"Positioning Ethanol, ETBE and E-85 for the 21st Century"

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The Role of Bioethanol in Global Climate Change

Projected Impacts of an Aggressive Research and Development Program on the Effectiveness of Bioethanol as an Option for Reducing Greenhouse Gas Emissions from the Transportation Sector

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Background

The United States Department of Energy (DOE) has supported a research and development program for the establishment of renewable, biomass-derived, liquid fuels for the better part of the last twenty years. These "biofuels" represent opportunities to respond to uncertainties about our energy security and the future health of our environment. Throughout its history, the Biofuels program has experienced an ongoing fiscal "roller coaster". Funding has ebbed and flowed with changing political and public attitudes about energy[1]. The program was initiated in a flood of funding in the late 1970s related to the energy shortages experienced in that period. The flooding turned rapidly to drought as falling oil prices dissipated public concern about energy supplies. In the late 1980s, funding for the program slowly increased, driven by national security issues.

Despite its turbulent fiscal history, the Biofuels Program has made tremendous technical progress. The centerpiece of the program is the development of what we refer to as "bioethanol"; ethanol produced from cellulose and hemicellulose contained in grasses, trees and waste biomass. The research and development carried out by DOE over the decade of the 1980s, for example, resulted in a three-fold reduction in the estimated cost of ethanol made from cellulosic biomass, based on comparisons of production costs developed at the beginning and end of the decade[2]. In the 1990s, the program has continued its track record of technical progress, especially in the area of genetic engineering to develop microorganisms that are capable of fermenting the broad spectrum of sugars found in biomass[3]. Himmel, *et al* provides a comprehensive overview of recent technical progress on bioethanol.[4] As impressive as this progress has been, the price of bioethanol remains too high to compete with existing cheap sources of gasoline as a direct fuel substitute. Thus, the Biofuels Program continues to push toward a goal of producing bioethanol at prices competitive with gasoline. In the meantime, the program has interim goals for bioethanol technology that will allow it to compete in fuel additive applications, such as the fuel oxygenate market.

The Office of Fuels Development (OFD) within DOE's Office of Transportation Technologies (OTT) manages the Biofuels Program. This Office focuses on cost effective fuel production technology, and works in conjunction with other programs and Offices within OTT which are responsible for end-use (i.e., vehicle-related) technology for biofuels. The Biofuels Program is organized along two major lines of research: 1) the development of biomass feedstocks, and 2) the conversion of biomass feedstocks to ethanol. Each of these efforts is supported by a number of the Department's national laboratories. Oak Ridge National Laboratory (ORNL) in Oak Ridge, Tennessee, is the lead lab for feedstock R&D. The National Renewable Energy Laboratory (NREL, formerly the Solar Energy Research Institute) in Golden, CO, is the lead lab for conversion technology development. DOE, NREL and ORNL work directly with universities and private industry partners in the development of biofuels technology.

Global climate change—a question of risk

Carbon dioxide is recognized as the most important (at least in quantity) of the atmospheric pollutants that contribute to the "greenhouse effect", a term coined by the French mathematician Fourier in the mid-1800s to describe the trapping of heat in the Earth's atmosphere by gases capable of absorbing radiation. By the end of the last century, scientists were already speculating on the potential impacts of anthropogenic carbon dioxide[5]. The watershed event that brought the question of global warming to the forefront in the scientific community was the publication of Revelle's data in 1957, which quantified the geologically unprecedented build-up of atmospheric carbon dioxide that began with the advent of the industrial revolution. Revelle characterized the potential risk of global climate change this way:

> *"Human beings are carrying out a large scale geophysical experiment of a kind that could not have happened in the past nor be produced in the future. Within a few centuries, we are returning to the atmosphere and the oceans the concentrated organic carbon stored in sedimentary rocks over hundreds of millions of years."*[6]

Despite 40 years of research since Revelle first identified the potential risk of global warming, the debate over the real impacts of the increased carbon dioxide levels still rages.[7] We may never be able to scientifically predict the climatic effects of increasing carbon dioxide levels due to the complexity of atmospheric and meteorological modeling.[8] Indeed, Revelle's concise statement of the risks at play in global climate change remains the best framing of the issue available for policy makers today. The question we face as a nation is how much risk we are willing to take on an issue like this. That debate has never properly taken place with the American public.

As Revelle's statement implies, the burning of fossil fuels is the major source of this build up of carbon dioxide. Thus, identifying alternatives to fossil fuels must be a key strategy in reducing greenhouse gas emissions. While no one single fuel can substitute for fossil fuels in an all of the energy sectors, we believe that bioethanol is a fuel which can make a major contribution to the reduction of carbon dioxide generated by automobiles burning gasoline.

Why bioethanol?

The strategic advantage of the Biofuels Program is that it speaks to more than one important issue on the national agenda. Each of these issues on its own is probably not enough in today's fiscally conservative setting to justify any R&D program. In fact, given the focus on reducing spending, only those R&D programs that offer multiple benefits and provide the most bang for the buck are going to receive a high priority. Furthermore, the types of issues addressed by federal R&D are those long-term questions that are, appropriately, characterized by higher risk and greater uncertainty. This increases the need to focus on technology that addresses multiple fronts. It is this multi-faceted, longer range and less certain framework within in which we view the Biofuels Program.

The Biofuels Program attacks four major national issues: 1) global climate change, 2) urban air pollution, 3) national security, and 4) the farm economy. National initiatives in these areas are embodied in four major pieces of legislation developed over the past ten years:

- ✓ The Clean Air Act Amendments of 1990 (1990 CAAA)
- ✓ The Energy Policy Act of 1992 (1992 EPACT)
- ✓ The Alternative Motor Fuels Act of 1988 (1988 AMFA)
- ✓ The "Freedom to Farm" Act

Because the focus of this paper is global warming, I will not spend time discussing the merits of bioethanol with respect to the other three national issues.[9] Suffice it to say that bioethanol brings to the debate on climate change the necessary ability to provide benefits on multiple fronts. This is particularly critical for climate change; so much so that early discussions on greenhouse gas controls were keenly interested in the notion of a "no regrets" policy.[10] In other words, experts and politicians alike recognized the need to identify strategies for reducing greenhouse gas emissions that were *not* narrowly focused on carbon dioxide. The Bush administration's William Reilly characterized the approach of reducing our dependence on fossil fuels as a "no regrets" policy because of the dual benefits of energy security and greenhouse gas reductions. While the term has gone the way of many "out-dated" catch phrases, it still has relevance today.

Life cycle emissions of CO_2 —what can we say about bioethanol?

The science of life cycle analysis has improved tremendously since The Coca-Cola Company first began looking at life cycles of its products and packaging in the 1970s. Life cycle inventories (LCIs) are the only effective way to assess the impact of any product on greenhouse gas emissions. The life cycle of a product includes all steps involving the product's manufacture, use and final disposal. This includes everything from the extraction of all raw materials from the environment to the final end use. The inventory itself is an accounting of all energy, raw material and environmental flows into and out of every step of the cycle. Conducting a comprehensive life cycle inventory is, thus, not a trivial exercise. Finally, a life cycle inventory for a product, in and of itself, actually has little value. In order to understand the impact of a product like bioethanol, it is necessary to compare this life cycle inventory to that of whatever product it will replace. Over the past decade, a number of researchers have conducted this type of comparative life cycle analysis for bioethanol and reformulated gasoline.

The first life cycle study of bioethanol

The first of these major undertakings was a project led by the National Renewable Energy Laboratory in 1991.[11,12] This study quantified emissions from feedstock and fuel production, as well as from transport of feedstock and fuel. Steps included in the life cycles of bioethanol and reformulated gasoline are shown in Figure 1. The study, conducted for the U.S. Department of Energy's Office of Transportation Technologies, looked at the life cycle emissions and energy consumption of bioethanol used in 10% blends with gasoline (E10) and of bioethanol as an alternative fuel blended with 5% gasoline (E95). The latter was used as a case study for the year 2010, while the former was used as a case study for the year 2000. These two fuels were compared to reformulated gasoline. The study envisioned a nascent bioethanol industry in the year 2000 utilizing municipal solid waste as an inexpensive feedstock for fuel production. By 2010, the study assumed that the bioethanol industry would have moved on to woody and herbaceous energy crops as feedstocks.

The recycle of carbon is a key issue in understanding the benefits of biomass as a source of energy. As Figure 2 shows, in an idealized life cycle, no net carbon is produced by the combustion of bioethanol. Each sugar unit in cellulose contains six carbon atoms. Two of these carbons are released as carbon dioxide from the fermentative production of ethanol. The remaining four carbon atoms are released at the tailpipe as carbon dioxide. These six molecules of carbon dioxide are recycled when they are incorporated photosynthetically into a new sugar unit in cellulose. Of course, life is not that simple. Not all of the carbon in ethanol is released as carbon dioxide. Some carbon leaves the tailpipe in the form of carbon monoxide, particulates and hydrocarbons. Thus, not all of the carbon emitted by the vehicle is recaptured by photosynthesis. Still, we can say that all carbon which leaves the tailpipe *as carbon dioxide* is recycled. In other words, the carbon dioxide emitted by combustion of bioethanol can be considered zero. This assumption is made in all of the life cycle studies done on bioethanol (and on corn ethanol, as well).

Carbon dioxide emissions associated with fossil energy use occur in both the bioethanol and the reformulated gasoline life cycles. When these emissions are taken into account, the net emissions of carbon dioxide for bioethanol are not zero. Table 1 summarizes the findings of the NREL study for carbon dioxide emissions from the three fuels evaluated. Emissions of carbon dioxide drop 90% when E95 is used in place of reformulated gasoline. The low blend scenario yields a carbon savings of 8.5%.

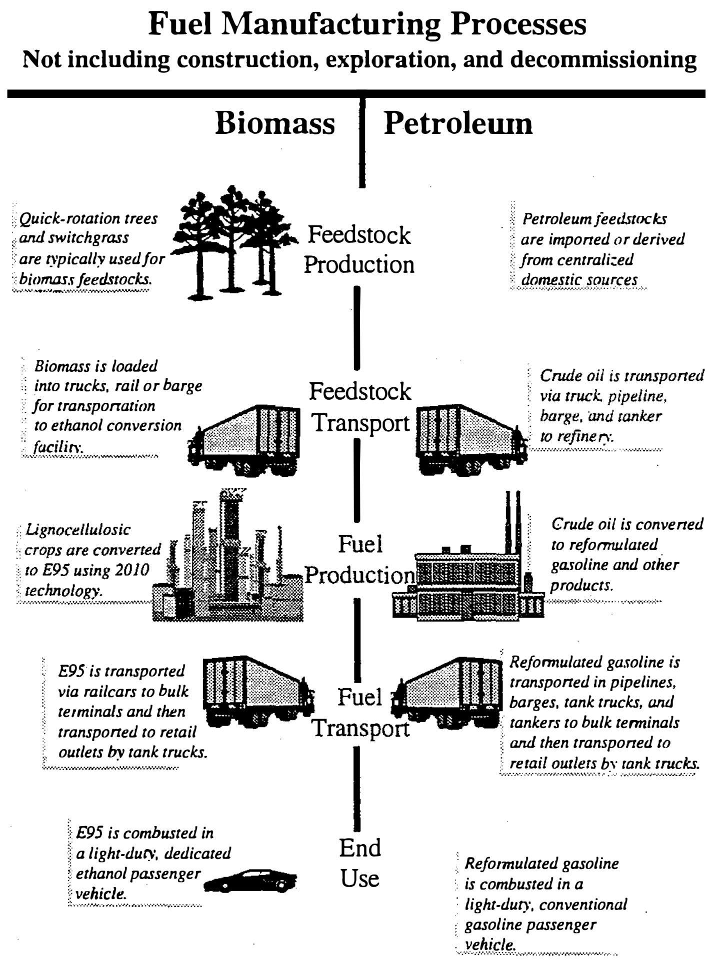


Figure 1: Steps Included in the Life Cycles of Bioethanol and Reformulated Gasoline

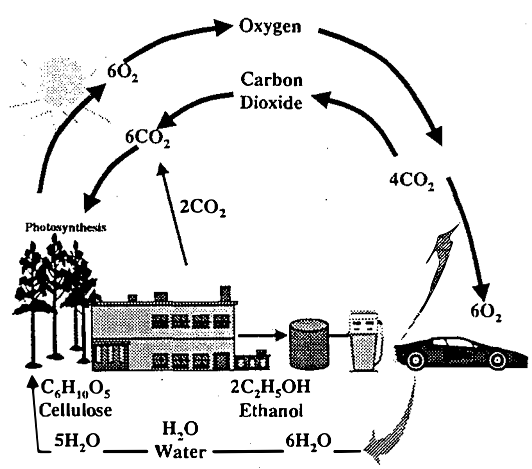


Figure 2: Carbon Recycle in the Bioethanol Life Cycle

Table 1 Comparison of Carbon Dioxide Emissions for E10, E95 and Reformulated Gasoline (Grams of Carbon per Mile Traveled)

Life Cycle Stage	RFG 2000	RFG 2010	E95 Avg	E10
Feedstock Production	12.97	14.70	5.81	0.24
Feedstock Transport	4.26	4.08	2.47	0.16
Fuel Production	25.76	26.94	3.61	0.26
Fuel transport	1.18	1.00	0.89	46.24
Fuel End Use	279.69	243.04	15.12	227.92
Total Life Cycle	323.87	289.76	27.91	274.81

Other studies

Since NREL's original study, a number of other analyses of bioethanol's life cycle have been completed. Figure 3 compares the results of some of these studies. The reductions of carbon shown in this figure allow a comparison on an equal basis of the amount of carbon saved per mile of travel delivered by a vehicle. There is quite a range of values for the degree of carbon dioxide reductions possible. The differences can be explained by a host of different assumptions used in the studies. For example, the studies which predict reductions of carbon dioxide greater than 100% assume a credit for carbon reductions associated with an electricity co-product in the fuel production stage.. Wang's studies include this credit, while the others did not. .NREL's estimates for E10 versus E95 are significantly different, owing to differences in fuel transport, vehicle efficiency and feedstock type.

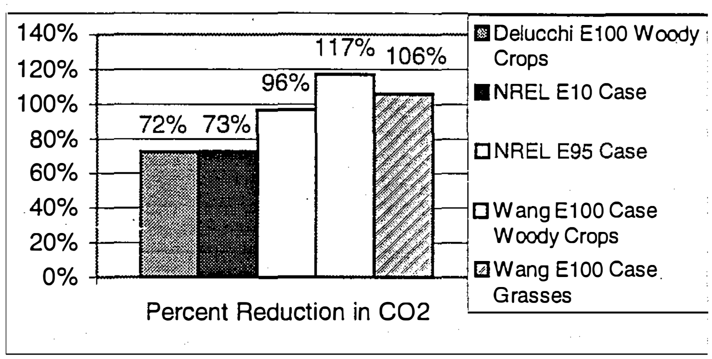


Figure 3 Carbon Savings Reported by Various Studies

Conclusions

In order to address the question of what role bioethanol can play in curbing emissions of carbon dioxide, we need two pieces of information:

- ✓ The net savings of carbon emissions possible per mile traveled on bioethanol versus gasoline, and
- ✓ The total amount of bioethanol we can expect to put in the market place

The life cycle studies presented here provide the answer to the first question. Published estimates of bioethanol capacity for reducing carbon dioxide emissions vary widely. Even so, the lowest estimate of bioethanol's potential as a tool for greenhouse gas mitigation confirms its significance. For the purposes of this discussion, I am assuming the range of 73% to 96% reported by NREL in 1993 as lower and upper bounds for an analysis of future potential benefits of introducing bioethanol in the transportation market. The lower estimate of 73% carbon reduction per mile is applies to the case of ethanol used solely as a blending agent. The higher estimate is applied to the case of ethanol used as a fuel substitute. In the latter case, the improved reduction of carbon emissions is mostly related to the improved efficiency of a dedicated ethanol fueled vehicle.

In order to understand how much bioethanol can be expected to penetrate the marketplace. we have to be able to predict future cost and availability of the fuel. The over-riding determinant of cost and availability of the fuel is the progress of research and development currently underway. Thus, it is important to understand the goals of our current research and development program.

Today's Targets for DOE's Bioethanol Program

The Biofuels Program has three basic goals in its current strategic plan[13]. This plan focuses on the timing of technology demonstrations in the years 2000 and 2005. The ultimate goal of the program is the establishment of technology that can provide bioethanol at costs close to that of gasoline.

Year 2000—Capturing Niche Markets

Commercial demonstration scale production of bioethanol will be on-line by the end of the year 2000 for one or more of the following waste feedstocks

- ✓ **Wood wastes/forest residues**
- ✓ **Grain processing wastes**

Year 2005—Introducing Energy Crops

Commercial demonstration scale production of ethanol will be on line in the year 2005 which utilizes switchgrass as part or all of its feedstock supply

Year 2020 and Beyond

Commercial production of bioethanol from dedicated energy crops at prices competitive with petroleum

The majority of the activities supporting the year 2000 goal involve process development, business planning and deployment activities. Activities supporting the year 2005 target are understandably more focused on applied research needed to develop major technology improvements. The main driving force for process improvement is the desire to push production costs down to minimize or eliminate subsidy requirements for bioethanol sold starting in the year 2000. In addition. because this mid term target addresses the transition to the first of our dedicated energy crops, process performance becomes even more critical in order to compensate for the higher anticipated cost of switchgrass as a feedstock relative to the waste materials used to achieve our near term goal.

Note that these goals focus on the demonstration of technology, without any specific indication of market penetration. There are many reasons for this. First, market penetration is a difficult thing to predict. It involves many factors, from government policy to future petroleum prices. Second, the biggest factor impacting penetration is the price of the fuel ethanol. The level of R&D available for bioethanol technology development dramatically impacts this price. Thus, while the overall framework of the Biofuels Program goals may not be dramatically affected by trends in research funding, the *impact* of the program on the fuel market in absolute terms is dependent on the level of research support. This leads to the logical question of just how much impact we could expect for bioethanol given a substantially increased R&D budget.

What could we do if money were no object?

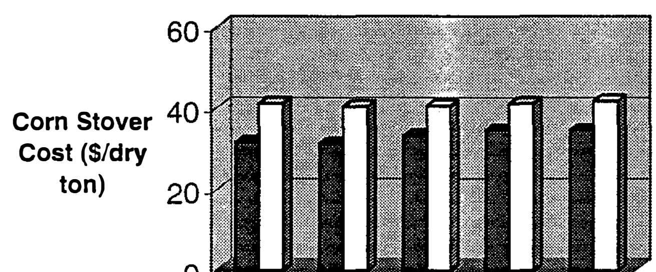
In the past year, the Office of Fuels Development at DOE has begun the task of bringing together all of the factors required to understand bioethanol market potential. These include:

- ✓ Targets for feedstock cost and availability
- ✓ Targets for fuel conversion cost
- ✓ Market constraints on fuel price

Our research program impacts the first two items. Each of these targets is discussed in the following two sections.

Providing Energy Crops

Oak Ridge National Laboratory has developed models for predicting the cost of biomass feedstocks used in bioethanol production.[14] Their projections consider two scenarios—a modest and an optimistic set of targets. The optimistic targets assume a sufficient budget for feedstock R&D that supports improved yields and rapid deployment of production technology for energy crops. Figure 4, Figure 5 and Figure 6 show the projected cost of three of the feedstocks for the optimistic scenario.



	2000	2005	2010	2015	2020
■Low	31.576	31.33	33.21	34.59	34.59
□High	41.24	40.438	40.605	41.268	41.856

Year

Figure 4: Optimistic Projections for the Cost of Corn Stover as a Feedstock for Bioethanol Production

Two major energy crops are being developed: switchgrass and short rotation woody crops. The former represents grasses that are grown and harvested annually. The latter are fast-growing trees that are harvested on a six-year cycle. In addition to these energy crops, Oak Ridge National Laboratory has considered existing agricultural residues such as corn stover as another (and quite substantial) source of cellulose for bioethanol production

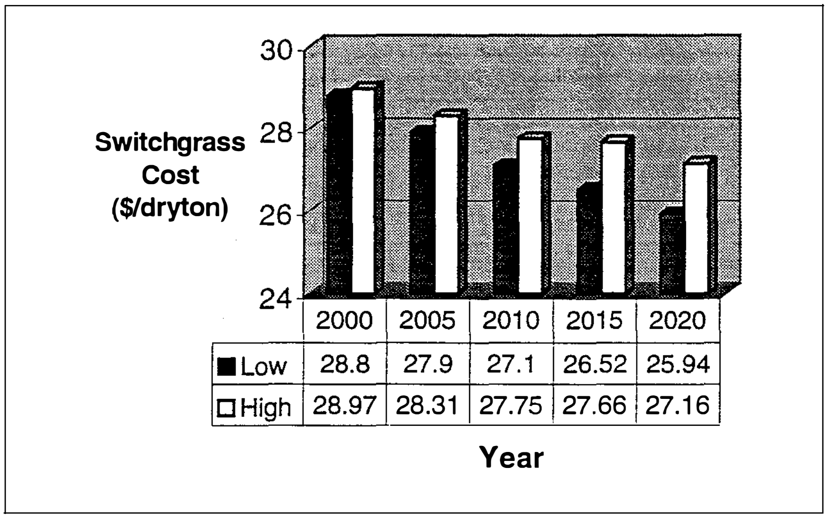


Figure 5: Optimistic Projections for the Cost of Switchgrass as a Feedstock for Bioethanol

Low and high estimates of feedstock costs shown in these figures correspond to the level of demand for these feedstocks. As feedstock demand increases, its price goes up. The Oak Ridge models take into account the competition of these feedstocks for agricultural land used for existing food crops. Their model sets a limit on the amount of new energy crops which can be produced. This is based on the point when competition for land causes the price of food crops to increase.

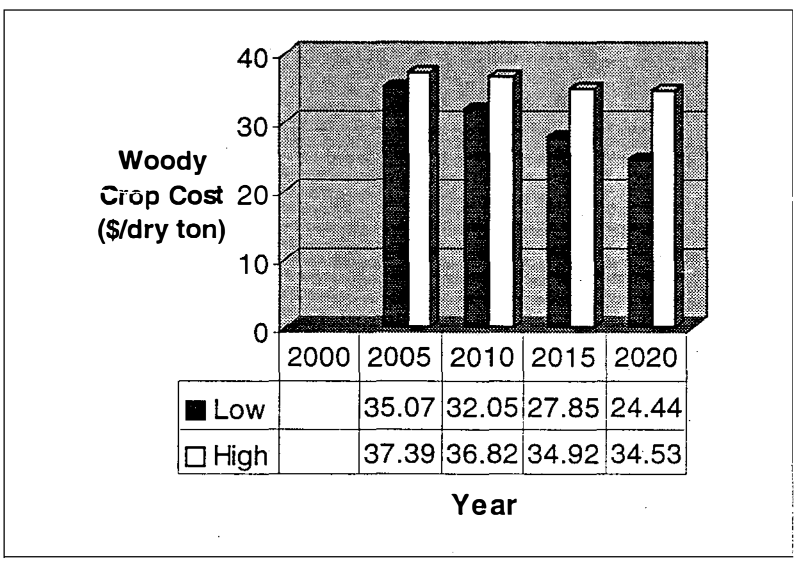


Figure 6: Optimistic Projections for the Cost of Short Rotation Woody Crops as a Feedstock for Bioethanol

The cost of corn stover is unaffected by research and development funding since this feedstock is a residue of current commercial corn production. Its costs tend to increase over time. Switchgrass and short rotation woody crop production drop in cost over time as a result of improved practices in their production. As demand for land increases, the benefit of improved yield diminishes. This is reflected in the lower rate of decline seen for the high demand cases.

Technology for Making Bioethanol

The capabilities of the bioethanol industry in the long term are difficult to predict. Nevertheless, it is important to look at such questions when making decisions about what technology options ought to be supported by federal funds over the next several decades. Lynd *et al* have ventured into the high risk game of making such predictions for the bioethanol industry in order to project the potential improvement of conversion technology.[15] The authors of this study acknowledge the inherent uncertainty in trying to predict the state of a mature technology that does not even exist today. Nevertheless, they also see that, for the sake of long term planning, we must venture into this uncertain terrain when making decisions about research and development for renewable energy technologies. The most important caveat regarding these projections is that R&D for conversion technology would have to occur at a much more aggressive pace than is currently being done if there is to be any possibility of ever seeing these projections come to fruition.

Converting biomass to ethanol involves the processing of three major components in the feedstock: hemicellulose (a polymer of C5 sugars), cellulose (a polymer of C6 sugars), and lignin (a complex polyaromatic material). The hemicellulose and cellulose fractions provide sugars for fermentation to ethanol. Lignin can be used as fuel for steam and electricity production.

Conversion of biomass to ethanol involves five major steps. These basic steps are shown in Figure 7. The bulk of our research focuses on improvements in biomass pretreatment and biological processing steps. The latter involves thermochemical treatment of biomass to loosen up the lignin/hemicellulose/cellulose structure, rendering it more amenable to further biological processing. Pretreatment usually results in release of hemicellulose sugars, and can also lead to release of some of the cellulosic sugars. Biological processing involves the use of enzymes to release sugars from cellulose and the use of microbes for fermenting sugars to ethanol.

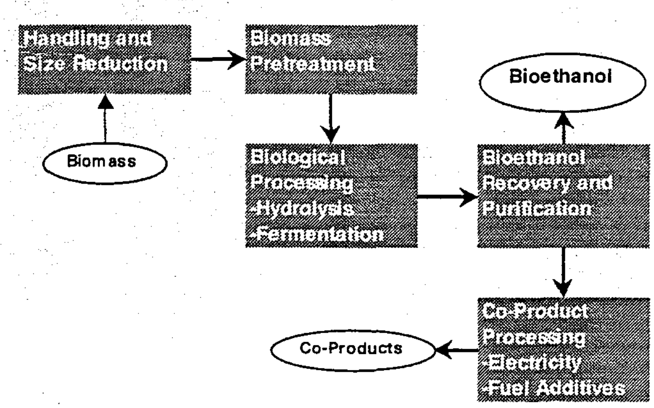
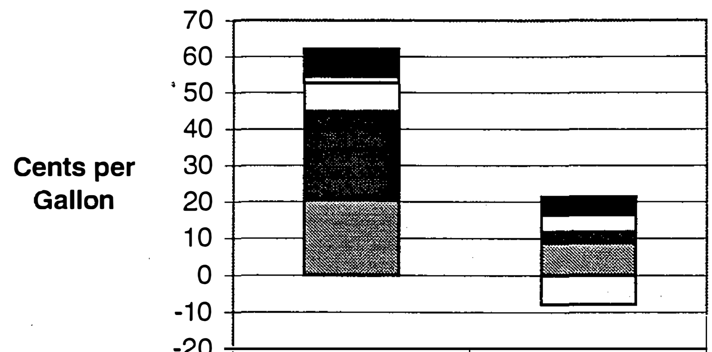


Figure 7: Schematic of Conversion Technology for Bioethanol

The point of departure for Lynd's "mature technology" analysis is an evaluation of the so-called "base case technology" for the production of ethanol from hybrid poplar, as it was envisioned by the National Renewable Energy Laboratory in 1991[16]. The base case technology scenario results in conversion costs of 62 cents per gallon allowing for a credit of around 9 cents per gallon for electricity sold from a bioethanol facility. Lynd *et al* show this cost dropping to as low as 13.5 cents per gallon in the mature technology scenario.



	Base Case	Lynd's "Mature" Technology
■ Other	7.7	5.06
□ Coproduct	1.65	-7.97
□ Ethanol Recovery	7.84	4.62
■ Biological Processing	24.6	2.95
▨ Pretreatment	20.3	8.85

Figure 8: What could "mature" technology for conversion look like?

Pretreatment costs are reduced by around a factor of two based on the use of a liquid hot water process (also known as aquasolv™). Biological processing costs provide the largest reductions in cost through the use of direct microbial conversion technology in which cellulase production, cellulose hydrolysis and fermentation all occur in one reactor system. This consolidation of the biological processes from three to one reactor system is doable, though attaining such a goal is clearly a reach.

In my analysis, NREL's 1991 base case projections for ethanol conversion technology are used to estimate the cost of bioethanol in the year 2010. The base case analysis was an attempt to look at the long-term technology required for economic utilization of energy crops. The Biofuels Program's multi-year technical plan projects that this target will be met in the year 2010. I further assume that the capability of the mature technology described by Lynd is available in the year 2020. The latter is admittedly a guess. Given a very aggressive research and development scenario, I assume that these optimistic performance targets could be achieved in a twenty-year time frame.

In order to complete the time-phased picture for bioethanol technology costs, I simply extrapolate the cost of ethanol conversion backwards assuming a linear trend. In all likelihood, the progression of technology improvements will not be linear, but rather logarithmic or sigmoidal.[17] Nevertheless, the presumption of linear progress illustrates the point I am trying to make about the potential for bioethanol technology in greenhouse gas mitigation.

The cost projections for the conversion technology for bioethanol are shown in Figure 9. This analysis puts the near-term (year 2000) cost of conversion at $0.91 per gallon of bioethanol. While my approach to these projections is undoubtedly very speculative, it has proved to be reasonably consistent with more rigorous cost analyses done at NREL using the ASPEN™ process simulator.[18]

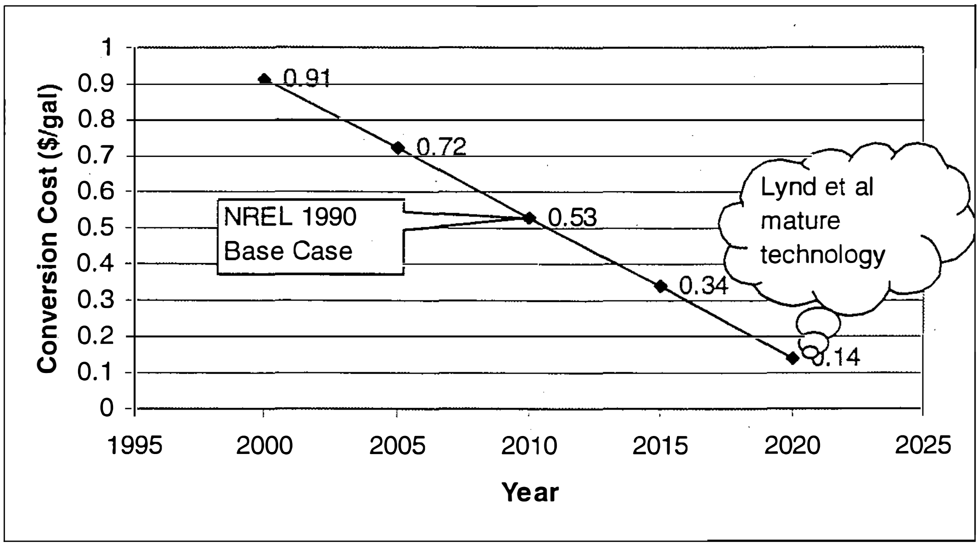


Figure 9: Improvements in Bioethanol Conversion Technology Costs Over Time

The "bottom line"—competing in the market place

Bioethanol at the refinery

Oak Ridge National Laboratory has completed an analysis of the potential demand for bioethanol as an additive in petroleum refineries in the year 2010.[19] This analysis is conservative in the sense that it describes the value of bioethanol strictly in terms of its use as a fuel additive or fuel extender up to a limit of 10% ethanol by volume in gasoline. This limitation sets a cap on the use of bioethanol. Oak Ridge uses a linear programming model to describe the optimal use of bioethanol in a refinery based on the physical and chemical properties of bioethanol relevant to the needs for conventional gasoline, reformulated gasoline and oxygenated fuel markets. Figure 10 presents the demand curve for bioethanol. The value of bioethanol drops as demand (and supply) for this additive increase. At the current level of market consumption, bioethanol commands a price of around $1.10 to $1.20 per gallon of bioethanol (around 1 to 1.5 billion gallons of ethanol per year).

Now, let's make the assumption that the refinery demand curve for bioethanol is, relatively speaking, constant from the year 2000 to the year 2020.[20] This allows us to compare bioethanol value in 2010 with the projected price for bioethanol in earlier and in later time frames. Figure 10 shows where the projected values for bioethanol coincide with projected prices for bioethanol. The annual bioethanol demand at which the bioethanol supply curves and the refinery demand curve intersect, indicating potential bioethanol fuel sales, are shown in Figure 11. Bioethanol could generate as much as 9.5 billion gallons per year in sales for the fuel additive market alone. The limit in bioethanol usage up to 10% blends forces the value of bioethanol to drop dramatically above a level of 9 billions gallons per year in sales.

As a strategy for "growing" the bioethanol industry, targeting the fuel blend market allows the industry to increase roughly eight-fold from its current size. At the same time, the blend market sets the stage for the ultimate goal of replacing gasoline. By the year 2015, we could establish an industry base for bioethanol production which can stand on its own economic merits.

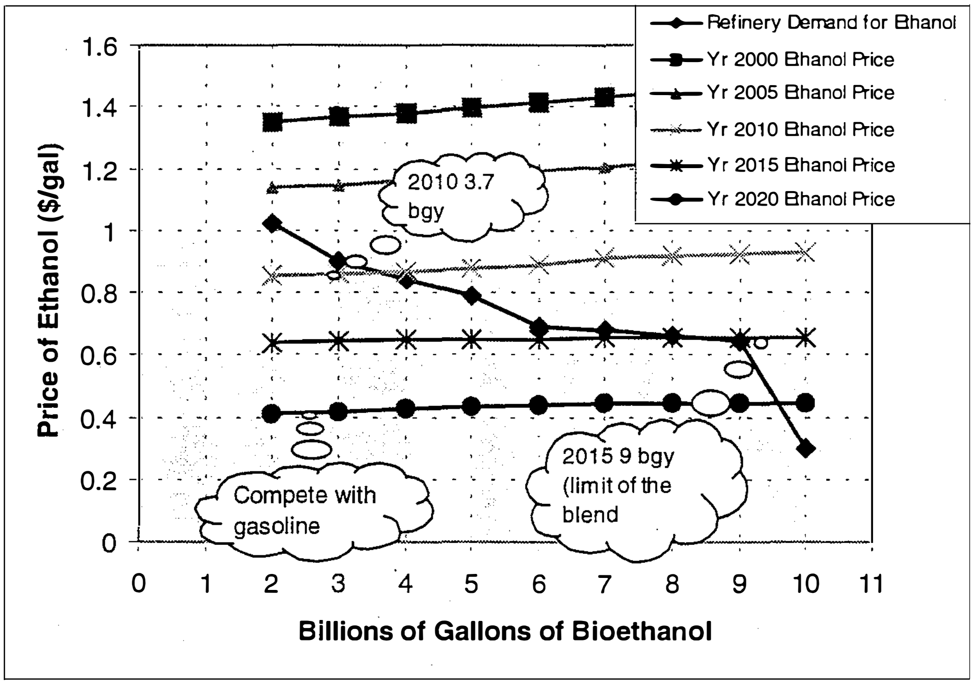


Figure 10: Supply versus Demand for Bioethanol

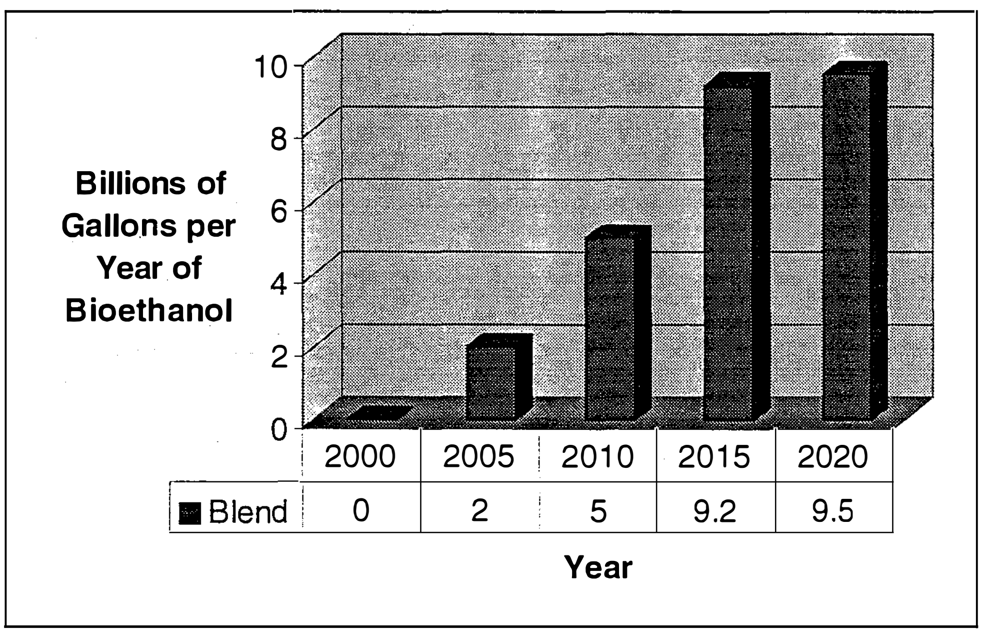


Figure 11: Demand for Bioethanol through the Year 2020

Bioethanol at the pump

Once bioethanol becomes available at levels greater than 9 billion gallons per year, its value as a blending agent drops precipitously. It is at this point that we need to think about a transition from the blend market to the neat fuel market in which bioethanol competes head-to-head with gasoline as a source of Btus for vehicles.

The aggressive assumptions for bioethanol technology development presented here lead to a situation in the year 2020 in which the cost of bioethanol is significantly lower than its value as a substitute for gasoline. The Energy Information Administration's projections for gasoline prices are shown in Figure 12. They report gasoline prices at the pump, which include federal and state taxes, as well as costs for distribution and marketing of the fuel. Using data on projected taxes and marketing costs, I have estimated the plant gate cost for gasoline. This cost can be compared directly with our projections for bioethanol cost. By separating tax trends from actual gasoline production costs, we see that gasoline cost is actually rising at a much greater rate than the retail price. This is due to the mitigating effects of projected lower federal tax rates for gasoline.

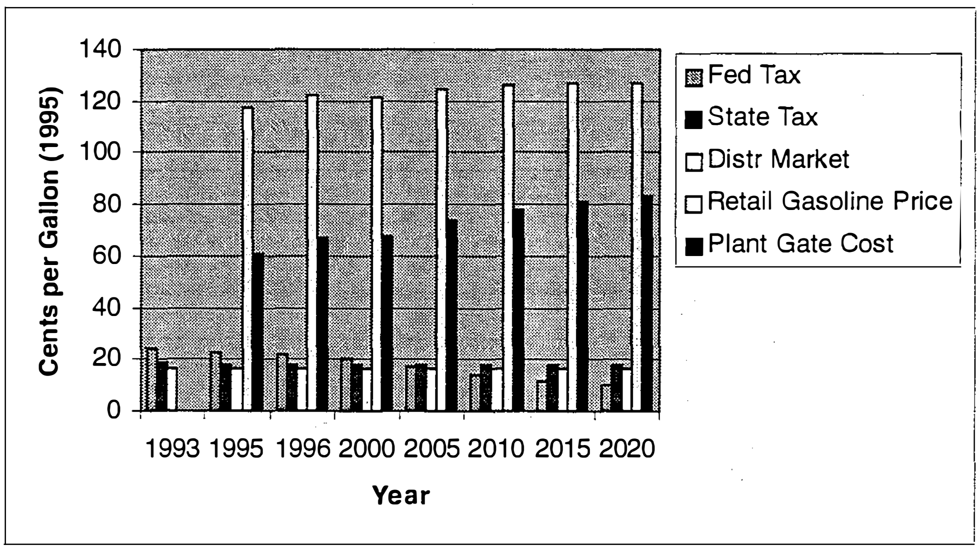


Figure 12: Projections for the Retail Price of Gasoline

Differences in the energy content of bioethanol and gasoline, as well as differences in the energy efficiency of gasoline engines and dedicated bioethanol vehicles, complicate the comparison of these two fuels. Figure 13 shows the net differential cost to the consumer of using bioethanol per gallon of gasoline displaced (taking into account the energy content and vehicle efficiency differences). Two costs are shown in each year reflecting low and high demand for bioethanol. What this figure demonstrates is that, if we can achieve the aggressive research goals outlined by Lynd, bioethanol will, for the first time, be competitive with gasoline in the year 2020. At this point, if the vehicles and associated infrastructure are in place, bioethanol sales could jump four-fold (see Figure 14). The limiting factor for use of bioethanol becomes feedstock supply.

Impacts on Carbon Dioxide

By now, the reader should have an appreciation for the complexity of analysis that goes into evaluating the role of bioethanol (or any other fuel) in global climate change. In order to get to the point of being able to discuss potential impacts on greenhouse gases, we have had to make use of life cycle studies, process analysis models, feedstock economic models, petroleum refinery models, petroleum cost projections and basic supply and demand analysis. Output from all of these analytical tools can be combined to show the net effect of bioethanol on greenhouse gas emissions from the transportation sector.

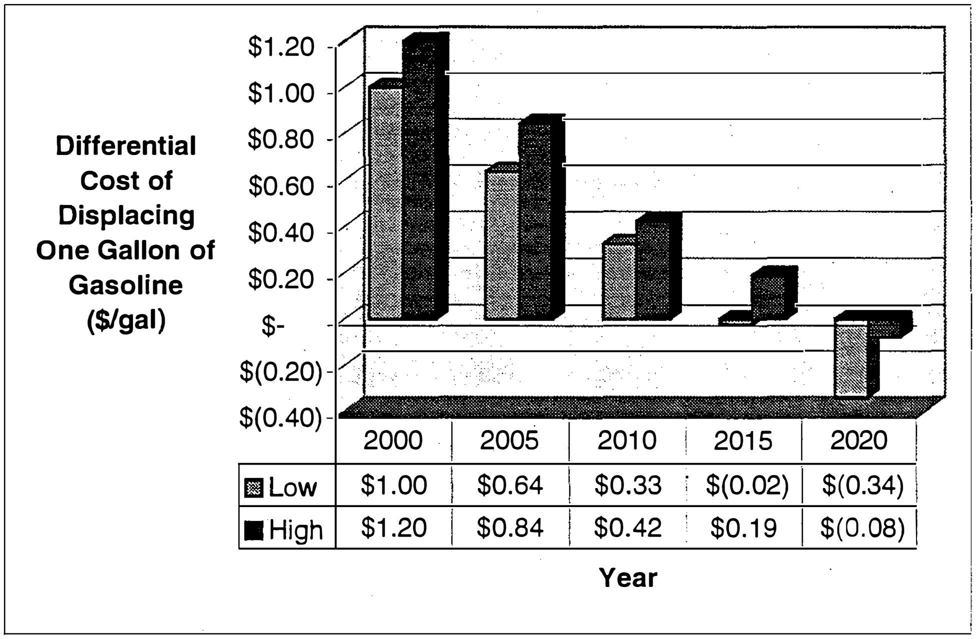


Figure 13: Net Cost to the Consumer of Displacing One-Gallon of Gasoline with Bioethanol

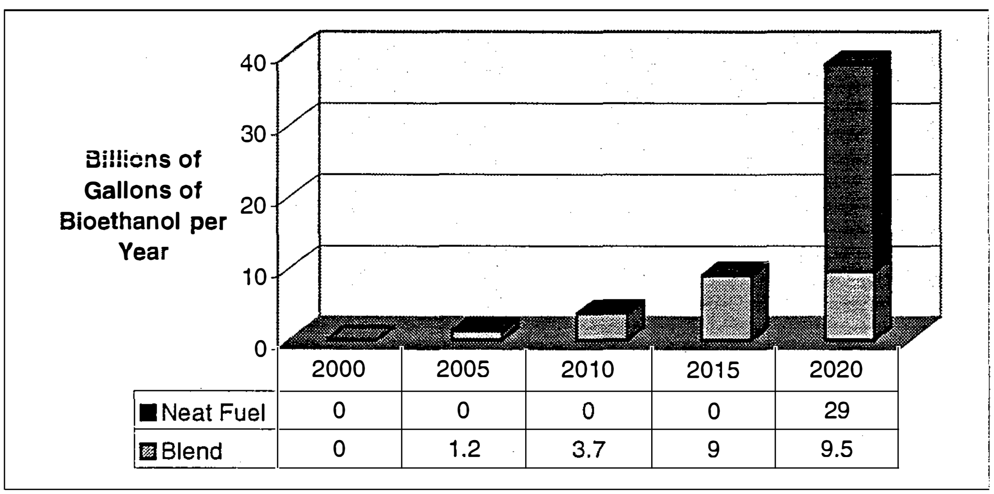


Figure 14: Market Penetration of Bioethanol Based on an Aggressive Research and Development Program

Greenhouse gas emissions from the U.S. transportation sector are shown in Figure 15 for "business as usual" and for the aggressive research and development scenario described in this paper.[21] Bioethanol's penetration of the fuel blend market results in a roughly 3% decrease in projected emissions of carbon dioxide by the year 2015 (or, 17 million metric tons of carbon equivalent avoided). The transition to the neat fuel market provides the real payoff. The combined blend and neat fuel markets captured in the year 2020 could reduce projected emissions from transportation by 14%, representing 79 million metric tones of carbon emissions avoided.

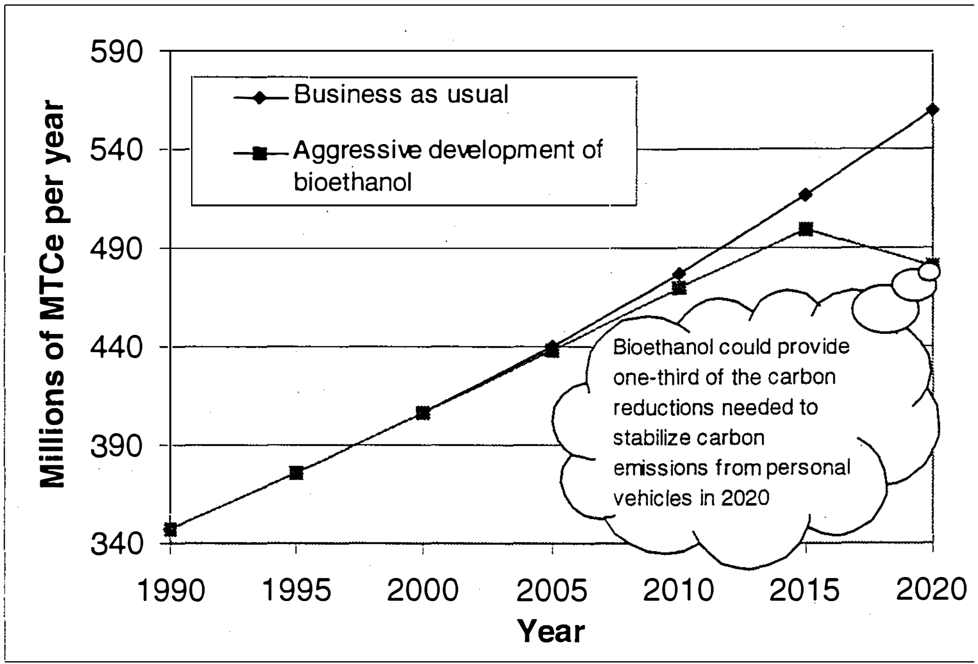


Figure 15: The Impact of an Aggressive Bioethanol Research and Development Program on Projected Carbon Emissions from the U.S. Transportation Sector

Conclusions and Closing Thoughts

I have taken the risk in this article of inundating with the reader with too much information. But, I firmly believe that the debate on climate change is important enough and complex enough to warrant this. I hope that the reader walks away with a broad sense of all the issues involved in understanding bioethanol and its role in climate change. Armed with this kind of information, we can begin a real debate on our Nation's strategy for climate change and how bioethanol may fit into it.

Here are some important "take home" lessons from this paper:

- ✓ No single technology, including bioethanol, can be expected to completely address climate change. Even the aggressive scenario presented here demonstrates a capability to provide at most 14% reductions in future carbon emissions. We should see bioethanol as one part of a comprehensive portfolio of technological and policy solutions.

- ✓ The future impacts of bioethanol shown here are NOT based on any tax incentive or subsidy approach. Such policies may well be needed to accelerate deployment of mitigation strategies. But, I think it is critical to demonstrate that technology solutions such as bioethanol are only enhanced by these policies, and do not require them.

- ✓ The aggressive research and development scenario envisioned here *does* require a consistent long-term commitment. The roller coaster history of funding for this program, if continued, will only assure failure.

- ✓ The U.S. Department of Energy's analysis of bioethanol has elucidated a rational strategy for deployment of bioethanol technology. The foundation of this strategy is recognition that fuel blend markets will continue to play a substantial role. Oil price projections for the next 20 years render a near term market penetration of bieothanol as a neat fuel very unlikely.
- ✓ While the focus of this paper has been on greenhouse gas mitigation, let us not forget that bioethanol has equally important impacts on questions of national energy security and other environmental issues.
- ✓ Finally, we are not done in our efforts to understand bioethanol's impacts. The analysis shown here is part of an ongoing effort to continually re-assess our situation with new data and to continually seek out ways to improve bioethanol's potential impact on climate change.

Acknowledgements

As recently as a year and a half ago, many of the analytical tools described in this paper were not readily available for use in this kind of integrated analysis. The persistent efforts of Mr. Tien Nguyen in the Office of Fuels Development to coordinate and communicate the Department of Energy's analytical capabilities have changed that situation for the better.

Endnotes and References

[1] See, for example, Farhar, B., *Trends in Public Perceptions and Preferences on Energy and Environmental Policy;* NREL/TP-461-485. National Renewable Energy Laboratory, Golden, CO 1993.

[2] Texeira, R.; Goodman, B. (Eds), *Ethanol Annual Report: FY 1990.* Solar Enegy Research Institute, SERI/TP-231-3996. Golden, CO 1991.

[3] Zhang, M., *et al. Science, 267,* pp 240-243. American Association for the Advancement of Science, Washington, D.C., 1995.

[4] Himmel, M., *et al.* "Chapter 1 Advanced Bioethanol Production Technologies: A Perspective". In *Fuels and Chemicals from Biomass* (Saha, B. and Woodward, J., Eds). ACS Symposium Series 666. American Chemical Society, Washington, D.C., 1997.

[5] Sarmiento, J. *Chemical and Engineering News, 71/22,* pp 30-43, 1993.

[6] Revelle, R.; Suess, H. *Tellus,* 9/1, pp 18-21, 1957.

[7] Schneider, S. *Science, 243,* pp 36-44, 1989.

[8] Oreskes, N., *et al. Science, 263,* pp 641-646, 1994.

[9] For a more comprehensive discussion of these others issues and bioethanol's impact on them, see Sheehan, J. "Chapter 1 Bioconversion for Production of Renewable Transportation Fuels: A Strategic Perspective", in *Enzymatic Conversion of Biomass for Fuels Production* (Himmel, M., Baker, J., Overend, R., Eds.). ACS Symposium Series 566. American Chemical Society, Washington, D.C., 1994.

[10] See, for example, "Best Plan On Global Warming Is Still To Have 'No Regrets'". *The Denver Post* Editorial. June 7, 1993.

[11] Riley, C. "Chapter 3 Total Fuel Cycle Emissions Analysis of Biomass-Ethanol transportation Fuel". In *Alternative Fuels and the Environment* (Sterrett, F., Ed.). Lewis Publishers, Boca Raton, FL, 1994.

[12] Tyson, K. *Fuel Cycle Evaluations of Biomass-ethanol and Reformulated Gasoline.* Vol 1. NREL/TP-463-4950. National Renewable Energy Laboratory, Golden, CO, 1993.

[13] Detailed plans in support of the program's goals are presented in *Multi-Year Technical Plan for Ethanol.* National Renewable Energy Laboratory, March 31, 1997 (Internal Report to the Office of Fuels Development, U.S. Department of Energy).

[14] Walsh, M. *et al. The Evolution of the Fuel Ethanol Industry: Feedstock Availability and Price.* Internal report to the Office of Transportation Technologies. Oak Ridge National Laboratory. Oak Ridge, Tennessee. June 5, 1997.

[15] Lynd, L., Elander. R.; Wyman, C. "Likely Features and Costs of Mature Biomass Ethanol Technology". In *Applied Biochemistry and Biotechnology.* Vol 57/58. The Humana Press, 1996.

[16] Hinman, et al. *Applied Biotechnology and Bioengineering.* Vol 34/35, pp639-657, The Humana Press, 1991.

[17] Hess, R. W. *Review of Cost Improvement Literature with Emphasis on Synthetic Fuels Facilities and the Petroleum and Chemical Process Industries.* Rand Corporation, Santa Monica, CA. 1985.

[18] Personal Communication Robert Wooley, National Renewable Energy Laboratory, Golden, CO, 1997. Costs of bioethanol for the year 2000 were predicted by linearly extrapolating backwards from assumptions about ethanol technology in the years 2010 and 2020, as indicated in earlier sections of this report. This extrapolation led to a projection of $0.91 per gallon for conversion costs exclusive of feedstock costs. When the updated ASPEN™ model costs are put on the same basis, this cost is $0.98 per gallon. Though this may be totally serendipitous, the two approaches to looking at year 2000 costs are remarkably close.

[19] Hadder, G. R. *Estimation of Ethanol Demand in Gasoline Production (Draft).* Oak Ridge National Laboratory, Oak Ridge, Tennessee, 1997.

[20] This is a very reasonable assumption given the projections from the Energy Information Administration at the U.S. Department of Energy. (See *Annual Energy Outlook 1998,* Energy Information Administration, U.S. Department of Energy, Washington, D.C., 1998.

[21] Difiglio, C. "Using Advanced Technologies to Reduce Motor Vehicle Greenhouse Gas Emissions". *Energy Policy,* Vol 25, Nos 14-15, pp1173-1178. 1997.