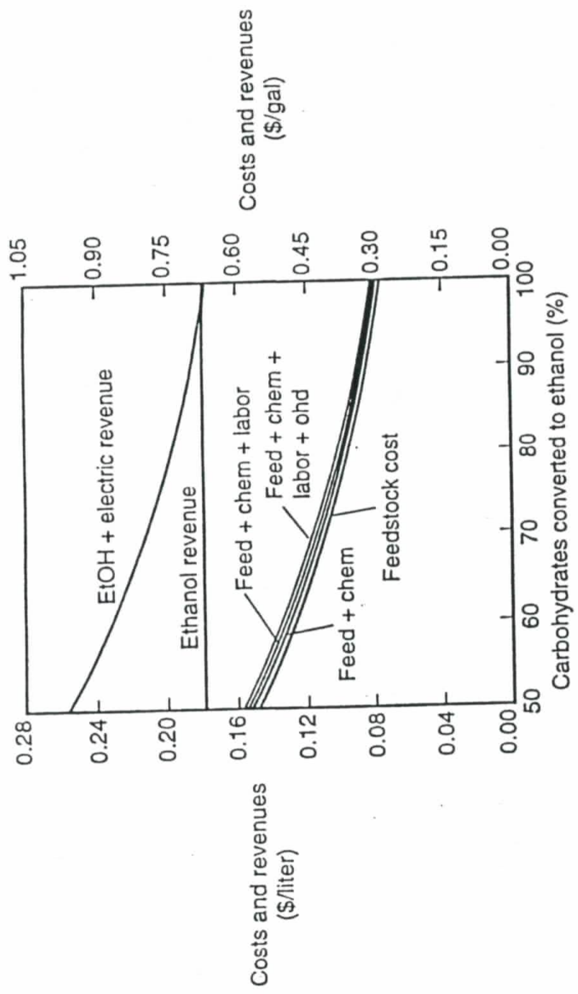


Figure 9. Revenue from sale of ethanol only and ethanol plus exported electricity as a function of the percentage of carbohydrates converted to ethanol for a feedstock containing 70% cellulose and hemicellulose and costing $37/tonne ($34/ton). Also shown are the estimated minimum costs for feedstock alone; feedstock with other chemicals; feedstocks, chemicals, and labor; and feedstock, chemicals, labor, and overhead.

- Income tax at 37%
- No sales expenses
- Capacity at 60% 1st year, 80% 2nd year, 100% thereafter.
- Straight-line depreciation over 5 years for ISBL, 15 years OSBL.

In addition to the annualized capital recovery factor, standard cost estimating methods also factor other costs from the capital investment. As mentioned previously, maintenance costs are determined at 3% of the total fixed investment. General plant overhead is then calculated as 65% of the maintenance cost. Insurance and property taxes are estimated at 1.5% of the total fixed investment.

Taking into consideration all costs estimated from the fixed capital investment, an allowable fixed capital investment (AFCI) can be calculated as:

$$\mathrm{AFCI} = \frac{(\text{Revenues - Costs})}{(0.20)(1.05) + 0.0678} \qquad (5)$$

Figure 10 summarizes the allowable fixed capital investment based on this equation for feedstock costs of $37/tonne ($34/ton) and $46/tonne ($42/ton) as a function of the ethanol yield from the carbohydrate fraction of a biomass feedstock containing 70% carbohydrates. From this figure, a capital investment on the order of $0.25–$0.30/annual L ($0.95–$1.10/annual gal) of capital investment is allowable for a feedstock cost of $46/tonne ($42/ton). However, at a lower feedstock cost of $37/tonne ($34/ton), a capital cost on the order of $0.35/annual L ($1.33/annual gal) can be accommodated for conversion of biomass into ethanol. For comparison, it is worth noting that similar modern (dry mill) large-scale corn ethanol plants typically cost on the order of $0.29/L ($1.11/annual gal) of capacity *(17)* and the costs continue to drop as improvements are made. To achieve such low capital costs for a biomass ethanol plant certainly requires advanced technology, but these goals can be realized as improvements continue to be made to increase yields, consolidate steps, and speed rates *(see for example reference 18)*. Large-scale plants are also more likely to realize this goal.

It must be remembered that neat ethanol would likely be used for markets that can benefit from ethanol's favorable properties in reducing air pollution. In such cases, the competition would really be RFG *(8)*, and Figure 7 also includes the expected RFG price as a function of the price of oil. As before, this assumes that ethanol can achieve 80% of the range of gasoline because of its ability to achieve a 25% advantage in efficiency compared to gasoline. For this case, ethanol would be valued at about $0.21/L ($0.81/gal) to compete with RFG in such markets for an oil price of $25/bbl.

Figure 11 shows that we could afford to pay nearly $0.50/annual L of capacity ($1.90/annual gal) for an ethanol plant that could sell gasoline at a price competitive with RFG and purchase feedstock for $37/tonne ($34/ton). This allowable fixed capital investment is certainly less than for typical corn ethanol plant capital investments today. Thus, ethanol from biomass will be competitive for RFG markets if the technology is advanced for ethanol production from lignocellulosic biomass through continued R&D.

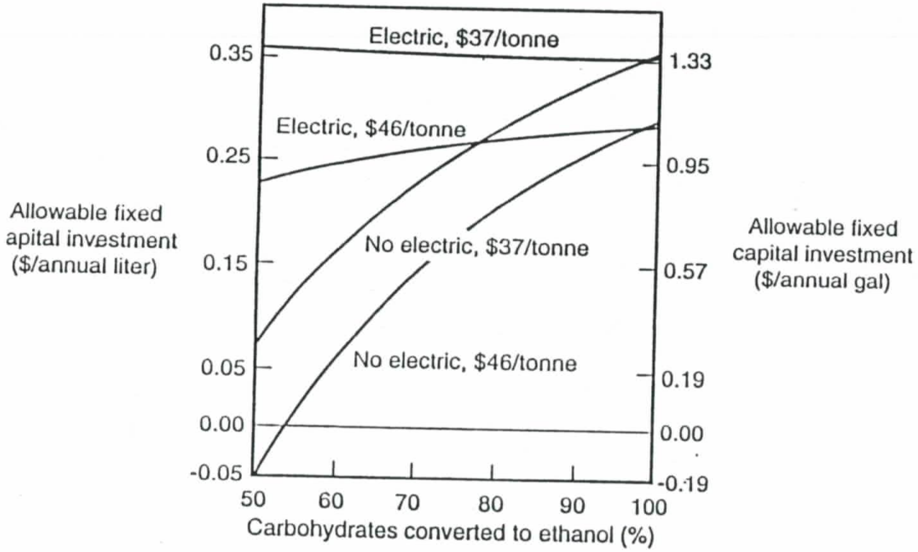


Figure 10. The allowable fixed capital investment for ethanol production from lignocellulosic biomass for varying carbohydrate conversion to ethanol for sale of ethanol only and of ethanol plus exported electricity. The feedstock is assumed to contain 70% cellulose and hemicellulose and cost either $37/tonne ($34/ton) or $46/tonne ($42/ton).

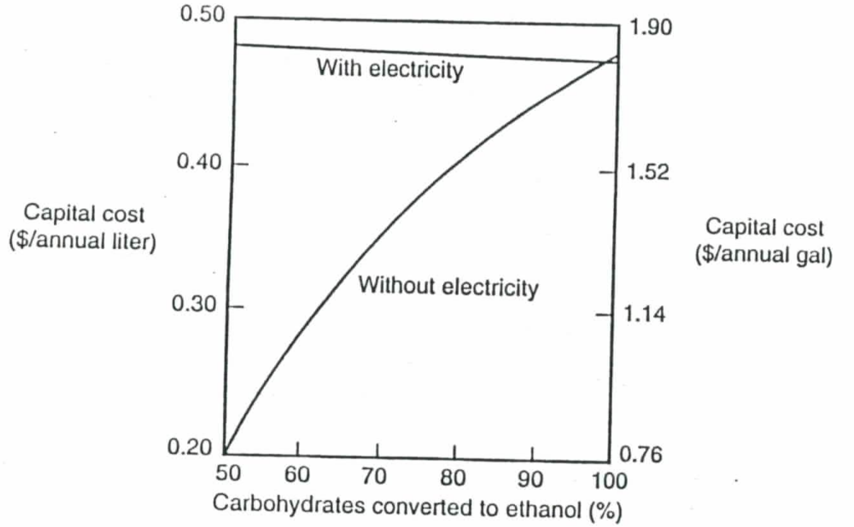


Figure 11. The allowable fixed capital investment as in Figure 10, but for an ethanol selling price of $0.21/L ($0.80/gal) and a feedstock cost of $37/tonne ($34/ton).

In closing, it is worth noting that ethanol today is primarily used for direct blending with gasoline in the United States. For such cases, ethanol typically sells in the range of $0.29/L to $0.32/L ($1.10–$1.30/gal). Such a price would allow a substantially higher capital investment in a biomass ethanol plant than shown here.

Conclusions

From this analysis, we can conclude that the production of low cost ethanol is possible from lignocellulosic biomass. Of course, high ethanol yields are vital to achieve economic viability. The latter is not surprising, and it is certainly true for any low-value, high-volume product to be competitive. It is also clear that a high carbohydrate content lowers the unit feedstock cost. Furthermore, it is important to use low-cost feedstocks for ethanol production to be competitive with conventional fuels. It is important to be sure value is obtained from the unconverted fractions if we are to achieve economic competitiveness, particularly for low ethanol yields. For example, this study assumes that unconverted fractions were burned to produce heat and electricity to power the process and to generate additional revenues from electricity exports. Greater electricity revenues result from more efficient plants, resulting in better economics; lower process energy use is possible compared to that assumed in this analysis. Other products could also be produced from the unconverted fraction if they generate appropriate revenues.

It is important to minimize all costs to maximize the margin available to cover capital recovery charges. Thus, the costs for nutrients and other chemicals must be minimized within the process. In addition, an efficient operation with a minimal operating staff is also important. The latter can also be achieved for a larger scale plant that realizes economies of scale. It must be realized that ethanol offers more than energy content, and if ethanol is valued for its ability to combat urban air pollution as a neat fuel or for direct blends in comparison to RFG, a higher fixed capital investment can still be profitable.

Overall, if high product yields, low operating costs, and reasonable coproduct markets are realized, the margin between revenues and operating costs is sufficient to provide a reasonable return on capital investment for a biomass ethanol plant similar in cost to a corn ethanol process. Through continued R&D, highly efficient, well-engineered processes should result that achieve this goal. Such cost-competitive lignocellulosic biomass-to-ethanol production would reduce oil imports, improve urban air quality, and curtail the buildup of greenhouse gases that lead to global climate change. On the other hand, this analysis suggests that an estimate of a high cost for ethanol production from biomass should not be interpreted as meaning that ethanol cannot be produced at low cost from lignocellulosic biomass but as evidence of a process design that does not achieve high product yields, low operating costs, adequate coproduct markets, and/or low capital costs.

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