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# Biomass: An Ideal Feedstock for Ethanol Production

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# BIOMASS: AN IDEAL FEEDSTOCK FOR ETHANOL PRODUCTION

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## INTRODUCTION

The recent Iraqi invasion of Kuwait reminded us once again that reliance on imported oil can cause strategic and economic vulnerability. The United States consumes about 17-18 million barrels of oil per day, approximately half of which is imported. Today's transportation fuels are almost totally derived from petroleum and account for about two-thirds of the petroleum consumed. Thus, transportation fuels are particularly vulnerable to disruptions in imported oil. In addition, imported petroleum accounted for about 40% of the balance-of-payments deficit for the United States in 1989.[1]

American oil consumption also exacerbates the growing environmental decay. Much of urban air pollution in the form of smog (ozone) and carbon monoxide (CO) is a result of the combustion of transportation fuels in vehicles.[2] The carbon dioxide ($CO_2$) emitted to the atmosphere from burning transportation fuels contributes to global warming.[3]

Ethanol produced from cellulosic biomass is an attractive alternative transportation fuel that promises to improve energy security, decrease the balance-of-payments deficit, reduce urban pollution, and mitigate the accumulation of carbon dioxide.[4] Work under way at the National Renewable Energy Laboratory (NREL) focuses on reducing the cost of producing ethanol so that it can compete with gasoline without the assistance of tax incentives.

This Article examines the use of ethanol as a fuel, the use of cellulosic biomass as a raw material for the manufacture of ethanol, and the process for

* This research is supported by the Ethanol from Biomass Program of the United States Department of Energy, Biofuels Systems Division.

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1. Wald, *Greater Reliance on Foreign Oil Feared as U.S. Output Tumbles*, N.Y. TIMES, Jan. 18, 1990, at A1, col. 1.

2. *See generally* OFFICE OF PUBLIC AFFAIRS, U.S. ENVIRONMENTAL PROTECTION AGENCY, EPA LISTS PLACES FAILING TO MEET OZONE OR CARBON MONOXIDE STANDARDS (1989).

3. *See generally* J. EDMONDS, W. ASHTON, H. CHENG, & M. STEINBERG, A PRELIMINARY ANALYSIS OF U.S. $CO_2$ EMISSIONS REDUCTION POTENTIAL FROM ENERGY CONSERVATION AND SUBSTITUTION OF NATURAL GAS FOR COAL IN THE PERIOD TO 2010 (Office of Energy Research, U.S. Department of Energy, 1989) (DOE/NBB-0085).

4. Wyman & Hinman, *Ethanol—Fundamentals of Production From Renewable Feedstocks and Use as a Transportation Fuel*, 24-25 APPL. BIOCHEM. BIOTECHNOL. 735 (1990); *see also generally* N. HINMAN, D. SCHELL, C. RILEY, P. BERGERON & P. WALTER, ETHANOL ANNUAL REPORT FISCAL YEAR 1990 (National Renewable Energy Laboratory, 1990) (SERI/TP-231-3996) [hereinafter 1990 ETHANOL REPORT].

and effects of converting biomass to ethanol.

## I. THE USE AND BENEFITS OF ETHANOL AS A FUEL

Ethanol can be used as a fuel in three different forms: (1) as anhydrous ethanol-gasoline blends currently used in the United States; (2) as a component of ethyl-*tert*-butyl ether (ETBE);[5] and (3) as anhydrous (100% ethanol) or hydrous (95% ethanol and 5% water) ethanol. Differences exist in automobile performance and emission levels among these fuels.

The leaning effect of 10% ethanol/90% gasoline blends on engines adjusted for gasoline can reduce carbon monoxide.[6] Although the effect depends on the emission control technology, an Environmental Protection Agency study indicates that carbon monoxide emissions are reduced 10%-30% for automobiles that are not even equipped with the latest adaptive learning technology.[7]

As with gasohol, the addition of ETBE to gasoline causes an engine to run lean, reducing CO emissions, even without the latest adaptive learning closed-loop technology.[8] The recently completed 1988-89 Colorado Oxygenated Fuel Program dramatically reduced ambient carbon monoxide concentrations in Denver by mandating the use of oxygenated additives in gasoline. During the program 90%-95% of the fuel sold contained 11% methyl-*tert*-butyl ether (MTBE). It is probable that ETBE would result in similar reductions in ambient CO concentrations. Because ETBE significantly lowers the Reid Vapor Pressure of gasoline, the use of ETBE-gasoline blends should lower volatile organic compounds (VOCs) along with ozone that results from the interaction of hydrocarbons and nitrogen oxides ($NO_x$).

The volatility of a fuel is one of the primary factors affecting VOC emissions. Compared to the concentrations from using 100% gasoline, using anhydrous or hydrous ethanol with low vapor pressures should lower concentrations of organic compounds in the air. In addition, the photochemical reactivity of ethanol is much less than that of hydrocarbons. Unlike the relatively high emissions of several types of hydrocarbons that are very reactive in producing ozone, anhydrous and hydrous ethanol combustion

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5. Reisch, *Ethyl-Tert-Butyl Ether Shows Promise as Octane Enhancer*, 66 CHEMICAL & ENGINEERING NEWS, Oct. 24, 1988, at 11.

6. Ideally, the air-fuel mixing device on an automobile engine provides the right mix of air and fuel to allow for complete combustion of the fuel. If not enough air is provided, the engine is said to be running "rich" and the fuel is not fully combusted. The result is undesirable production of carbon monoxide. The addition of oxygenated compounds, such as ethanol, to gasoline provide additional oxygen and has the same effect as adding more air. This is known as the "leaning effect." The result is fuller combustion of the fuel and less carbon dioxide production.

7. NATIONAL ADVISORY PANEL ON COST-EFFECTIVENESS OF FUEL ETHANOL PRODUCTION, U.S. DEPARTMENT OF AGRICULTURE, FUEL ETHANOL COST-EFFECTIVENESS STUDY, FINAL REPORT (1987).

8. M. JACKSON, W. WIESE & J. WENTWORTH, TECHNICAL PROGRESS BOOK TP-6 (Society of Automotive Engineers 1964) (preprint 486A).

produce very low levels of smog-producing compounds.[9] Pure ethanol burning engines may also be effective in reducing $NO_x$ emissions because ethanol burns at a lower temperature than gasoline and $NO_x$ formation decreases as temperature decreases.[10] Thus, ethanol's lower fuel evaporative emissions, lower photochemical reactivity, reduced tailpipe hydrocarbon emissions of reactive hydrocarbons, and lower $NO_x$ levels should result in a reduction of ozone levels when using anhydrous and hydrous ethanol fuels.

## II. CELLULOSIC BIOMASS AS A RAW MATERIAL FOR ETHANOL PRODUCTION

Cellulosic biomass is the most abundant form of terrestrial plant matter. It is composed primarily of cellulose, hemicellulose, and lignin, as well as small amounts of extractives and minerals. Cellulose consists of chains of the six carbon sugar glucose. Hemicellulose consists of chains of five carbon sugars, and lignin is a polyaromatic material. As shown in Figure 1,[11] cellulose biomass is generally composed of 40%-50% cellulose, 20%-40% hemicellulose, and 15%-22% lignin.

Sources of cellulosic biomass suitable for ethanol production include underutilized forests and forest residues, agricultural residues, municipal solid waste (MSW), waste and low-value material from industrial processes, and energy crops. Energy crops (short-rotation woody crops and herbaceous crops) are being developed by a U.S. Department of Energy sponsored program through Oak Ridge National Laboratory. For the United States, it is estimated that energy crops could provide about 1126 million dry tons of cellulosic biomass per year. This quantity of feedstock could generate 124 billion gallons of ethanol per year. Underutilized wood, agricultural residues, and MSW could also generate significant quantities of ethanol.

## III. PRODUCTION OF ETHANOL FROM CELLULOSIC BIOMASS

### A. *Production Process*

The process for producing ethanol from cellulosic biomass is outlined in Figure 2.[12] After being milled to a small particle size, the feedstock is pretreated with dilute sulfuric acid to break the hemicellulose chains into their component sugars (mainly xylose in hardwoods). Several options have been considered for conversion of the xylose into ethanol including the use of certain strains of yeast, fungi, and bacteria. As yet, none of these is

9. *See generally* D. SPERLING, NEW TRANSPORTATION FUELS: A STRATEGIC APPROACH TO TECHNOLOGICAL CHANGE (1988).

10. *See generally* ENCYCLOPEDIA OF CHEMICAL TECHNOLOGY (1984 Supp.).

11. *See generally* 1990 ETHANOL REPORT, *supra* note 4.

12. *See generally id.*

optimal. Another approach involves the use of a genetically engineered bacteria to produce large quantities of xylose isomerase enzyme that converts xylose into an isomer called xylulose that many yeast can ferment to high yields.[13] In a most promising approach, a genetically engineered bacteria has been developed that appears to be able to ferment xylose directly to ethanol at yields exceeding 90%.[14]

Enzymes called cellulase are used to break down (hydrolyze) cellulose to form glucose sugar that can be fermented by yeast into ethanol. The most promising enzyme-based process is the simultaneous saccharification and fermentation process (SSF).[15] The SSF process combines the hydrolysis and fermentation steps in one vessel. The presence of yeast along with the enzymes minimizes the accumulation of sugar that inhibits cellulases and results in high ethanol yields and higher rates of reaction.

After conversion of the hemicellulose and cellulose to ethanol, the remaining material is mostly lignin. Because lignin has a high energy content it can be used as boiler fuel to supply all the heat and electricity necessary for the ethanol production process and the excess electricity can be sold. Research is also under way to examine use of lignin for the production of fuel additives and chemicals.

### *B. Progress and Potential for Improvement*

Progress with the enzyme-catalyzed process has been substantial over the last ten years. As shown in Figure 3,[16] ethanol selling prices have dropped from $3.60/gal. in 1980, to $1.35/gal. in 1989, to $1.27/gal. today.[17] This reduction in selling price is due to improvements in enzymes, use of better fermentative microbes, improved rates and yields of the SSF process, and advances in xylose fermentations through genetic engineering. Technical targets, shown in Figure 4,[18] have been identified to bring the selling price down to about $0.67/gal. by the year 2000. At this price ethanol is competitive with fossil transportation fuels when oil is $26 per barrel.

### *C. Near-Term Opportunities*

Production costs for ethanol from biomass using current technology are

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13. Lastick, Mohagheghi, Tucker & Grohmann, *Simultaneous Fermentation and Isomerization of Xylose to Ethanol at High Xylose Concentration*, 24-25 APPL. BIOCHEM. BIOTECHNOL. 431 (1990).

14. Ingram & Conway, *Expression of Different Levels of Ethanologenic Enzymes from Zymononas mobilis in Recombinant Strains of Escherichia coli*, 54 APPL. ENVIRON. MICROBIOL. 397 (1988).

15. J. Wright, *Ethanol from Biomass by Enzymatic Hydrolysis*, 84 CHEM. ENGINEERING PROGRESS, Aug. 1988, at 62-74.

16. *See generally* 1990 ETHANOL REPORT, *supra* note 4.

17. *See generally id.*

18. *See generally id.*

shown in Table 1. For this case, the feedstock, which was assumed to cost \$42/dry ton, accounts for \$0.46/gal. of the total production cost of \$1.27/gal. If a cheaper feedstock is available, the production costs will be lower and could reach a level that is competitive in today's ethanol market. For example, if the feedstock was free, ethanol made with today's technology would cost \$0.81/gal. This compares favorably to the current market price of about \$1.20/gal. Examples of potentially inexpensive cellulosic biomass that could provide near-term opportunity include wastepaper, agricultural residues such as corn cobs, low-value fiber in grain processing operations, and cellulosic wastes from industrial operations.

## IV. EFFECT OF GLOBAL WARMING

In the process shown in Figure 5, all fuels and chemicals used for production of the biomass feedstock are presumed to be made from biomass, hence the $CO_2$ released during feedstock production is derived from biomass. Likewise, during the conversion of the biomass feedstock to ethanol, all $CO_2$ released is derived from the biomass feedstock. Finally, because the ethanol is derived from biomass, all the $CO_2$ released during combustion of this fuel in automobiles and trucks is derived from biomass. Thus although $CO_2$ is released during the production of the biomass feedstock, during the conversion process, and during the utilization of the fuel, all of the $CO_2$ released is derived from biomass. Through the process of photosynthesis, this $CO_2$ is recaptured to provide a new crop of biomass feedstock. Thus, the $CO_2$ produced does not accumulate in the atmosphere and does not contribute to global warming.

In contrast, use of conventional fossil fuels does result in accumulation of carbon dioxide. This is because oil, coal, and natural gas are obtained below ground and converted to fuels and combusted above ground producing $CO_2$. However, because there is no mechanism analogous to photosynthesis to recapture this $CO_2$ to create a new crop of fossil fuel resource, $CO_2$ accumulates in the atmosphere and contributes to global warming.

## CONCLUSION

The dependence of the United States on imported oil as a source of transportation fuels is a significant factor in the strategic, economic, and environmental considerations of this nation. Ethanol produced from cellulosic biomass could serve as an alternative transportation fuel which would reduce our dependence on imported oil. It is estimated that energy crops could provide over 124 billion gallons of ethanol per year which is more than the total United States gasoline consumption of 112 billion gallons per year. In addition, ethanol from cellulosic biomass will be useful in dealing with urban air pollution and global warming. Moreover, energy crops will provide a way to use our ever increasing idle crop land for the good of our country and will provide a new source of revenue to our farmers.

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TABLE 1

PRODUCTION COSTS—TOTAL COST BASIS

| Cost of Ethanol | MM$/Yr | Cents per Gallon |
|---|---|---|
| Costs of Production | | |
| Feedstock | 26.9 | 45.9 |
| Chemicals | 8.3 | 14.1 |
| Labor | 1.6 | 2.7 |
| Maintenance | 3.9 | 6.6 |
| Overhead | 4.2 | 7.2 |
| Taxes and Insurance | 1.9 | 3.3 |
| Gross Cost of Production | 46.7 | 79.8 |
| Byproduct Credits | | |
| Electricity | 4.1 | 7.1 |
| Solids Disposal | (0.4) | (0.7) |
| Net Costs of Production | 43.0 | 73.4 |
| Annual Capital Charge @ 20.00 TIC | 28.2 | 48.3 |
| Ethanol Cost | 71.2 | 121.7 |

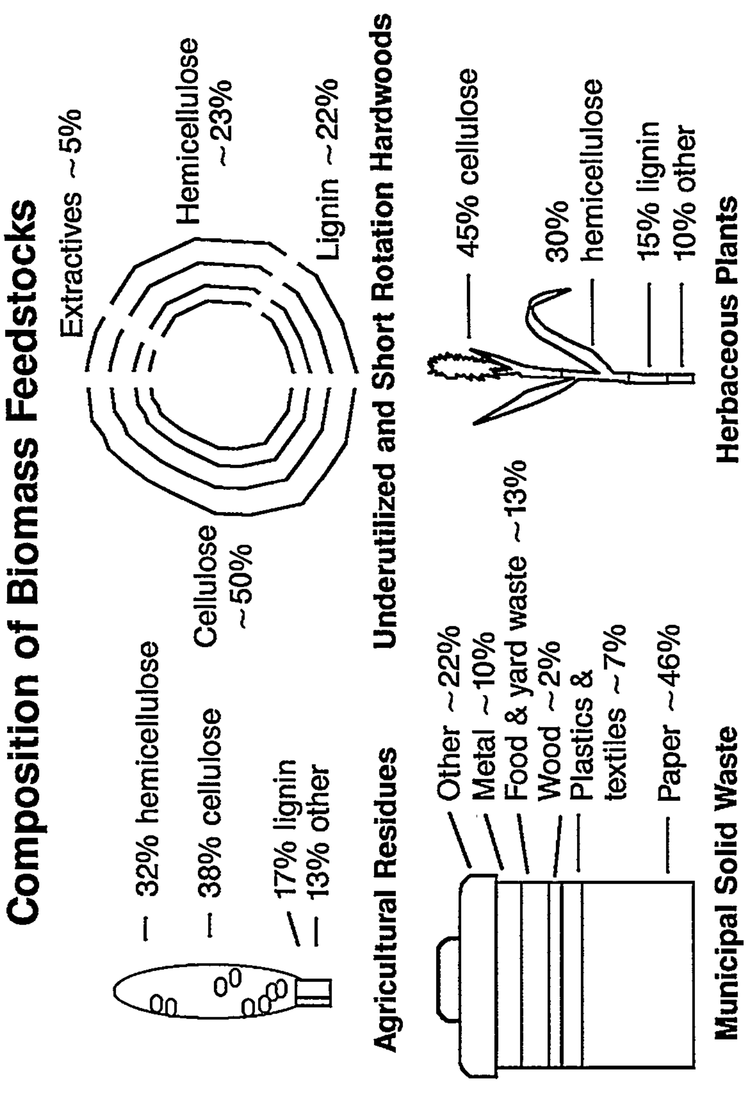
Composition of Biomass Feedstocks
32% hemicellulose
38% cellulose
17% lignin
13% other
Agricultural Residues
Extractives ~5%
Hemicellulose ~23%
Cellulose ~50%
Lignin ~22%
Underutilized and Short Rotation Hardwoods
Other ~22%
Metal ~10%
Food & yard waste ~13%
Wood ~2%
Plastics & textiles ~7%
Paper ~46%
Municipal Solid Waste
45% cellulose
30% hemicellulose
15% lignin
10% other
Herbaceous Plants

Figure 1

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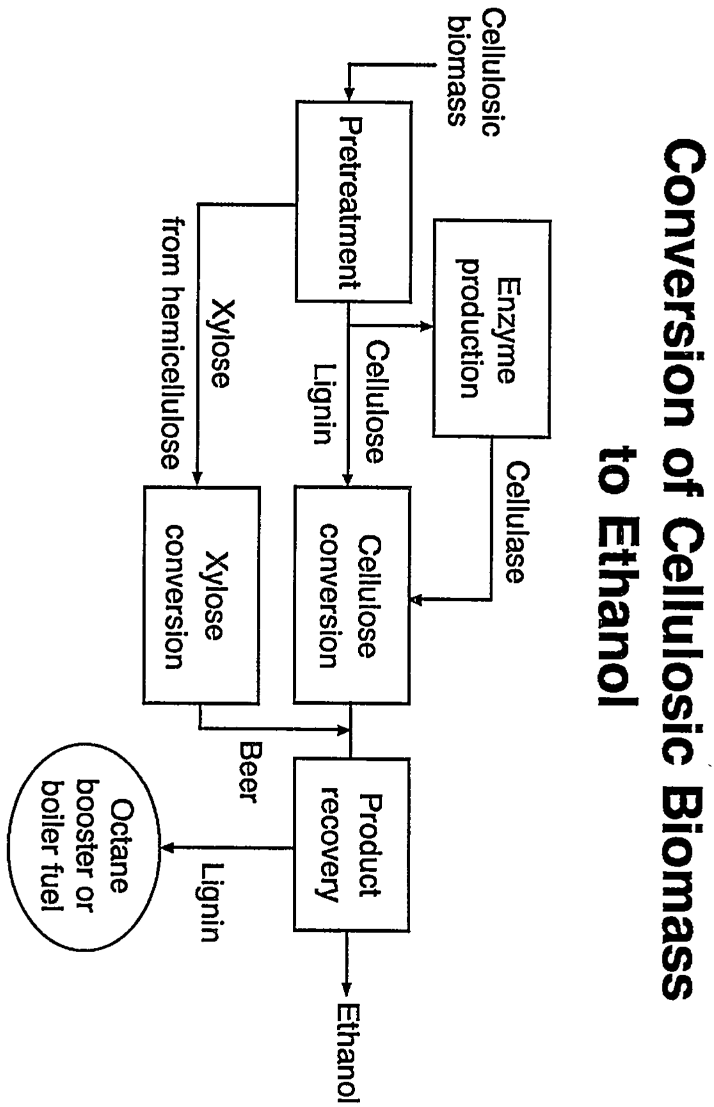


Figure 2

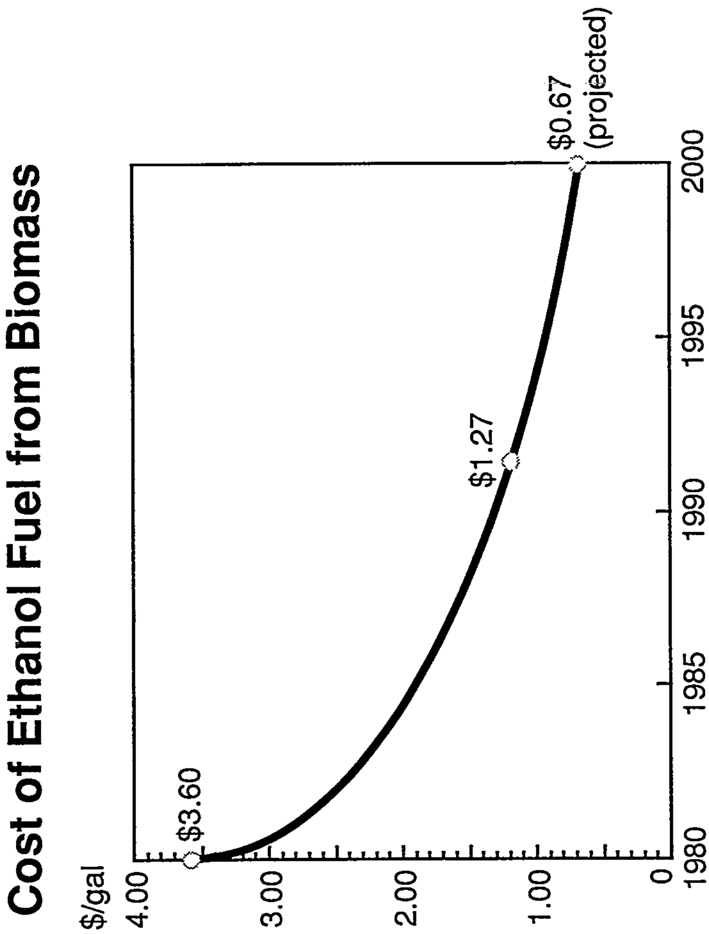
Cost of Ethanol Fuel from Biomass
$/gal
4.00
3.00
2.00
1.00
0
1980
1985
1990
1995
2000
$3.60
$1.27
$0.67
(projected)

Figure 3

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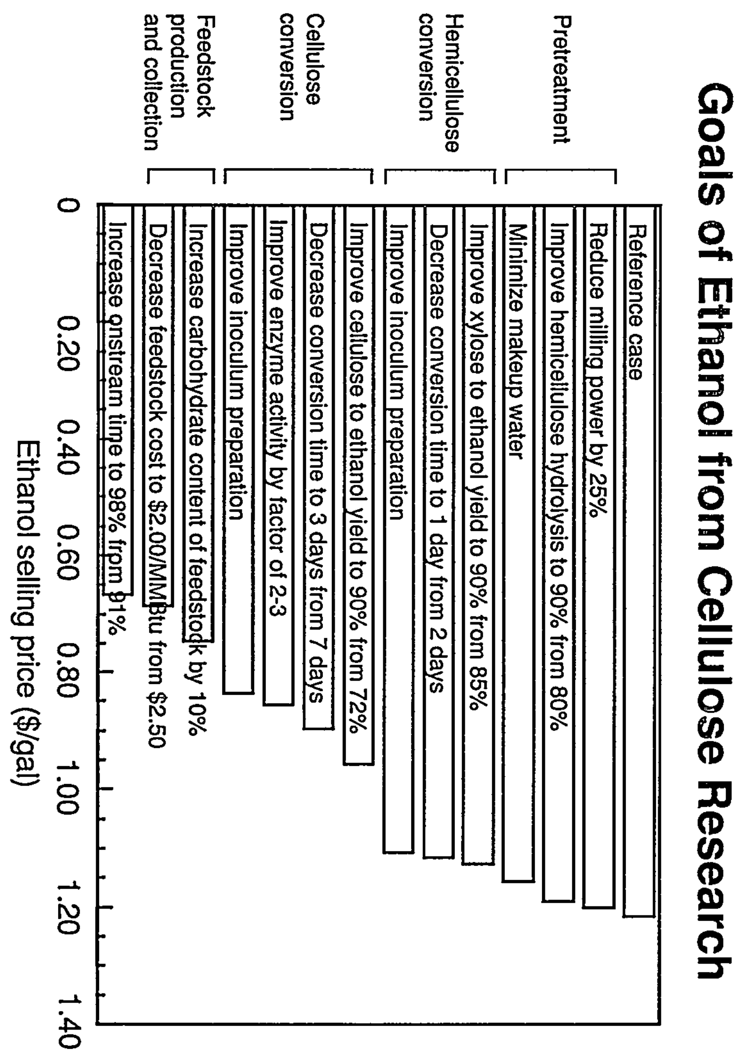


Figure 4