GREENHOUSE GAS EMISSIONS FROM ETHANOL AND MTBE
A COMPARISON

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What will be the impact on greenhouse gas emissions from the expanded use of ethanol resulting from the proposed Renewable Oxygenate Standard (ROS)? Those opposed to the mandate rely on several studies to bolster their argument that using ethanol produces little or no environmental benefits.[1] Most of these studies fundamentally rely on an excellent and in-depth 1991 study by Mark DeLuchi.[2]

DeLuchi analyzed the life cycle greenhouse gas emissions for MTBE blended reformulated gasoline, ethanol and methanol. He generated 31 different scenarios. In these scenarios DeLuchi translated all greenhouse gas emissions into CO_2 equivalents.[3]

DeLuchi's estimates of emissions from ethanol vary dramatically depending on the assumptions used in the production/emission model.[4] DeLuchi's widely quoted conclusion is, "The general message of these corn-to-ethanol scenarios is that one can pick values for a set of assumptions that will support virtually any conclusion about the impact of the corn-to-ethanol cycle."[5]

DeLuchi concluded, for example, that when ethanol is made from corn, and coal is used as the fuel, greenhouse gas emissions could decrease by as much as 65 percent compared to using MTBE reformulated gasoline or they could increase by as much as 80 percent. For corn derived ethanol using biomass as the fuel, the range is from a 100 percent reduction in emissions compared to an equivalent amount of MTBE RFG to a 10 percent increase.[6]

DeLuchi's work is an excellent starting point for policy analysis. For purposes of public policy two further steps are needed. First, his analysis must be updated to include new information. Second, policy analysts must identify which of DeLuchi's scenarios have the highest probability of reflecting real world conditions and therefore, of reflecting the true environmental impact of an expanded use of ethanol.

Based on the latest information regarding the energetics of ethanol and methanol and based on the most realistic of DeLuchi's scenarios, we conclude that an increased use of ethanol is highly likely to reduce greenhouse gas emissions.

Using the assumptions set forth below for ethanol and MTBE blending systems and based on the most widely quoted studies,[7] we believe the following information below reflects a realistic range of greenhouse gas emissions on a gram of CO_2-equivalent per mile of light duty vehicle traveled.

Neat gasoline is used as the base case. Thus, for example, MTBE blended reformulated gasoline generates from 4 percent less to 8 percent more greenhouse gases than neat gasoline depending on the scenario. Ethanol derived from corn in plants fueled by natural gas generates from 40 percent less to 10 percent less greenhouse gases than neat gasoline.

The range of CO_2-equivalent emission changes from base-case neat gasoline emissions are a result of the range of assumptions concerning the energy efficiencies of production technologies, coproduct energy and emission credit allocations, the type of agricultural practices used and the global warming potential variations of different non-CO_2 gases.

Greenhouse Gas Emissions Relative to Neat Gasoline

MTBE (methyl tertiary butyl ether) in RFG[8]	-4% to +8%
Ethanol in RFG: corn derived and coal fueled	-35% to -0%
Ethanol in RFG: corn derived and natural gas fueled	-40% to -10%
Ethanol in RFG: corn derived and corn stover fueled	-60% to -40%
Ethanol in RFG: cellulose derived and biomass fueled	-100% to -70%

The maximum benefits of using ethanol occur when farmers and ethanol producers use the most energy efficient practices and when the emissions and energy consumption generated and used inraising and converting the corn into its various end products are allocated on an average base over all of the coproducts. The least reduction in greenhouse gas emissions occurs when farmers and ethanol producers use relatively inefficient production and manufacturing techniques and when low credits are given to coproducts.

In virtually all likely scenarios ethanol blends have a dramatically beneficial greenhouse gas emission advantage over MTBE blended RFG.

Table 1. Energy Used to Make Ethanol from Corn and Cellulose (Btus per gallon of ethanol)

		Corn Ethanol (Industry Average)	Corn Ethanol (Industry Best)	Corn Ethanol (State-of-the-Art)	Cellulosic Crop-Based Ethanol
FEEDSTOCK PRODUCTION	**Fertilizer**	14,800	7,760	4,360	6,200
	Pesticide	715	715	715	350
	Fuel	3,196	3,088	2,992	5,870
	Other (feedstock)[1]	10,720	10,184	9,650	4,150
	Total (feedstock)	**29,431**	**21,747**	**17,717**	**16,570**
PROCESSING ENERGY INPUT	**Process Steam**	38,500	32,150	28,000	49,075
	Electricity	5,100	1,700	1,700	8,925
	Bulk Transport[2]	1,330	1,100	800	1,330
	Other (process)[3]	1,450	1,282	1,050	2,100
	Total (processing)	**46,380**	**36,232**	**31,550**	**61,430**
TOTAL ENERGY INPUT		**75811**	**57979**	**49267**	**78000**
ENERGY OUTPUT	**Energy in Ethanol**	76,000	76,000	76,000	76,000
	Co-product Credits[4]	24,950	32,693	32,693	115,400
	Total Energy Output	**100,950**	**108,693**	**108,693**	**191,400**
NET GAIN	**Net Energy Gain**	**25,139**	**50,714**	**59,426**	**113,400**
	Percent Gain	**33%**	**87%**	**121%**	**145%**

1 Includes energy for average crop irrigation, drying, seed, lime, on-farm electricity, machinery, and bulk crop transportation.
2 Bulk transport of ethanol is primarily by truck except for large plants which employ more energy efficient rail transportation.
3 Process (other) includes energy required for local delivery transportation of ethanol, energy for process water, and other minor plant energy needs like waste water recycling and treatment.
4 Co-product energy credits for corn-based ethanol in wet-milling are from corn oil, 21% protein feed, 60% gluten meal, and carbon dioxide. In dry-milling, corn processing to ethanol produces corn oil, distillers dry grain with solubles (DDGS), and carbon dioxide. Credits for cellulose-based ethanol are primarily for the energy content of lignin by-product as a boiler fuel when ethanol is made from wood. Greater quantities of lignin are produced when ethanol is made from virgin wood than from wood waste streams such as sulfite liquor from paper mills. Lignin refined further into phenolic chemicals can contribute more toward energy credits available to ethanol.

SOURCES: "Farmers Fueling America: A Special Report on Ethanol," Farm Journal Custom Publishing Co., 1991; High Plains Corporation, Wichita, Kansas, June 1992; Keeney, D. R., and Deluca, T. H., "Biomass as an Energy Source for the Midwestern U.S.," American Journal of Alternative Agriculture, draft copy, in press, 1992; "Annual Report on Fuel Ethanol," Solar Energy Research Institute, Golden, Colorado, 1990; "Agricultural Chemical Usage: 1991 Field Crops Summary," U.S. Department of Agriculture, ERS, Washington, D.C., 1992.

DISCUSSION

Six key elements are involved in analyzing the comparative greenhouse gas impacts of ethanol and MTBE in reformulated gasoline.

1. Primary energy consumption

DeLuchi's and other studies assumed an ethanol production energy efficiency that is close to 1, that is, there is no net energy benefits from producing ethanol from the farm to the processing plant. These studies rely on ethanol plant data from the early to mid-1980s. As best as we could extract from the studies quoted here, the calculations of emissions are based on an energy inefficient ethanol production system that consumes somewhere between 85,000 to 91,200 Btus of energy per gallon ethanol. No coproduct credits are given.

Our own analysis indicates that based on industry averages of farm and ethanol production energy use that a total of 75,811 Btus are used per gallon produced (see Table 1).[9] Based on industry best practices, that is, the most efficient farmers and manufacturing facilities, 57,979 Btus per gallon are used. *Since the analysis of the impact of the ROS is based on the expanded use of ethanol it is reasonable to assume that new ethanol facilities will integrate the best existing energy use technologies.* Two thirds of the energy used to make ethanol is consumed in the manufacturing stage. Ethanol facilities have reduced their energy consumption per gallon by more than 65 percent since 1982.[10]

Table 2. Energy Comparison of Methanol Synthesis Processes Currently Employed in the United States (Btus per gallon of methanol)

		ICI		Lurgi		Chem Systems	
		low	high	low	high	low	high
INPUT	Syngas	77,566	77,566	77,566	77,566	77,566	77,566
	Power Feed Compression	2,637	8,165	—	8,165	—	5,670
	Gas Recycle	3,033	822	4,593	879	1,814	454
	Oil Circulation	—	—	—	—	879	397
	TOTAL	**83,207**	**86,553**	**82,130**	**86,638**	**80,259**	**84,029**
OUTPUT	Methanol	56,560	56,560	56,560	56,560	56,560	56,560
	Heat Recovery	3,798	3,856	7,740	7,909	8,477	8,505
	Purge Gas	3,260	3,289	3,260	3,317	3,260	3,912
	TOTAL	**63,618**	**63,705**	**67,560**	**67,786**	**68,297**	**68,977**
	Thermal Energy Gain (Loss)	(19,589)	(22,848)	(14,570)	(18,852)	(11,962)	(15,052)
	Thermal Efficiency	76.5%	73.6%	82.3%	78.2%	85.1%	82.1%

SOURCE: International Energy Agency, "Production of Alcohols and Other Oxygenates from Fossil Fuels and Renewable Resources," Office of Energy R&D, Energy, Mines and Resources Canada, June 1990. Wyman, C.E., et al., "Ethanol and Methanol from Cellulosic Biomass," in Renewable Energy, T.B. Johansson, et al., eds. (Washington, D.C.: Island Press, 1993).

We also believe it is appropriate to allocate some of the energy used to grow and process the corn into ethanol to the other products made from the corn. Although DeLuchi and others acknowledge the importance of production energy allocation among the ethanol and its coproducts, they do not give appropriate emission credits in their analyses. Ethanol is only one of a number of products—corn oil, carbon dioxide, starch, corn syrup, corn meal—produced from the energy used to grow and process the corn. There are a number of methodologies used to allocate coproduct credits. Our own analysis indicates that using the appropriate coproduct allocation techniques the energy used to make a gallon of ethanol ranges from 25,286 to 50,861 Btus.[11]

For plants and farms using best practices 87 percent more energy is contained in the ethanol than the fossil fuel energy used to grow the crop and convert it into ethanol and its byproducts.[12]

Ethanol production, therefore, generates a net energy benefit. More energy is produced out of the system because of the large amount of free solar energy used to grow the corn. The production of MTBE and methanol, on the other hand, result in energy sinks.

According to a preliminary Department of Energy report by Singh and McNutt, over 129,920 Btus of primary energy are required to produce a gallon of MTBE.[13] Since a gallon of MTBE contains only 93,571 Btus of energy, this results in a net primary energy loss of 36,349 Btus for every gallon of MTBE produced.[14] ILSR's estimates based on industry and agriculture averages are that 50,861 Btus of fossil fuel primary energy (75,811 Btus minus 24,950 Btus in coproduct energy credits) are needed to produce a gallon of ethanol that contains 76,000 Btus. This results in a net primary energy gain of 25,139 Btus per gallon. Using industry and agriculture best practices, which may be more appropriate bases for a public policy that will encourage an expanded use of ethanol because of the historical tendency of farmers and industry to adopt more efficient practices once they have been proven workable, the total fossil fuel energy input to making a gallon of ethanol is 57,979 Btus minus the co product credits of 32,693. This results in a net energy gain of 50,714 Btus per gallon.

Tables 1 and 2 present our life cycle analysis of the energetics of ethanol and methanol based on the actual data obtained from ethanol plants and well documented methanol process technologies. The energy numbers for methanol agree with those presented by many studies. We have used Singh and McNutt's numbers for MTBE production. The isobutylene energy values are derived from several primary sources and are based on primary data based on leading methanol technologies: ICI, Lurgi, and Chem Systems processes.[15]

Ethanol, relying on sunlight as the major source of energy for crop growth, is a net energy generator. Methanol production is a net energy sink, consuming about 40 percent more primary energy than is contained in the fuel or chemical.

The use of more up-to-date energetics data would reduce the comparative carbon dioxide gas equivalent emissions of ethanol blends and MTBE blended fuels in DeLuchi's scenarios by 5-10 percent.

2. NOx Contribution

Ethanol production consumes about two-thirds of all fossil fuel energy consumed from growing crops and converting them into ethanol. But the farmer is by far the largest producer of oxides of nitrogen. NOx results from the production and use of fertilizers in growing of corn and also from the combustion of ethanol blended fuel in air.[16] NOx has been viewed by some as a major contributor to global warming and therefore plays an important role in evaluating the environmental impact of expanded ethanol production.

It is important to point out that with respect to the generation of greenhouse gases from farming, whether NOx or other emissions, one might reasonably argue that the impact of the renewable oxygenate rule would be close to zero. Corn or other crops currently used for ethanol would be grown anyway, regardless of the new ethanol markets. For example, in 1980, when less than 50 million gallons of ethanol were produced, 84 million acres of corn were planted. In 1985, when 600 million gallons of ethanol was produced, 83 million acres of corn were planted. In 1993 when over 1.1 billion gallons of ethanol were sold, farmers planted only 73 million acres of corn.[17] Production of ethanol currently consumes less than 5 percent of the corn crop annually. There is a surplus of corn produced in the United States.

Analyses done by the U.S. Department of Agriculture suggest that there would be little or no impact on corn production and use until ethanol production exceeds 3 billion gallons per year, twice as much as the current estimates of ethanol consumption under the ROS.[18]

Ethanol sales may raise the price of corn and certainly does divert corn starch from other markets and increases the production of high grade corn protein. But it has little or no impact on the acreage of corn grown. Thus with or without the expanded ethanol market, farming will emit the same amount of greenhouse gases.

If the production of ethanol were to double or triple in all likelihood the ethanol would be produced in significant quantities from cellulose, not starch. DeLuchi and other researchers agree that cellulose-to-ethanol production of ethanol, even based on their very conservative current assumptions, have a significantly benign environmental impact compared with both neat gasoline and MTBE-blended RFG.

The second observation concerning NOx is that the estimates of its impact on global warming are very tentative. DeLuchi's report was based on the model developed by the Intergovernmental Panel on Climate Change (IPCC) in 1990, a report that concluded that NOx was a "surprisingly important greenhouse gas." In a 1992 report, however, the IPCC dramatically revised its previous conclusions. It concluded that its previous Model had overestimated NOx's contribution to global warming by a factor of 5. DeLuchi disseminated a post-publication advisory noting this dramatic change.[19] His advisory notes, "In light of the IPCC's overestimation of the GWP (Global Warming Potentials) for NOx...when you read my discussions of the role of NOx emissions, keep in mind that the 1990 IPCC GWP was overestimated by a factor of 5 and that the GWP for NOx might even be zero."[20]

If we dramatically reduce the NOx contribution to greenhouse gas CO_2-equivalency, emissions for the base case corn-ethanol would change from 235.5 to 47.1 grams per mile, which translates into a 32 percent change in the overall results presented in DeLuchi's analyses.[21]

3. Type of Fuel Used by Ethanol Facilities

DeLuchi's analyses assumed that ethanol facilities are fueled by coal.[22] Yet natural gas is the fuel of choice for most new ethanol plants.[23] According to a recent survey almost 90 percent of all planned ethanol production plants will use natural gas as their primary fuel source.[24] Substituting natural gas for coal reduces by 10-30 percent the equivalent carbon dioxide emissions from ethanol compared with MTBE/reformulated gasoline.

4. Emissions Allocation to Coproducts

Although DeLuchi and other studies acknowledge its importance, they did not allocate appropriate greenhouse gas emissions among the multiple products produced in the corn to ethanol process. As discussed above the fuel and other inputs used to process the corn into ethanol are also used to make a variety of other non-combustion products (e.g. corn oil, corn meal, starch, carbon dioxide). Several allocation methodologies can be used.[25] The most realistic allocation methods for byproduct credits would reduce ethanol's overall emission impact by up to one third of the base case, according to DeLuchi. He further acknowledged that "...if emissions are allocated to all products (ethanol, DDGS, corn oil, etc.) on the basis of their value or energy content, the corn-to-ethanol cycle produces less CO2-equivalent emissions than does the gasoline cycle."[26]

One might argue that similar allocation of greenhouse gas emissions should be applied to the manufacture of MTBE. But since methanol and isobutane are produced as independent products from natural gas and petroleum refining, the other products of which are largely used for combustion they would not qualify for byproduct emission credits.

5. Embodied Energy

Another uncertain variable is the amount of emissions from the manufacture and assembly of materials used to make farm equipment and ethanol plant equipment. We have found it impossible to segregate the "embodied emissions" portion in DeLuchi's analyses from total emissions and therefore cannot quantify its impact. But it appears that the analyses assume a larger amount of energy embodied in making ethanol than in making MTBE or in making neat gasoline. That seems doubtful.

6. The Displacement of Crude Oil

Current studies comparing MTBE and ethanol assume a 6 percent ethanol blend versus an 11 percent blend for MTBE. Ethanol contains more oxygen and therefore less of it is needed to meet the Clean Air Act's oxygen content requirement. Thus MTBE displaces a higher volume of gasoline. Therefore MTBE would displace more crude oil than ethanol. But MTBE is in part made from crude oil and is totally made from fossil fuels (methanol is derived from natural gas).

It should be noted that all studies conclude that ethanol's environmental advantages increase as greater proportion of the gas tank is occupied by the fuel. Ethanol can be legally blended at 10 percent versus MTBE's 15 percent. Ethanol blends at 10 percent provide much greater carbon monoxide reduction benefits and would displace far more fossil fuels, given its net energy advantage over MTBE, than either an 11 percent or 15 percent MTBE.

THE CASE OF ETBE

We have devoted the majority of this paper to comparing ethanol and MTBE but the ROS also allows refineries to produce an ethanol ether, ETBE to meet their oxygenate requirements. Although the process that makes ETBE is similar to the one that produces MTBE, the emission profile of ETBE looks much better then MTBE's. This is due to the fact that a greater amount of ethanol is contained in ETBE than methanol in MTBE.[27] Since ethanol is a net energy generator compared with methanol which is a net energy sink, ETBE looks very good when the energy model data is converted to emissions.

A recent study by the Governor's Ethanol Coalition calculated that for each unit of ethanol energy combined with isobutane to make ETBE, 3.2 units of gasoline energy derived from petroleum is replaced.[28] Additional energy savings, and thus emission savings, occur when ETBE is used as a high octane blendstock to replace aromatics and toxic compounds such as benzene.

ETBE has a substantially lower blending reid vapor pressure than does MTBE, thus allowing higher-RVP blend stock to be used to produce ETBE-blended RFG. This has two advantages. First, lower RVP ETBE emits fewer hydrocarbon emissions. Second, ETBE allows blenders to use a higher RVP base gasoline. This "lighter cut" gasoline requires lower in-plant energy and thus lower plant fuel requirement and a further reduction in greenhouse gases in the life cycle of ETBE-blended reformulated gasoline.

Based on ARCO Chemical Company's ETBE data as presented in the Governor's Ethanol Coalition report, and using the IPCC model as presented in the DeLuchi's study and the joint Argonne National Laboratory/U.S. Department of Energy reports, we have found that ETBE-blended reformulated gasoline has a life cycle CO_2-equivalent emissions in the range of -10 to -20 percent compared with unblended gasoline.[29]

CONCLUSION

Table 3 presents the results of our emissions analysis for reformulated gasoline, based on DeLuchi's model and our energy studies for ethanol, methanol, MTBE, and ETBE as shown in Tables 1 and 2. The base case is neat gasoline. The last column indicates the change in greenhouse gas emissions on a carbon dioxide equivalent basis from neat gasoline.

Methanol derived from coal represents the worst case scenario, resulting in a very significant increase in greenhouse gas emissions. Methanol derived from natural gas does much better but still represents a negative environmental impact compared to neat gasoline. Ethanol from cellulose or from corn when cellulosic fuels are used represents the best case with very significant reductions in greenhouse gas emissions from neat gasoline.

In the short term the most likely scenarios are the represented in the top four rows. In all cases ETBE significantly reduces greenhouse gas emissions compared to MTBE. In virtually all cases ethanol made from corn reduces greenhouse gases more than MTBE. The greatest advantage occurs when natural gas fuels ethanol production facilities.

TABLE 3. Greenhouse Gas Emissions from RFG Blended with Different Oxygenates Presented as CO2-Equivalent (percent change from neat gasoline)

Oxygenate	Primary Energy Source Used in Oxygenate Production	Primary Energy Used in Fuel Production (Btus per gallon)	Fuel Energy Content of the Oxygenate (Btus per gallon)	RFG Emission Range (percent change from neat gasoline)
MTBE	Natural Gas, Oil	129,920	93,571	-4% to +8%
ETBE	Natural Gas, Oil	103,553	96,880	-20% to -10%
Ethanol (corn)	Coal	50,861	76,000	-35% to -0%
Ethanol (corn)	Natural Gas	50,861	76,000	-40% to -10%
Ethanol (corn)	Corn Stover	0	76,000	-60% to -40%
Ethanol (cellulose)	Biomass	0	76,000	-100% to -70%
Methanol[1]	Natural Gas	80,259	56,560	+0% to +20%
Methanol[1]	Coal	80,259	56,560	+50% to +75%

1 Calculations for methanol energy are based on the Chem Systems production technology. Chem Systems technology is the most widely used process for methanol production from natural gas in the U.S. We have used lower-end estimates for methanol production. See Table 2 for detailed energy balance.

NOTE: Institute for Local Self-Reliance calculations based on the Intergovernmental Panel on Climate Change (IPCC) Emissions Model and the ILSR ethanol and methanol energy studies. The percent emission change from neat gasoline is calculated by first determining the emissions savings from the base case in terms of grams of CO2-equivalent emissions per mile travelled by a Low-Duty Vehicle (LDV), and then converting them to the percentage range presented in the last column.

NOTES AND REFERENCES

1. Sweeney, J.L., "Evaluation of the EPA's Proposal for Renewable Oxygenates," Final Report. Stanford University, Palo Alto, California, May 1994; Singh, M., and B. McNutt, "Energy and Crude Oil Input Requirements for the Production of Reformulated Gasoline," Argonne National Laboratory, and U.S. Department of Energy, Washington, DC, Report No. ANL/ESD-19, October 1993; McNutt, B., and M. Singh, "Energy Requirements and CO2-Equivalent Emissions of RFG," Draft. U.S. Department of Energy, Washington, DC, May 1994; "Fuel Cycle Evaluations of Biomass-Ethanol and Reformulated Gasoline," Vol. II and Appendices. National Renewable Energy Laboratory and U.S. Department of Energy., 1993.
2. DeLuchi, M.A., "Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity," Volume I: Main Text, Report No. DE92-012102, Argonne National Laboratory and U.S. Department of Energy, Washington, DC, November 1991.
3. Greenhouse gases include oxides of nitrogen, hydrocarbons, methane, CFCs, CO, etc. In the conversion of non-CO2 to CO2-equivalency, the global warming potential (GWP) of the individual gas is taken into account based. This potential is based on a model by the IPCC. As is discussed below, the IPCC has significantly changed its estimates of the GWP of several gases. The most important change, with regard to the potential environmental impact of ethanol, relates to NOx.
4. See figure 6, page 102, fromDeLuchi, op. cit. for graphic presentation of scenario analyses.
5. Scenario 27: Corn-Ethanol Emission Estimates, page 118-120, presented in DeLuchi, M.A., "Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity," Volume I: Main Text, Report No. DE92-012102, Argonne National Laboratory and U.S. Department of Energy, Washington, DC, November 1991.
6. See figure 6, page 102, DeLuchi, M.A., "Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity," Volume I: Main Text, Report No. DE92-012102, Argonne National Laboratory and U.S. Department of Energy, Washington, DC. November 1991.
7. Sweeney, J.L., "Evaluation of the EPA's Proposal for Renewable Oxygenates," Final Report, Stanford University, Palo Alto, California, May 1994; Singh, M., and B. McNutt, "Energy and Crude Oil Input Requirements for the Production of Reformulated Gasoline," Argonne National Laboratory, and U.S. Department of Energy, Washington, DC, Report No. ANL/ESD-19. October 1993; McNutt, B., and M. Singh, "Energy Requirements and CO2-Equivalent Emissions of RFG," U.S. Department of Energy and Argonne National Laboratory, Washington, DC, Released March 17, 1994 (withdrawn for revisions, personal communication with M. Singh, Argonne National Laboratory, Washington, DC, June 6, 1994); National Renewable Energy Laboratory and U.S. Department of Energy, "Fuel Cycle Evaluations of Biomass-Ethanol and Reformulated Gasoline," Volume II and Appendices, November 1993; Tyson, K.S., C.J. Riley, and K.K. Humphreys, "Fuel Cycle evaluations of Biomass-Ethanol and Reformulated Gasoline," National Renewable Energy Laboratory and U.S. Department of Energy, Volume I,. November 1993; Whitten, G.Z., "Comparison of the Air Quality Effects of Ethanol and MTBE in Reformulated Gasoline in the Chicago Region in 1995," Systems Applications International, California, July 1992.
8. This information is taken from Table 3 below.
9. Morris, D., and Ahmed, I., *"How Much Energy Does It Take to Make a Gallon of Ethanol?,"* Institute for Local Self-Reliance, Washington, DC, 1992. The 75,811 Btus of energy input excludes the co-product credits of 24,950 Btus per gallon of ethanol produced.
10. Recent advances in separation and purification techniques, such as molecular sieves that replace energy intensive distillation systems, increased coproduct recovery, and less energy intensive agricultural practices such as reduced and no-till techniques that use less diesel fuel have improved ethanol production efficiencies two fold since the 1980s.
11. In the state-of-the art ethanol production facility, the energy requirements for making a gallon of ethanol drops to only 16,574 Btus when an energy credit of 32,693 Btus (same as allocated for current industry best) is allocated for ethanol coproducts.
12. See David Morris and Irshad Ahmed, *Op Cit.* Assuming industry averages, the net energy output is 33 percent. Best practices data was based on actual operating data in 1992. Assuming state of the art practices, that is, those represented by the next generation of techniques or technologies, the net energy output is 121 percent greater than the energy input. We are using the best practices scenario from the 1992 report here because the

analysis focuses on the environmental impact of increased ethanol production. It is a realistic assumption that farmers and industrial engineers will become increasingly efficient, as they have in the past, by adopting the best technologies and techniques from others.

13. Singh, M., and B. McNutt, "Energy and Crude Oil Input Requirements for the Production of Reformulated Gasoline," Argonne National Laboratory, and U.S. Department of Energy, Washington, DC, Report No. ANL/ESD-19, October 1993; McNutt, B., and M. Singh, "Energy Requirements and CO2-Equivalent Emissions of RFG," U.S. Department of Energy, Washington, DC, May 1994.
14. A gallon of ETBE contains 96,880 Btus of energy while its production consumes, according to our calculations (based on average ethanol production energy and accounting for higher production energy requirements for ETBE since its production requires additional distillation step for water removal), 114,422 Btus per gallon of ETBE. This number drops to 103,553 Btus per gallon of ETBE based on today's most efficient ethanol industry figures (column 2 of Table 1). The difference between MTBE and ETBE is only due to substituting ethanol for methanol, and the majority of the energy input comes from isobutane and steam accounting for over 92,806 Btus of energy per gallon of ether produced. This 92,806 Btus can be construed as the ether-base energy that would be constant regardless of MTBE or ETBE production. This high energy constant is due to high energy requirements of field butanes production from natural gas (92,630 Btus per gallon of Ether). Ether production energy data from Table 9, page 17, Singh, M., and B. McNutt, "Energy and Crude Oil Input Requirements for the Production of Reformulated Gasoline," Argonne National Laboratory, and U.S. Department of Energy, Washington, DC, Report No. ANL/ESD-19, October 1993; McNutt, B., and M. Singh, "Energy Requirements and CO2-Equivalent Emissions of RFG," U.S. Department of Energy, Washington, DC. May 1994.
15. The Chem Systems process is the most widely used process for making methanol in the U.S. and is the process of choice used in the analysis by several of the latest reports, including the Argonne National Laboratory and the U.S. Department of Energy studies referenced in this analysis.
16. Air contains 78-percent nitrogen and is the main source of nitrogen derivatives in combustion gases.
17. Farm Crop Production-1993 Summary, "Agricultural Statistics," U.S. Department of Agriculture, January 1994; Agricultural Statistics-1992; Agricultural Statistics-1982.
18. Ahmed, I., and D. Beach, "Industrial Uses of Agricultural Materials," Situation & Outlook Report, U.S. Department of Agriculture, Economic Research Service, Washington, D.C. December 1993.
19. DeLuchi, M.A., Memorandum to Readers of ANL/ESD/TM-22, Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity, April 22, 1992.
20. Ibid.
21. Total non-CO2 emissions for base case ethanol as presented by DeLuchi calculates it at 235.5 g/mi and total CO2 at 352.5 g/mi. Total base case CO2-equivalent emissions are 588.1 g/mi.
22. He also examined the impact of using biomass as a fuel, but not natural gas.
23. According to a recent survey conducted by Kathy Bryan of Gist-brocades in May 1994, about two thirds of current ethanol production is fueled by coal. But of planned ethanol plants, 89 percent plan to rely on natural gas.
24. See Kathy Bryan, *Ethanol Boiler Feedstock Survey*. Gist-brocades. May 1994.
25. See Morris and Ahmed, *Op. Cit.*
26. Conservatively, at one point, DeLuchi's model indicates that 45 percent of all life cycle emissions from ethanol should be assigned to coproducts, however, it does not apply it to the final results across the board. Scenario 27-f: Corn-Ethanol LD ICEVs, presented in DeLuchi, M.A., "Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity," Volume I: Main Text, Report No. DE92-012102, Argonne National Laboratory and U.S. Department of Energy, Washington, DC, November 1991.
27. ETBE production consumes .425 tons of ethanol per ton of ETBE made, while only .366 tons of methanol is required to make a ton of MTBE.
28. "Clean Energy and the Environment," Renewable Ethanol and ETBE, A report from the Governors' Ethanol Coalition, Lincoln, Nebraska, 1994.
29. U.S. Environmental Protection Agency and ARCO Chemical Company, "Potential Decrease in Auto Emissions with Blending of ETBE in Reformulated Gasoline (RFG)," ETBE Offers Many Environmental Benefits in Clean Energy and the Environment, Governors' Ethanol Coalition, Lincoln, Nebraska, 1994.