



POINT / COUNTERPOINT

The Costs Of Biofuels

Two views on whether corn ethanol and, eventually, ethanol from cellulosic biomass will efficiently deliver **NATIONAL ENERGY SECURITY**

THE DRUMBEAT in favor of biofuels has only increased since President George W. Bush's 2007 State of the Union address calling for a 20% cut in gasoline use, much of it to be replaced with alternative fuels such as biofuels. Indeed, industry has begun investing in biofuels and biofuels R&D as never before. Consumers, too, are eager for anything that might trim the cost of a gallon of gasoline.

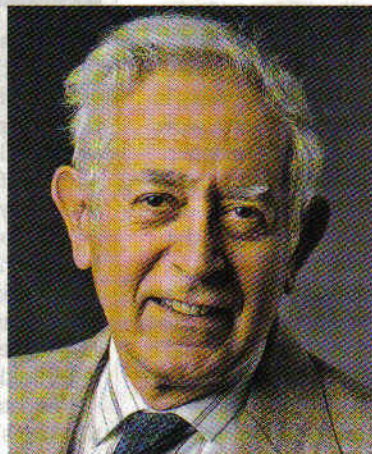
But the criticisms and questions that dog the use of biofuels remain formidable. Can the U.S. really afford to devote its entire corn crop to the production of ethanol, as might be required under some of the targets set by President Bush? What will happen to the price of corn, and what impact will this have in terms of feeding those who are hungry in this world? What are the true energy costs of biofuels, and can their use mitigate global climate change, as is widely anticipated?

As part of its ongoing coverage of the biofuels story, C&EN has asked two prominent biofuels experts to square off in opposition to or in support of biofuels. David Pimentel, an entomologist and professor of agricultural sciences at Cornell University, has raised objections to biofuels since the early 1970s. A recognized authority on the subject, he believes biofuels' costs far outweigh their potential benefits.

Taking the opposite view is Bruce E. Dale, a professor of chemical engineering



DEBATES Dale (left), a chemical engineering professor at Michigan State University, contends that well-chosen metrics need to be used in order to evaluate the true costs and benefits of biofuels; Pimentel, an entomologist and professor of agricultural sciences at Cornell University, argues that biofuels are costly from both economic and environmental perspectives and also raise significant ethical concerns.



and materials science and associate director of the Office of Biobased Technologies at Michigan State University. He also serves as editor-in-chief of *Biofuels, Bioproducts & Biorefineries*, a new Wiley journal. Dale argues that a fair analysis of biofuels reveals their value as a replacement for fossil fuels. He believes they should be an important contributor to energy security in the U.S. and one answer for reducing CO₂ inputs into the atmosphere.—WILLIAM SCHULZ

DALE POINT



As with other products, biofuels should be compared with their alternatives according to well-chosen metrics. It is no more ra-

tional to support or oppose biofuels without relevant performance standards than it is to support or oppose ballpoint pens without appropriate criteria. Therefore, what are the appropriate comparison standards for biofuels?

Two issues are pivotal for all petroleum alternatives: national security by significantly reducing petroleum dependence and climate security by significantly reducing greenhouse gases. Biofuels should substantially reduce petroleum used and greenhouse gases generated compared with their petroleum-derived alternatives. Ideal biofuel metrics are petroleum consumed and greenhouse gases generated per mile

traveled. Unfortunately, this calculation requires detailed vehicle performance information that is likely unavailable. Reasonable substitute metrics are biofuel energy produced per unit of petroleum consumed over the biofuel life cycle and biofuel energy produced per unit of greenhouse gases generated. Ethanol replaces gasoline in internal combustion engines. Thus, the ethanol-to-gasoline comparison is relevant. The data of Farrell et al. summarized in the table allow us to compare ethanol and gasoline (*Science* 2006, 311, 506).

Generating 1 MJ of gasoline requires 1.1 MJ of petroleum, while only 0.04 MJ of petroleum is required to generate 1 MJ of ethanol from corn ("ethanol today" scenario). The reduction in petroleum required per

INS AND OUTS

Comparing energy inputs to produce fuel for internal combustion engines

	ENERGY INPUT (IN MJ) TO GENERATE 1 MJ FROM FUEL					GREENHOUSE GASES EMITTED ^a
	PETROLEUM	NATURAL GAS	COAL	OTHER	TOTAL	
Gasoline	1.10	0.03	0.05	0.01	1.19	94
Ethanol today	0.04	0.28	0.41	0.04	0.77	77
Cellulosic ethanol ^b	0.08	0.02	0.02	0.02	0.10	11

^a Kilograms of CO₂ equivalent per MJ of fuel; emissions from producing the fuel and burning it. ^b Negative value for coal because lignin generated in the process is used as fuel in place of coal.
SOURCE: Alex Farrell, adapted from *Science* 2006, 311, 506

megajoule of fuel to the consumer is therefore 0.04 minus 1.1 divided by 1.1 multiplied by 100 equals 96%. Corn ethanol allows us to improve vehicle mileage per unit of petroleum consumed by a factor of 1.1 minus 0.04 divided by 0.04 equals 26.5. Effectively, ethanol achieves almost 800 miles per gallon of oil (26.5 times 30, for a vehicle getting 30 mpg). We have no other “drop in” gasoline alternative that so greatly increases miles per unit of oil consumed.

Greenhouse gas reduction is also significant. For the “ethanol today” scenario, the greenhouse gas reduction compared with gasoline is 18%—77 minus 94 (kilograms of CO₂ equivalent per megajoule of fuel) divided by 94 times 100. For the “cellulosic ethanol” scenario, the corresponding values are 93% reduction in petroleum use and a very large 88% reduction in greenhouse gases. Ethanol therefore achieves real improvements in both petroleum consumption and greenhouse gases generated compared with gasoline. Relevant, rigorous data sets that allow comparison of other biofuels with petroleum-derived fuels are currently unavailable.

Corn ethanol production technology is still improving, and its fossil-fuel use is declining. For example, new enzymes have recently been introduced that significantly reduce energy consumption in corn ethanol facilities. Likewise, cellulosic ethanol production technology is improving rapidly. In contrast, petroleum discovery, production, and processing are becoming more energy intensive as the quality of petroleum declines (more viscous, higher sulfur crude oil) and as petroleum is produced in more remote locations (for example, deepwater Gulf of Mexico) and under harsher climatic conditions. Simply stated, the future trends for petroleum are negative while the trends for ethanol are positive.

Irrelevant and misleading metrics such as the “net energy” metric advanced by Dr. Pimentel to criticize ethanol do not

promote good strategic decision-making. Net energy is defined as the fuel’s heating value minus the sum of all fossil energy inputs—coal, natural gas, and petroleum—required to produce the fuel. Net energy is irrelevant because it lumps all fossil energy carriers together and considers a megajoule of coal as equivalent to a megajoule of petroleum or natural gas. This is obviously wrong; otherwise, we would not pay more than five times as much for a megajoule of petroleum as we do for a megajoule of coal. Coal’s energy content is simply not as valuable or as versatile as oil’s. All megajoules are not created equal.

Net energy analysis is misleading because ethanol’s net energy was never compared with gasoline’s net energy. The comparison is easily done. From the table above, ethanol’s net energy is 1.0 minus the sum of (0.04 + 0.28 + 0.41) times 100, which equals +27%, while gasoline’s net energy is 1.0 minus the sum of (1.1 + 0.03 + 0.05) times 100, which equals -18%. Gasoline’s net energy is therefore significantly lower than ethanol’s. We would have been saved much confusion and trouble if Dr. Pimentel and his coworkers had compared ethanol’s net energy with the net energy of gasoline, but they never did so. Comparisons between our realistic alternatives are essential for good decision-making.

Other metrics are also relevant. For example, the scale of production and cost of biofuels are important criteria. Ethanol from grain and sugar crops will probably never exceed 10% of total U.S. motor fuel needs, a modest but important fraction. As to cost, Brazil now produces ethanol from sugarcane for less than the energy equivalent cost of gasoline. Cellulosic ethanol

could eventually supply hundreds of billions of gallons of liquid fuel at production costs well under \$1.50 per gal of gasoline equivalent. Does any reasonable individual think that gas prices are headed down over the long term?

Some possible metrics for biofuels require more thought. For example, available land, potential environmental degradation, and competition with food production are believed to be major limitations for biofuels. Careful systems-level thinking creatively resolves these and other issues, especially for cellulosic biofuels.

PIMENTEL POINT



For millions of years, green plants contributed to the formation of our oil, natural gas, and coal. By 1850, when wood accounted for 91% of U.S. energy consumption and the U.S. population was less than 10% of the current 301 million people, serious wood shortages already existed. Now, with only about 4.5% of the world population, the U.S. is the largest per capita fossil energy consumer of any country in the world. Because 90% of U.S. oil has been mined, the U.S. now imports more than 63% of its oil at a cost of \$200 billion per year.

Faced with a diminishing supply of oil, converting grain or other biomass into ethanol fuel as a substitute has become popular. Using corn or any other biomass requires large land areas of fertile soil, large quantities of water, and sunlight for green plant production. Green plants in the U.S. combined collect only about 53 exajoules (about 50×10^{15} Btu) of sunlight energy per year. Meanwhile, people in the U.S. consume slightly more than twice that amount of energy from fossil fuels.

Enthusiasts suggest ethanol produced from corn grain and cellulosic biomass, like grasses, could replace much of the oil used in the U.S. Consider that 20% of the U.S. corn crop was converted into 5 billion gal of ethanol last year, but that replaces only 1% of U.S. petroleum consumption. If the entire corn crop were used, it would replace a mere 7% of petroleum consumption. This will not make the U.S. independent of foreign oil.

If we get beyond the first emotional “food versus fuel” reaction, we find that fuel prices affect the cost of literally everything we eat.

Our up-to-date analysis of all the 14 energy inputs that typically go into corn production, plus the nine inputs invested in fermentation and distillation operations, confirms that the energy expended (mostly high-value oil and natural gas) to produce a gallon of corn ethanol is 40% more than is in the ethanol itself. Often, investigators omit some of the energy inputs required in corn production and processing. These include energy for farm labor, farm machinery, energy production of hybrid corn seed, irrigation, and processing equipment. Omitting some energy inputs suggests that a corn ethanol production system provides a positive energy return. Investigators also differ about the energy value of the by-products from making corn ethanol. By-product credits range only from 10 to 60% for the distillers grain, which is not a fuel but cattle feed. In any event, corn ethanol is an inefficient choice from an energy standpoint.

The production of corn ethanol is subsidized by state and federal governments to the tune of more than \$6 billion per year according to a 2006 report, "Biofuels—At What Cost? Government Support for Ethanol and Biodiesel in the United States," released by the International Institute for Sustainable Development in Geneva. Thus the subsidies for a gallon of ethanol are more than 90 times the subsidies for a gallon of gasoline (approximately 3 cents per gal). If the subsidies for ethanol production were making the U.S. oil independent, perhaps these exorbitant subsidies might be justified.

The environmental impacts of corn ethanol are significant and diverse. They include severe soil erosion of farmland plus the heavy use of nitrogen fertilizer and pesticides. Large quantities of carbon dioxide are produced and released into the atmosphere because significant amounts of fossil fuel energy are used in ethanol production. In addition, during the fermentation process, about 25% of the carbon from the sugars and starches is released as carbon dioxide into the atmosphere. These two large releases of carbon dioxide significantly contribute to global warming. Note, each gallon of ethanol requires 1,700 gal of water (mostly to grow the corn) and releases 12 gal of noxious sewage effluent into the environment.

Using food crops, such as corn grain, to produce ethanol also raises major ethical concerns. More than 3.7 billion people in the world are currently malnourished, so

the need for grains and other basic foods is critical. Growing crops for fuel squanders land, water, and energy resources vital for the production of food for people. Associated with the use of corn for ethanol are major increases in the price of beef, chicken, pork, eggs, and milk for the U.S. consumer, according to Lester Brown, president of the Earth Policy Institute, and Jacques Diouf, director-general of the United Nations Food & Agriculture Organization.

As an alternative to corn, some ethanol proponents suggest that all 600 million acres of U.S. grassland should be harvested and that the cellulosic biomass should be converted into ethanol. If it is assumed that 100 gal of ethanol could be produced per acre of grass, all U.S. grass would replace slightly more than 10% of U.S. petroleum use. Producing ethanol from cellulosic biomass is significantly more energy intensive than producing it from corn because straw contains half the sugars and starches needed for fermentation. For this reason, additional energy inputs are required in the processing of cellulosic biomass. With current technology, 50% more energy is required to produce a gallon of ethanol from cellulosic biomass than from corn. Moreover, converting U.S. grass into ethanol negatively impacts the 100 million cattle, 7 million sheep, and 4 million horses that currently require this forage for food.

The conversion of any biomass into liquid fuels is costly in terms of fossil energy, vital farmland, and freshwater. Even if the biomass conversion processes are made more efficient, the limited availability of U.S. biomass will not be sufficient as a reliable source of liquid fuel. Energy conservation and development of renewable energy sources, such as solar cells, should be given research priority.

DALE COUNTERPOINT



Dr. Pimentel's critique of ethanol continues as it began years ago, unencumbered by valid comparisons and uninformed by different perspectives. A long list of baseless or misleading charges against ethanol is given, many of which cannot be answered in this short response. I will try to refute some charges, offer new perspectives, and outline how cellulosic ethanol can provide large amounts of fuel while improving the environment, enhancing rural economies, and increasing world food supplies.

Dr. Pimentel emphasizes that his analysis includes 14 energy-consuming operations required for ethanol production. Even if 14,000 such operations were included, the analysis would still be irrelevant. One megajoule of coal is simply not equivalent to 1 MJ of petroleum. If you doubt this, try grinding up some coal, put it in your gas tank, and see how far you can drive on coal's energy content. Pimentel's "net energy" analysis is akin to adding 10 U.S. dollars, 10 Mexican pesos, and 10 Indian rupees to get \$30—an absurdity. Different energy carriers and different currencies have different qualities. They cannot simply be added together as Dr. Pimentel does.

Ethanol is indeed subsidized. I would much prefer that all subsidies be ended, including the subsidy on gasoline, which has been estimated by the Government Accountability Office and the *New York Times* to be several dollars per gallon of gas (NSIAD-91-250; *New York Times*, "Fuels for the Future News," May 16, 1997, respectively). For example, many of our military assets are explicitly devoted to protecting oil supply lines. The 7th Fleet will not be needed to protect our domestic corn fields and grasslands.

Ethanol is said to require lots of water. Actually, gasoline production uses more than 10 times as much water as does corn ethanol production. It is true that plants transpire about 200 kg of water per kg of dry plant matter produced. So what? The water transpired by plants originally fell as rain or snow and is purified as it passes through the plant to the atmosphere where it will fall again as rain or snow. When has water quality ever been improved by contact with petroleum?

Ethanol production is said to release large amounts of carbon dioxide and "sewage" and to promote soil erosion. Actually, all water discharges must meet local regulations. Soil erosion on U.S. cropland has declined by almost 50% in recent years.

No one knowledgeable about cellulosic ethanol believes that the process is energy intensive. Process residues, when burned, will provide more than enough steam and electricity to run cellulosic ethanol plants. Perennial grasses, grown as energy crops, will be important feedstocks for cellulosic ethanol production. Significantly increasing their per-acre yields is very achievable. Contrary to Dr. Pimentel's assumption of 100 gal of cellulosic ethanol per acre, about 500 gal per acre is currently possible, with 1,500 gal per acre a feasible 10-year goal.

Perennial grasses are excellent builders of soil, and they sequester large amounts of atmospheric carbon dioxide. They also trap inorganic nitrogen in plant matter, thereby reducing nitrous oxide (a potent greenhouse gas) and limiting nitrate leaching to ground- and surface waters.

Ethanol production is said to raise food prices. If we get beyond the first emotional "food versus fuel" reaction, we find that fuel prices affect the cost of literally everything we eat, while corn prices have a comparatively small effect on the cost of some food items. Corn ethanol is less expensive to produce than gasoline, helping keep a lid on fuel prices and therefore on food prices. Cellulosic ethanol will become much cheaper than gasoline, thereby reducing delivered food prices.

There is another crucial fact to consider: Neither the U.S. nor any other developed country uses its land to grow much human food. What we actually grow is animal feed. Nearly 90% of our 650 million acres of crop and good pasture land is used to grow animal feed. Most of this feed is for beef and dairy cattle, which are nutritionally

versatile animals. Animals, like humans, require two primary nutrients: protein and digestible energy (calories). Grasses can be processed to recover protein suitable for animal feed. Grasses pretreated to enhance their biological conversion to ethanol should also be quite digestible by ruminant animals. Taken together, these developments will increase the per-acre productivity of protein and digestible energy. Food will become cheaper because animal feed will become more abundant and cheaper. Coproducing animal feed and fuel will also reduce the total acreage required to meet our feed and fuel needs. Credible scenarios exist in which no new land would be required to meet demands for food, feed, and fiber while still providing more than 100 billion gal of cellulosic ethanol per year.

Finally, cellulosic materials are bulky and would not be transported long distances. They will be processed relatively close to where they are grown, providing opportunities for rural communities to increase their wealth by adding value to plant biomass. This important opportunity to strengthen rural communities throughout the world

via biofuel production merits serious and sustained research and policy attention.

All paths to a more sustainable future will require us to make choices among alternative fuels. When appropriate comparisons are made, biofuels, particularly cellulosic biofuels, stand out as attractive alternatives.

PIMENTEL COUNTERPOINT



Thorough research on biofuels is essential because the nation needs liquid fuels. In providing them, all data and energy inputs must be carefully assessed. This is critical for our future national security and to ensure the preservation of the very natural resources that support human life.

Dr. Dale suggests that in measuring the benefits of biofuels, we should assess only the petroleum inputs and not include any of the other energy inputs, like natural gas. This approach is not scientifically sound because natural gas is a vital energy resource in the production of corn ethanol. In fact, nearly one-third of the total energy

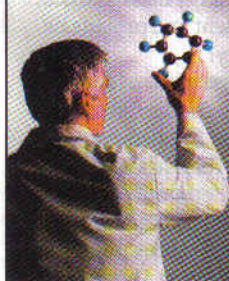
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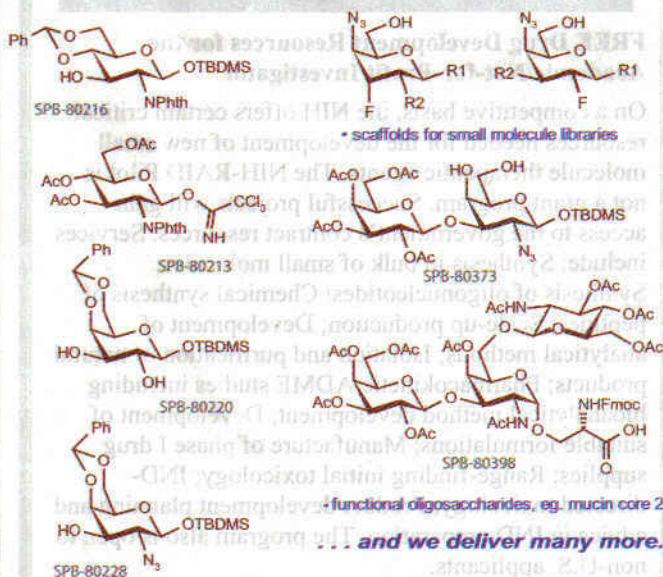


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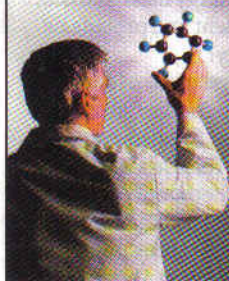
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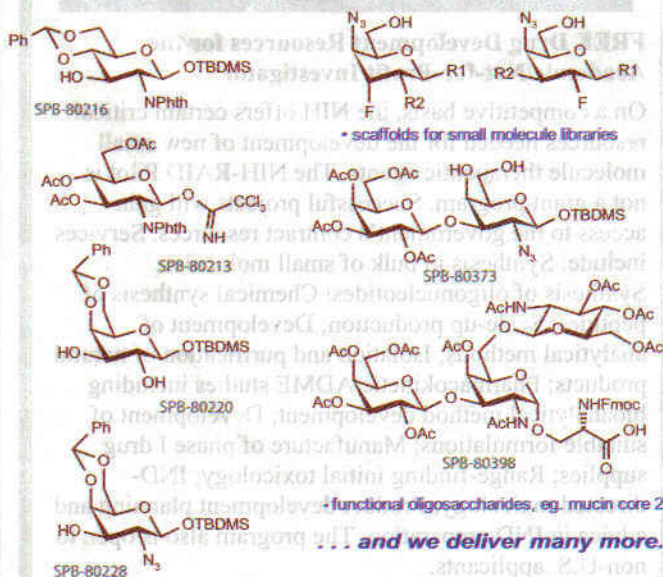


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