The Carbohydrate Economy, Biofuels and the Net Energy Debate

David Morris
Institute for Local Self-Reliance
August 2005

Other publications from the New Rules Project of the Institute for Local Self-Reliance:

Who Will Own Minnesota's Information Highways?
by Becca Vargo Daggett and David Morris, June 2005

A Better Way to Get From Here to There: A Commentary on the Hydrogen Economy and a Proposal for an Alternative Strategy
by David Morris, January 2004 (expanded version forthcoming, October 2005)

Seeing the Light: Regaining Control of Our Electricity System
by David Morris, 2001

The Home Town Advantage: How to Defend Your Main Street Against Chain Stores and Why It Matters
by Stacy Mitchell, 2000

Available at *www.newrules.org*

ILSR

The Institute for Local Self-Reliance (ILSR) is a nonprofit research and educational organization that provides technical assistance and information on environmentally sound economic development strategies. Since 1974, ILSR has worked with citizen groups, governments and private businesses in developing policies that extract the maximum value from local resources.

Institute for Local Self-Reliance
1313 5th Street SE
Minneapolis, MN 55414
Phone: (612) 379-3815
Fax: (612) 379-3920

www.ilsr.org

The Carbohydrate Economy, Biofuels and the Net Energy Debate

David Morris, Vice President
Institute for Local Self-Reliance
August 2005

Biomass should be viewed not as a silver bullet, but as one of many renewable fuels we will and should rely upon.

The Big Picture

It is important to state the obvious at the outset. The soil cannot satisfy 100 percent, or even a majority of our energy needs. To supply 100 percent of our fuels and electricity we would need over 7 billion tons of plant matter, over and above the 1 billion tons Americans already use to feed and clothe ourselves and supply our paper and building materials. Even the land-rich U.S. lacks sufficient acreage to come close to growing that quantity.

Biomass should be viewed not as a silver bullet, but as one of many renewable fuels we will and should rely upon. As a teammate with direct sunlight, wind energy, tidal power, the earth's heat and other renewable resources, biomass can play an important role, in part because of its unique characteristics. For biomass alone among renewable fuels comes with a built-in storage system, and can be processed into solid products.

Biomass is stored chemical energy. It requires no batteries or other types of storage systems. Converted to liquid or gaseous fuels, biomass is easily distributed. That makes biofuels attractive for transportation fuels, especially if viewed, not as a primary energy source but as a supplementary energy source to electricity.

Since biomass can also be made into bioproducts, it can substitute not only for petroleum-derived fuels but petroleum-derived chemicals and materials.[1] Some 18 percent of petroleum consumed in the United States is used to make petrochemicals, the manufacture and disposal of which generates significant toxic emissions.

David Morris is Vice President of the Washington, D.C. and Minneapolis-based Institute for Local Self-Reliance. He is the author of *Ethanol Policy and Development: 1978-1992* (1992) and *The Carbohydrate Economy: Making Chemicals and Industrial Materials from Plant Matter* (1993). He is also the author or co-author two peer reviewed energy balance studies: *How Much Energy Does It Take to Make a Gallon of Ethanol?* (1995) and *How Much Energy Does It Take to Make a Gallon of Soydiesel?* (1996). David has been an advisor or consultant to the energy departments of Presidents Ford, Carter, Clinton and George W. Bush. He currently serves on a Congressionally-created Advisory Committee to the United States Department of Agriculture and Department of Energy on biomass and biofuels.

About 2,000 such manufacturing facilities, each producing about 50 million gallons of ethanol, would be needed to supply sufficient liquid fuels to satisfy the needs of a transportation system primarily propelled by electricity.

A Dual Fueled Transportation System: Biofuels and Electricity

All strategies to reduce or eliminate our reliance on oil depend on a dramatic change in the way our vehicles are designed and the fuels they use.

Electricity is the cheapest and most efficient transportation fuel. Electric vehicles also are quiet in operation and non-polluting, at least in terms of tailpipe emissions. Their drawback so far has been in the cost, weight, and performance of electric batteries. Battery performance is improving rapidly, but today, and in the near future, all-electric vehicles may have performance limitations (e.g. limited range).

An electric vehicle that comes with an engine backup overcomes these limitations. Some of the more popular hybrid vehicles (e.g. Toyota's Prius) sold today can, sometimes with a little tweaking, run on electricity for short distances. A plug-in hybrid electric vehicle (PHEV) whose batteries can be recharged from the electricity grid, coupled with a larger battery capacity could make electricity the primary transportation energy source. A biofueled PHEV engine may account for 10-60 percent of the miles driven. Thus the quantity of engine fuel needed by vehicles will decline by 40-90 percent.

These reduced fuel requirements would allow biofuels to become the primary or even sole source of non-electric energy for vehicles, rather than the current 10 percent blend with gasoline. A 2003 report by the Institute for Local Self-Reliance describes such a transportation strategy in some detail.[2] Sufficient land area does exist in the United States to cultivate the 1-2 billion tons of plants needed to meet these reduced engine fuel requirements.[3]

Biochemicals and Biofuels: The Rise of Biorefineries

When biofuels, like ethanol or biodiesel, are made from plant matter, a significant portion of that plant matter remains available for other uses. It can be converted into a number of end-products: food, energy, non-energy products (e.g. chemicals, dyes, inks, textiles, plastics).

Since biochemicals are much more valuable than biofuels, earning a market price two to ten times higher per pound, it is likely that in the near future biochemicals and other bioproducts will become a biorefinery's principal product, at least in dollar value. Biofuels will become the byproduct. Any remaining materials will provide the energy needed to run the processing facility.

The end use of a future biorefinery's raw material may breakdown roughly into three equal parts: one-third for chemicals, one-third for liquid biofuels, one-third to supply the energy–thermal and electric–for the facility.

About 2,000 such manufacturing facilities, each producing about 50 million gallons of ethanol, would be needed to supply sufficient liquid fuels to satisfy the needs of a transportation system primarily propelled by electricity. The chemical products from these facilities could displace almost all of our petrochemicals, and a significant portion of our inorganic chemicals as well. The remaining feedstock could provide all of the energy needed to run the facilities.

A Carbohydrate Economy: Achieving Energy Security and Rural Security

A carefully designed biofuels strategy may be the answer not only to our oil import-problems but to another global dilemma as well: the plight of agriculture.

Agriculture remains the world's largest economic sector. More than two billion people depend on the land for their livelihoods. A strategy that dramatically increases the markets for plant matter can significantly benefit the world's farmers and rural areas. A carbohydrate economy also has the potential to reduce the current trade tensions among the world's farmers.

World trade negotiations currently pit farmers from poorer countries against farmers from richer countries. A carbohydrate economy can open huge new domestic markets for plant matter. Rather than competing for relatively stable export markets, farmers could sell into rapidly expanding internal markets. To put it another way, instead of carbohydrates competing with carbohydrates, carbohydrates would compete against hydrocarbons, a win-win situation for farmers and rural communities worldwide.[4]

Doubling or even tripling the total amount of plant matter marketed will benefit farmers. But the benefit may be modest if the expanded market is not accompanied by a dramatically-changed agricultural market structure. Farmers have learned from decades of bitter experience that expanded markets and even improved productivity do not inevitably translate into higher commodity prices and increased farmer income.

For farmers and rural areas to truly reap the rewards of a carbohydrate economy they must gain some of the value created by processing the agricultural raw materials into finished products. That can occur only if the farmer and rural residents own a share in the processing or manufacturing facility.

In the United States, the tripling of ethanol consumption since 2000 may have raised the price of corn by 10-15 cents per bushel. But the 20,000 or so U.S. farmers who own a share of an ethanol plant receive far more, in annual dividends, usually 50-75 cents per bushel.

A biorefinery enables farmer and local ownership because, unlike petroleum, plant matter in its raw state is bulky and expensive to transport. Thus most biorefineries buy their raw materials from within 50-75 miles of the facility (and often sell their end-products in a radius not that much wider).

In part because of the transport economics, the size of biorefineries is only a fraction that of petroleum refineries (1-10 percent). That modest scale enables farmers and local residents to raise sufficient equity investment to own the facility.

Assuming 500 individual farmer-investors in each biorefinery, a majority of full time grain farmers could become owners in a value-added manufacturing facility. This could change the face of agriculture, and its internal economic dynamics.

This massive potential to couple a biofuels strategy with one that maximizes the benefit to rural communities will not be easy to achieve. It requires a coherent approach that cuts across bureaucratic and sector lines. That will be a challenge, but a worthwhile challenge to take up. Regrettably, for 25 years a disproportionate amount of the discussion about biofuels, and much of its intellectual resources, have been occupied in debating

For farmers and rural areas to truly reap the rewards of a carbohydrate economy they must gain some of the value created by processing the agricultural raw materials into finished products. That can occur only if the farmer and rural residents own a share in the processing or manufacturing facility.

the issue of energy balances. It is to that issue that we now turn our attention.

Net energy is an issue worthy of investigation.

Unfortunately, this small piece of the puzzle has tended to dominate the discussion of biofuels. In the process, important issues like the ownership structure of a carbohydrate economy or its implications for world trade and rural development have largely been ignored.

Net Energy of Biofuels: The (Endless) Debate

Just as biomass has unique characteristics (e.g. built-in storage) that make it attractive, it also has several characteristics that may demand more sophisticated strategies than those required to promote other renewable energy sources.

Renewable fuels like sunlight and wind are widely available regardless of public policy. Thus a renewable energy strategy for these fuels can focus almost entirely on how to harness them efficiently and economically. Biomass, on the other hand, is only available in significant quantities when cultivators are involved. Thus a biomass strategy must gain the enthusiastic and widespread farmer involvement.

Another characteristic of biomass that distinguishes it from other forms of renewable energy derives from the fact that it is solid matter: cultivation and processing can have significant adverse environmental impacts. Thus a biomass strategy must encourage cultivation, harvesting and processing technologies that minimize negative environmental impacts.

Among the many environmental factors to consider is that of energy balance, that is, the amount of energy it takes to grow a crop and convert it into biofuels and other products compared to the amount of energy contained in the resulting biofuel and bioproducts.

Net energy is an issue worthy of investigation. Unfortunately, this small piece of the puzzle has tended to dominate the discussion of biofuels. In the process, important issues like the ownership structure of a carbohydrate economy or its implications for world trade and rural development have largely been ignored.

It often seems that every article, every interview, every public discussion about our most used and visible biofuel, ethanol, starts, and sometimes ends, with the question, "Doesn't it take more energy to make ethanol than is contained in the ethanol?"

In 1980, the short and empirical answer to this question was yes. In 1990, because of improved efficiencies by both farmer and ethanol manufacturer, the answer was, probably not. In 2005 the answer is clearly no.

Yet the question will not go away. One might argue that this is because credible studies by one or two scientists continue to keep alive the claim that biofuels are net energy losers. Yet many grain and oilseed farmers[5] wonder why it is that biofuels like ethanol and biodiesel are singled out for such an aggressive and persistent attack on the net energy issue.

They compare the discussion of biofuels with that of hydrogen, a fuel that has captured the imagination of federal and state governments. Converting the transportation sector (and other sectors as well) to hydrogen has become a national priority. Thousands of articles have been written about hydrogen. Most are wildly enthusiastic. Some are negative. But very, very few even raise the net energy issue.

A Lexis/Nexis search identified over 300 articles published just since 2000 that discuss the energy balance of ethanol, the vast majority with a negative slant; fewer than 5 even mention the net energy issue with respect to hydrogen. Yet for hydrogen the energy balance is not a controversial question. It is well documented that hydrogen's energy balance is negative: It takes more natural gas to make hydrogen from natural gas than is contained in the hydrogen.

Another frustration by biofuels advocates is that the net energy discussion looks backwards, not forwards. Instead of focusing on the efficiencies of the best farmers and the newest facilities and a strategy to make these efficiencies the overall industry and agriculture average, the studies present averages largely reflective of the efficiencies of ethanol facilities that are 20 years old. This is not helpful to long range planning.

Understanding the Net Energy Debate

The remainder of this paper focuses on the energy balance of biofuels. In doing so, it inevitably focuses largely on the studies of David Pimentel, a Professor of Entomology at Cornell University (now Emeritus). For as long as ethanol has been a matter of public policy, David Pimentel has been its most vocal, sometimes its only, and always its most visible critic.

Pimentel began his association in 1979 when he chaired an advisory committee of the U.S. Department of Energy examining the viability of fuel ethanol (and coal derived methanol).[6]

Since then, Pimentel has authored or co-authored more than 20 technical articles on ethanol. Over time his input and output numbers have varied. But his conclusion remains constant: more fossil fuel energy is needed to grow corn and convert it into ethanol than is contained in the ethanol.

In 2005, still another article by Pimentel appeared. This one was co-authored by Tad Patzek, a professor in the Department of Civil and Environmental Engineering at the University of California-Berkeley.[7] This study raised the net energy debate to a new level by extending the criticism of corn-derived ethanol to ethanol derived from cellulosic materials like wood or switchgrass and to diesel fuel substitutes derived from sunflowers and soybeans. It also insisted, in passing, that ethanol from sugar cane was a net energy loser.[8]

"There is just no energy benefit to using plant biomass for liquid fuel", Pimentel concluded.[9]

Indeed, this latest study reached a remarkable and highly provocative conclusion: the energetics of making ethanol from switchgrass or wood are considerably worse than for making ethanol from corn, and the energetics of making biodiesel from soybeans or sunflowers may be more bleak than making ethanol from corn.[10]

Each time a new Pimentel article appears, Cornell University's competent press office broadcasts a provocative press release and news article announcing its latest pessimistic conclusions, timing its release for maximum visibility. The new article appeared in March 2005 but the press release was issued in July, apparently to coincide with a Congressional vote on an energy bill containing incentives for making ethanol from cellulose and biodiesel from oilseeds.

Each press release invariably leads to a flurry of stories in print and broadcast media throughout the U.S. and Canada and reinvigorates the debate about the efficacy of converting plants into fuels. Each barrage of media

This latest study reached a remarkable and highly provocative conclusion: the energetics of making ethanol from switchgrass or wood are considerably worse than for making ethanol from corn, and the energetics of making biodiesel from soybeans or sunflowers may be more bleak than making ethanol from corn.

David Pimentel's pessimism about biofuels derives from a methodological approach that leads him to a far more sweeping and highly controversial conclusion: the world's population has vastly exceeded its biological carrying capacity.

coverage elicits detailed rebuttals from the biofuels industries. But these occur after the fact and rarely if ever make it into the mainstream media. Indeed, their very detailed nature inhibits their visibility.

Reporters move on to other stories. After a few weeks the buzz dies down. But the seeds of doubt have been sown and they continue to grow.

Journalists are not to blame for these increasingly predictable cycles of negative publicity regarding biofuels. They lack the time and expertise, even if they have the inclination, to examine competing scientific studies. Those who do undertake such an examination quickly discover how challenging the task can be. For the studies are anything but accessible and transparent. Researchers may use different measures (e.g. high heating values versus low heating values) or different conversion systems (e.g. Btus per gallon versus kilocalories per 1000 liters). Or sometimes even mix measures within a single study (e.g. kilocalories per 1000 liters and kilocalories per 1000 kilograms).

Some studies are very detailed, running to 100 and even 200 pages. Pimentel's studies, on the other hand, are very short, usually consisting of a couple of tables with brief references and brief descriptive text.[11] Pimentel and Patzek's latest study, for example, contains a two paragraph discussion of switchgrass to ethanol, a two paragraph discussion of wood to ethanol, a four paragraph discussion of the energetics of soydiesel and a two paragraph discussion of the energetics of sunflower diesel. All of the text simply repeats numbers from the table. No explanatory discussion is offered.

Few roadmaps are available that highlight the specific areas of disagreement.[12] This commentary attempts to offer such a guide.

Net Energy of Biofuels: Six Key Points

Reporters and interested parties who want to examine the numbers and report on or participate in the debate, might take into account six key points.

1. David Pimentel's pessimism about biofuels derives from a methodological approach that leads him to a far more sweeping and highly controversial conclusion: the world's population has vastly exceeded its biological carrying capacity.

Pimentel's analysis leads him to conclude that the world's population of 6.5 billion people has far surpassed the planet's capacity to feed that population. As he writes, "For the United States to be self-sustaining in solar energy, given our land, water and biological resources, our population should be less than 100 million…" (the July 2005 population is 295 million).[13] Pimentel further maintains, "the optimum (world) population should be less than…2 billion.[14]

Pimentel's pessimism about the world's capacity to feed its human population carries over to his view about the limited potential of renewable energy in general. In this he is joined by Patzek, who with Pimentel recently concluded that nuclear power may be the only answer.

> *"We want to be very clear: solar cells, wind turbines, and biomass-for-energy plantations can never replace even a small fraction of the highly reliable, 24-hours-a-day, 365-days-a-year, nuclear, fossil, and hydroelectric power stations. Claims to the con-*

trary are popular, but irresponsible…new nuclear power stations must be considered."[15]

Do two-thirds of us have to die in order to allow the remaining third to live a comfortable life on a sustainable basis? Must we rely on nuclear power to provide us a reliable and sufficient source of energy? These questions dwarf that of whether the energy balance of biofuels is slightly negative. One would hope that reporters and others would attend to the catastrophic predictions that result from the full-scale application of Pimentel's methodological approach, rather than the tiny negative impact predicted by its application to a tiny slice of the world's biological resources.

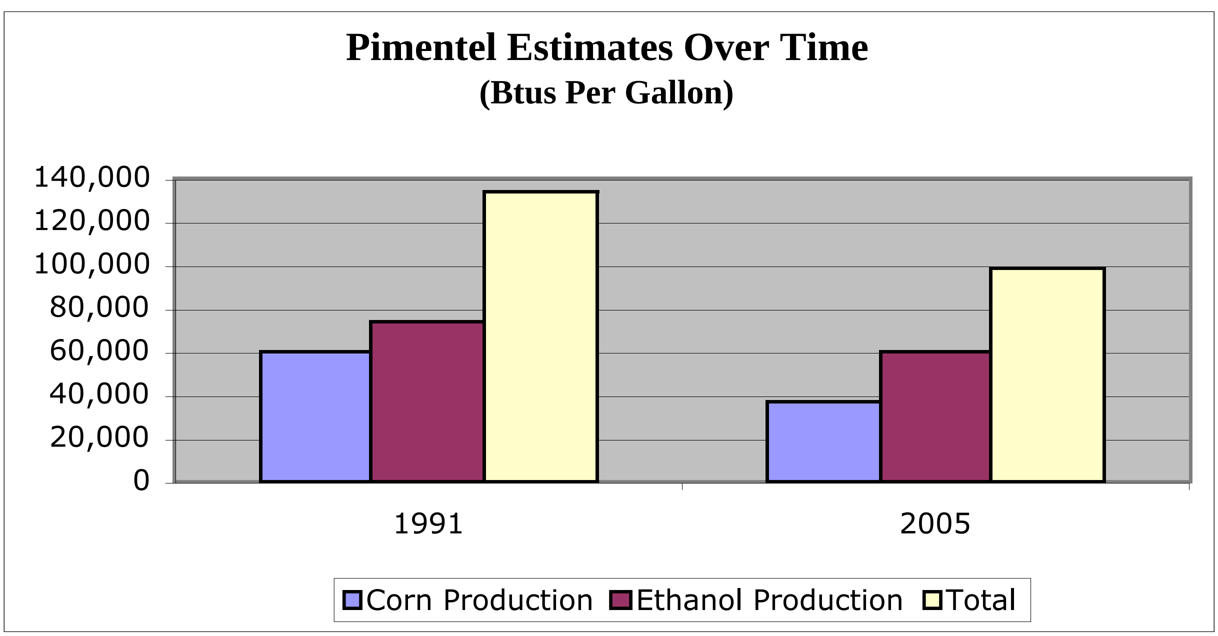
2. Policymakers base their decision on whether to aggressively expand biofuels on the latest production technologies and techniques. Therefore, net energy analyses should look forward, not backward. That means, in part, according a higher importance to data from the latest and next-generation manufacturing technologies and agricultural practices over industry averages largely based on the output from older plants.

Averages can be deceiving, particularly in the biofuels industry where until the recent dramatic increase in capacity, the bulk of the industry's manufacturing facilities was 20 years old.

The empirical data overwhelmingly affirms that farmers and ethanol manufacturers are far more energy and resource efficient than they were 20 years ago. The trajectory is positive and the prospects for even further improvement are bright.

Since 1980, for example, new ethanol plants have reduced their energy inputs per gallon of ethanol produced by about 50 percent. In 1980 total energy use was about 69,000 Btus per gallon. Today it is closer to 35,000 Btus. Today, those who invest in ethanol facilities can receive performance guarantees from engineering firms for a thermal efficiency in the low 30,000 Btus per gallon and an electricity efficiency of about 0.76

The empirical data overwhelmingly affirms that farmers and ethanol manufacturers are far more energy and resource efficient than they were 20 years ago. The trajectory is positive and the prospects for even further improvement are bright.



Thus it would appear more fruitful for the focus to be on the very wide divergence of estimates related to cellulosic ethanol and biodiesel rather than the very modest differences that remain regarding corn derived ethanol.

kWh per gallon.

One reason for this reduction in energy inputs is a shift in ethanol production from wet mills to dry mills. Wet mills are more energy intensive than dry mills.

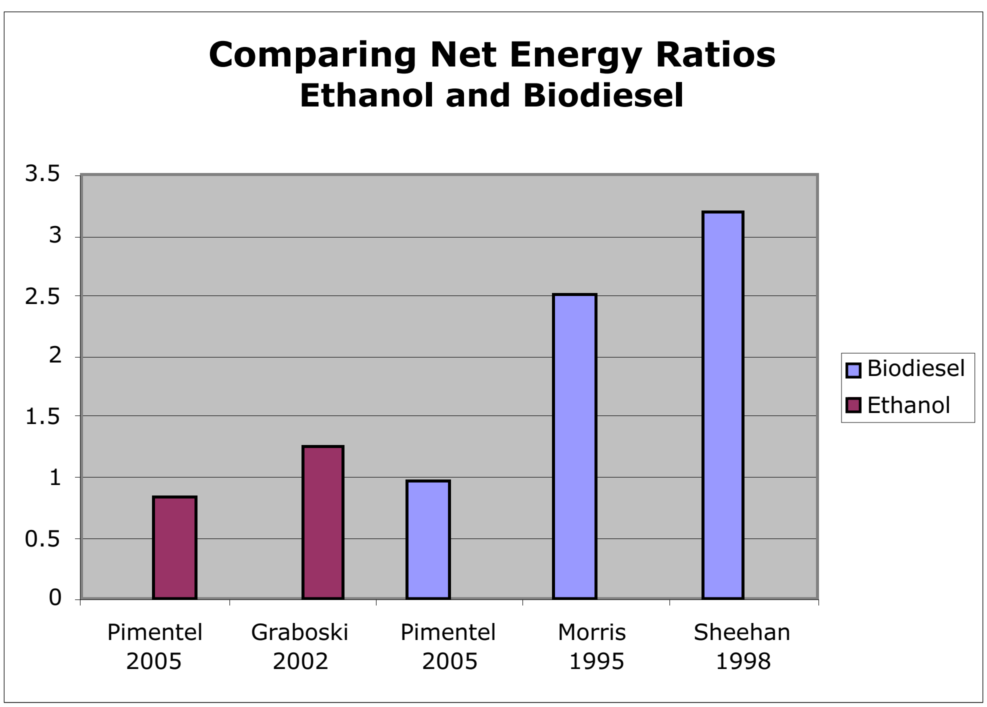
Wet mills were built in the late 1970s and 1980s primarily to manufacture high fructose corn sweetener. They make a variety of products from corn and are more energy intensive than dry mills. They dominated the industry in 1990, producing over 80 percent of all ethanol. In the last 15 years, however, most new ethanol facilities have been dry mills. By 2000 the proportion of production by wet mills had fallen to 55 percent. By the end of 2005 it will be closer to 25 percent. Over 90 percent of all new production now comes from dry mills.

Improved efficiency has come not only in the manufacturing facility but on the farm as well. Since 1980, for example, corn farmers have increased yields from 100 to 140 bushels per acre while using 20-25 percent less fertilizer, herbicide and insecticide per bushel cultivated.[16] A significant number of farmers engage in conservation tillage, a cultivation technique that significantly reduces soil erosion as well as diesel or gasoline use.

Pimentel appears to agree that the trajectory has been positive. He estimates that the amount of energy used to grow a bushel of corn has declined by more than a third between 1991 and 2005 while energy used to make a gallon of ethanol has fallen by about 20 percent.[17]

3. Although an enormous amount of attention has been focused on the debate about the energetics of corn to ethanol, the differences actually have narrowed to the point that they are relatively modest. On the other hand, Pimentel and Patzek's new estimates of the energy balance of making ethanol from cellulose and biodiesel from oil seeds diverge dramatically from those of other studies.

Pimentel's 1991 energetics study of corn derived ethanol found a net energy ratio of 0.68 while his and Patzek's 2005 study esti-



mates a net energy ratio of 0.85. Those who have found a positive ratio estimate it to be in the 1.25-1.4 range. Overall the positive ratios are about 60 percent greater than Pimentel and Patzek's.

On the other hand, Pimentel and Patzek's net energy ratio analysis of biodiesel is 0.98[18] while those of other studies are in the 2.5-3.2 range, some 150 percent to 200 percent higher.[19]

Cellulosic ethanol can achieve a positive net energy ratio even higher than that of biodiesel, in large part because the portions of the lignocellulosic feedstock not converted to ethanol can be burned (or gasified) to provide all of the energy needed for the conversion process.

Thus it would appear more fruitful for the focus to be on the very wide divergence of estimates related to cellulosic ethanol and biodiesel rather than the very modest differences that remain regarding corn derived ethanol.

4. All other studies done after 1992, except for Pimentel and Patzek's have found a positive energy balance of corn to ethanol.[20]

Being in a small minority doesn't mean one is necessarily wrong, but it does indicate the preponderance of scientific opinion is on the other side. Apparently stung by criticism of his loner status, in his latest article Pimentel (and Patzek) insist, "In contrast to the USDA, numerous scientific studies have concluded that ethanol production does not provide a net energy balance…".[21]

The sources cited in the article do not justify this statement. [22]

Of the 9 cited, only one was an actual scientific study. That 1989 study found a small 4 percent net energy loss and assumed a very low yield of 90 bushels per acre. Five of the sources were press releases or short statements critical of ethanol that did not analyze net energy issues.[23] The other three contained no independent research. They simply cited Pimentel's data. [24]

Pimentel and Patzek cite no studies, nor press releases or public statements, condemning the energetics of cellulose to ethanol nor biodiesel. We are not aware of any such studies or statements.

5. Biofuels displace large quantities of imported oil, regardless of the net energy findings, because their production relies on non-petroleum fuels.

Too often people read about net energy studies that arrive at a negative result and interpret the result this way: "It takes more than a gallon of oil to produce a gallon of ethanol." That is inaccurate. Even Pimentel's studies do not assert this, although he rarely clarifies the distinction between fossil fuels and petroleum.

Biofuels production overwhelmingly relies on natural gas and coal, not petroleum. For growing corn and making ethanol from the corn, petroleum (diesel or gasoline) comprises 8-17 percent of the fossil fuel energy used. Coal or natural gas account for the other 83-92 percent (assuming the cellulosic portion of the incoming feedstock is not used to provide thermal and electric energy at the manufacturing plant).

Thus, the net energy ratio with respect to petroleum would be close to 8 to 1. In other words, every Btu of ethanol produced displaces about 8 Btus of petroleum. [25]

For most policymakers, the highest priority of a biofuels policy is to reduce our depen-

Biofuels production overwhelmingly relies on natural gas and coal, not petroleum …every Btu of ethanol produced displaces about 8 Btus of petroleum.

Pimentel vs. Graboski: The Energy Input Differences

(Btus per Gallon of Ethanol)

	Difference Btus/Gal.	% of Total Difference
CORN PRODUCTION		
Labor	2,158	4.99%
Marchinery	4.494	10.39%
Fuel (Diesel, gas, LPG)	544	1.26%
Irrigation/electricity	37	0.09%
Nitrogen	2,698	6.24%
Phosphorous	1,154	2.67%
Potassium	856	1.98%
Lime	1,092	2.53%
Seeds	2,206	5.10%
Herbicides/Pesticides/Other	3,411	7.89%
TOTAL FARMING INPUT DIFFERENCE	**16,750**	
ETHANOL PRODUCTION		
Corn Transport	3,287	7.60%
Water	1,353	3.13%
Stainless Steel	1	0.00%
Steel	180	0.42%
Cement	120	0.28%
Steam	-10,272	-23.76%
Electricity	15,195	35.15%
95% EtOH > 99.5% EtOH	135	0.31%
Sewage Effluent	1,037	2.40%
Plant, Other	-1,238	-2.86%
TOTAL PROCESSING INPUT DIFFERENCE	**26,485**	
TOTAL DIFFERENCE	**43,235**	

dence on imported oil.

6. Energy balance analyses should take into account the quality of the energy produced

The energy content of a fuel is important, but so is the quality of that energy, that is, its usefulness. For example, we use more energy to generate a kilowatt-hour of electricity than is contained in that electricity. But electricity is a high quality fuel, in part because it can be transported easily and in part because it can be used in ways that heat energy cannot. We strive to maximize the amount of electricity we extract from a given amount of heat, but we do not dismiss the utility of electricity because of the energy losses involved in its production.

Biofuels also constitute high quality fuels. They combine energy and storage. Energy from wind and sunlight, on the other hand, is available only intermittently– when the wind blows and the sun shines. Those forms of renewable energy require additional storage systems, like batteries. This should be taken into account in any comparative energy analysis.

Biofuels, like electricity, do require more energy to make than is contained in the fuel. But in the case of biofuels, this additional energy comes from the sun. Solar energy, not fossil fuels, powers the chemical-building photosynthesis process.

Taking a Closer Look At The Numbers [26]

When faced with the masses of data that comprise the core of energetics studies, most would-be participants in the net energy debate instinctively shrink back. Just translating the numbers from various studies into a form of measurement that allows for easy comparisons can be challenging.

Those who do take the time to review the various studies will discover that only a handful of factors account for over 80 percent of the variations among net energy studies of ethanol. These include: 1) yields of ethanol per bushel (or tons) and yields of crop in bushels (or tons) per acre; 2) energy used to manufacture nitrogen and other fertilizers; 3) energy used to make the ethanol; 4) the energy value of the co-products; 5) the energy used to make the machinery used on the farm and in the ethanol facility. [27]

At one time, other factors accounted for a significant difference. For example, Pimentel's 2001 estimate of irrigation energy was an order of magnitude higher than other estimates. But his and Patzek's 2005 study reduces the 2001 estimate by 90 percent.[28] As the table on the previous page notes, this puts him very, very close to the estimates of other researchers. [29]

Let's explore these factors one at a time.

1. Crop Yields per Acre and Biofuel Yield per Bushel

As noted before, agricultural yields, at least with regard to corn (the nation's largest crop), have increased by some 40 percent since 1980 (soybean yields have increased more slowly). We are getting more output per unit of input, whether that input be land, fertilizer, pesticide or energy. Pre-1990 studies used yield estimates of about 110 bushels per acre. Post 2000 studies use more up-to-date yields of 130-140 bushels per acre and those that look toward the year 2010 use yields closer to 150 bushels per acre. [30]

Pimentel's 2005 corn crop yield estimate is comparable to those used by other

Biofuels, like electricity, do require more energy to make than is contained in the fuel. But in the case of biofuels, this additional energy comes from the sun.

Substituting just the new ethanol plant performance guarantees for Pinentel's input numbers would make his overall net energy assessment positive.

researchers.

Ethanol yields per bushel have also increased steadily. In 1980, an ethanol dry mill extracted about 2.5 gallons of ethanol for every bushel of corn processed. Today firms that build ethanol facilities will include a performance guarantee of a minimum of 2.68 gallons of ethanol(denatured) per gallon. Next generation plants could approach 2.75 gallons per bushel.

Since 1980, Pimentel has not increased his estimate of 2.5 gallons of ethanol per bushel. Raising his yield to that of current performance guaranteed yields alone would reduce by about 7 percent his energy input numbers.

2. Energy Used to Make Fertilizers and Seeds

Nitrogen fertilizer requires significant energy for production. Pimentel's fertilizer application figures do not differ significantly from those of other studies. [31] But his estimates of the amount of energy needed to make a pound of fertilizers does. In earlier studies, his estimates were about 50 percent higher than other investigators (33,000 Btus per pound of nitrogen produced versus about 22,000). His 2005 estimate has dropped to 29,000 Btus per pound.[32]

In previous estimates, the nitrogen fertilizer energy input accounted for a large majority of the energy input of all fertilizers. But in the 2005 study it accounts for only a little more than half. Another way to look at this is the ratio between Pimentel's estimates and Graboski's. For nitrogen, Pimentel's estimate in Btus per gallon of ethanol produced is 1.3 times that of Graboski. For phosphorous, however, the ratio jumps to 11.8, for potassium 3.7 and for lime it is 10.9. There is also a huge difference in the estimate of the amount of energy used to make the corn seeds, with Pimentel estimating 2206 Btus per gallon and Graboski estimating it at trivial.

Graboski offers a thorough analysis of how he arrived at his numbers. Pimentel is less forthcoming. Indeed, Pimentel's numbers have changed, sometimes dramatically, over the years. For example, his estimate of the energy input for phosphorous, in Btus per gallon of ethanol produced, has ranged from 2,753 in 1991 to 1,145 in 1998 to 821 in 2001. The 2005 study offers an estimate of 1,261. Graboski's estimate is 90 percent less, at 107 Btus per gallon. Similar variations have occurred in Pimentel's estimates for potassium, which ranged from a high of 1,396 Btus per gallon in 1991 to a low of 565 in 2001. His 2005 study estimates 1,172. Graboski's estimate of 317 Btus per gallon is close to Pimentel's 2001 figure.

3. Energy Used to Make the Ethanol and Co-products

Gross processing energy estimates are usually given on a per-gallon of ethanol produced basis. Pimentel's estimates have varied significantly, even over a short time frame.[33] His 2005 study estimates about 53,000 Btus per gallon of ethanol produced for steam and electricity. Other industry average estimates are in the 40,000-49,000 Btus per gallon range.

As mentioned above, those building the latest plants are offering performance guarantees of about 23,000 Btus per gallon thermal energy (without drying, which translates into about 33,000 Btus per gallon with the distillers grain drying). The guarantee also includes a limit of 0.77 kWh per gallon produced. Combined these translate into about 38,000 Btus of total energy per gallon produced.

Substituting just the new ethanol plant performance guarantees for Pinentel's input numbers would make his overall net energy assessment positive.

Pimentel also adds energy inputs for water and for sewage effluent. Although these have a minor impact on the total energy input estimate, they may reflect a tendency to look to older plants rather than the latest ones. New ethanol plants do not have sewage effluent. They have zero wastewater, instead discharging their boiler water blowdown into an evaporation pond.

4. The Energy Value of Co-products

One of the most controversial issues in net energy analyses regarding biomass is how to value the co-products coming from the ethanol manufacturing facility. Varying opinions are understandable, because there are a number of ways to estimate that value (e.g. by the percentage of the byproduct by weight, by market value, by energy content, by replacement value).

Almost all energy balance studies go into this issue in some detail. Pimentel's studies, on the other hand, while including a co-product value, do so grudgingly[34] and in cursory fashion. The one or two paragraph discussion is easily overlooked.

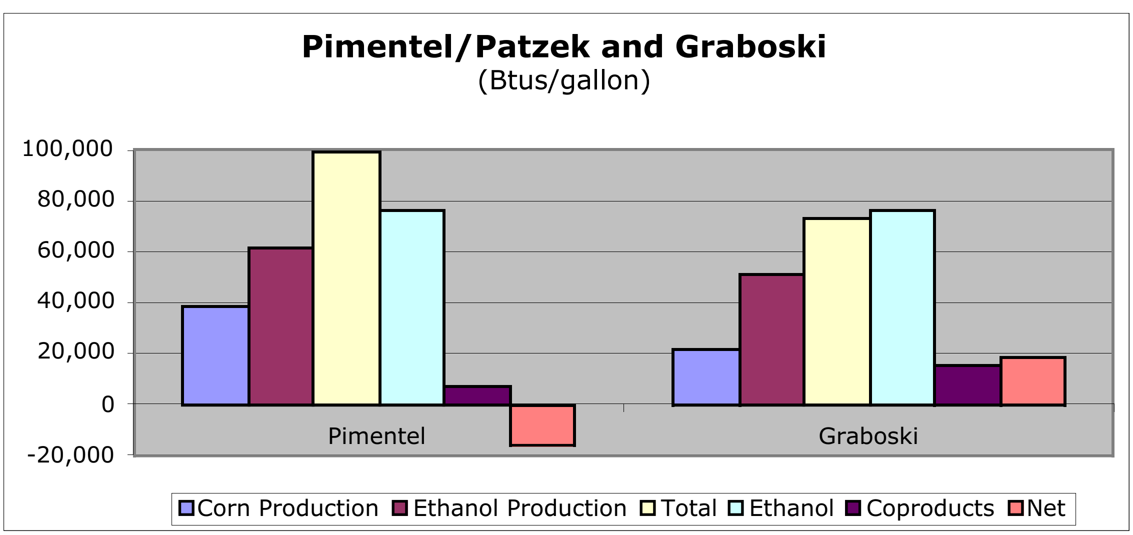
More importantly, neither Pimentel's energetics tables, nor his executive summaries nor Cornell's press releases include the energy value of co-products in their overall estimates. That omission greatly exaggerates the negative results in the public's eye.[35]

Pimentel's aversion to including an energy credit for coproducts is puzzling. If we include all the energy used to grow and process a crop on the input side of the equation, we should include all the energy value of all of the end-products on the output side.

A dry mill produces three end-products: ethanol, a high protein animal feed and carbon dioxide in almost equal proportions. Some larger facilities market the carbon dioxide produced for industrial purposes, although only one net energy study to our knowledge has estimated the energy value of that coproduct.[36]

Ethanol is made from the starch contained in the corn plant. The ethanol production process concentrates the protein con-

Pimentel's aversion to including an energy credit for coproducts is puzzling. If we include all the energy used to grow and process a crop on the input side of the equation, we should include all the energy value of all of the end-products on the output side.



The energy content of the portion of the lignocellulosic feedstock not converted into ethanol is sufficient to provide all of the energy needed for the manufacturing process.

tained in corn. The end result is an animal feed higher in quality than that of the original corn. This is one reason that worries about biofuels production reducing food production are exaggerated, at least with respect to protein. The world does not suffer from a lack of sugars or starches.

The animal feed is called distillers grain and it can be fed either wet or dried. If a mill is located near a feedlot, the distillers grain may be fed wet. That saves a significant amount of energy, in the range of 10,000 Btus per gallon that would otherwise dry the feed for sale to remote markets.

As noted, several methodologies can be used to estimate the energy value of co-products. From a strict energy input-output perspective one might expect the energy content of the co-product to be used as the output estimate. The energy value of the distillers grain would be about 28,000 Btus per gallon of ethanol. That is sufficient to displace a considerable amount of the heat energy needed in making the ethanol and drying the distillers grain. Using this measure would double the positive net energy estimates of most studies.

However, virtually all observers view this as an inappropriate measure because it values the caloric value of the feed rather than its protein value. They assume the ethanol producer will not burn the animal feed. This is a reasonable ethical consideration, although given high current natural gas prices, it might not be a reasonable market consideration. In some cases it may be more profitable now to use the distillers grain as fuel rather than as feed.

When it comes to cellulose to ethanol, the byproducts have no food value. Thus researchers assume they will be used as a fuel. In this case, the energy content of the portion of the lignocellulosic feedstock not converted into ethanol is sufficient to provide all of the energy needed for the manufacturing process.

Another methodology used to allocate the energy inputs based on how much is used for the production of each co-product. A computer model is used to allocate the energy. For example, as noted before, drying the distillers grains requires about 10,000 Btus per gallon, all of which would be allocated to the production of the animal feed, not the ethanol. Using this allocation method, researchers have estimated a positive net energy value of 1.57-1.77.[37]

Energy inputs can be allocated by the weight of each coproduct, or the market value of each coproduct. Most researchers use still another measure: the replacement value of the coproduct. This is done by estimating the amount of energy needed to grow and process another crop for which the coproduct substitutes. For example, in the case distillers grains, soybeans are a likely animal feed replacement. Thus the energy needed to grow and process soybeans into soy meal becomes the basis for estimating the energy value of the distillers grains. Using this measure, the energy value of the co-product drops to about 14,000 Btus per gallon.

Even when replacement rather than direct energy value is used, disagreement can still arise. Pimentel, for example, argues that the value of distillers grain is lower than soy meal because distillers grain has a lower protein content. He lowers the replacement energy value proportionately.

Michael Graboski of the Colorado School

of Mines, on the other hand, argues that it is not the amount of protein that should be the basis for comparison but the effective protein level. For ruminant animals, which constitute over 99 percent of the distillers grain market, the protein in distillers grain is more effectively absorbed by the animal than the protein in corn or soybean meal.[38] Moreover, since distillers grains contain all of the oil in the corn, it has a higher energy content as a feed than either corn or soy meal. [39]

Graboski arrives at a replacement value of the distillers grain that is 100 percent higher than that estimated by Pimentel.

Over time, Pimentel's coproduct estimates have fallen considerably. His 1991 study used a range of 11,000-32,000 Btus per gallon. His 2001 study lowered and narrowed this range to 6,382-19,140 Btus per gallon. His 2003 and 2005 studies used a single figure at the lowest end of the previous range, about 6,600 Btus per gallon of ethanol produced. Interestingly, the mid range of his 1991 and 2001 estimates puts him very much in line with other researchers' estimates.

5. Energy Used to Make the Machinery and Feed the Workers

Pimentel includes several inputs other researchers ignore. One is the food energy consumed by workers. Other researchers argue that people are going to eat anyway, whether corn or ethanol is produced.

Pimentel includes on the input side of the energy balance equation the energy used to make the farming and manufacturing machinery. Other researchers ignore this input, citing the difficulty of calculation and the methodological pitfalls involved. For example, how far back does one go? Do you include the energy used to make the machinery that was used to make the materials used to make the farm equipment? How far forward do you go? Do you take into account the embodied energy in the scrap product, given the very high recycling rate of metals? What lifetime do you assume for each material and piece of equipment?

As a result of these methodological and estimation challenges, very few net energy or life cycle analyses of any product include capital or embodied energy. Thus it is impossible to compare the embodied energy used, say, in the production of gasoline versus the embodied energy used in the production of ethanol.

Pimentel uses a single 1979 source to justify his embodied energy estimates and offers no textual explanations to explain his numbers. Michael Graboski, on the other hand, includes a six page, well-documented appendix that contains a step-by-step explanation of how he arrives at his estimates of the energy embodied in machinery. Graboski concludes that manufacturers have become dramatically more efficient in their use of materials and energy in the last 30 years. He estimates that embodied energy accounts for less than 1 percent of the overall energy used to grow the crop and process it into ethanol. [40]

Pimentel uses a single 1979 source to justify his embodied energy estimates and offers no textual explanations to explain his numbers. Michael Graboski, on the other hand, includes a six page, well-documented appendix...

A few words about biodiesel and cellulosic ethanol

So far this discussion has focused on corn-derived ethanol because all previous studies by Pimentel (and Patzek) focused solely on this feedstock and end-product. A few words must be said, however, about their new estimates of the energy balance of biodiesel and cellulosic ethanol. Here, as noted before, their estimates diverge dramati-

When it comes to soydiesel animal feed is the primary product. The soy meal accounts for over 80 percent of the end products produced, by weight, and about 67 percent of their combined value. Yet Pimentel and Patzek give the soy meal an energy credit that is only about 15 percent of the input energy.

cally from those of other researchers. While Pimentel and Patzek estimate a net energy loss for biodiesel, for example, other researchers see a 150 percent and 200 percent net energy gain!

This astonishing divergence demands that close attention be paid to their methodology and data. Unfortunately, their biodiesel and cellulosic ethanol sections appear hastily done and are frustratingly brief. The study on soydiesel, for example, consists of two tables and four paragraphs of text that simply repeat the numbers in the tables. A similar brevity and lack of explanation characterizes the sections on switchgrass and wood to ethanol.

As a result, it is impossible to intelligently analyze their numbers. But a few observations can be made.

1. An arithmetic error, perhaps the result of a typo, has exaggerated even the modest net energy loss Pimentel and Patzek have estimated for biodiesel. Their own data leads to an estimate of a tiny 2 percent energy loss, not an 8 percent loss.[41]

2. It is unclear where Pimentel and Patzek have included the energy used to modify the vegetable oil into an ester suitable for use as a diesel fuel. If they had done so, they would have had to estimate the credit given to glycerine, the very valuable coproduct produced by the esterification process.

2. In corn-derived ethanol, as noted above, the animal feed is a byproduct, accounting, by weight, for about one third of the output (one half if carbon dioxide is excluded from the calculation) and about 40 percent of ethanol's market value. When it comes to soydiesel, on the other hand, animal feed is the primary product. The soy meal accounts for over 80 percent of the end products produced, by weight, and about 67 percent of their combined value. Yet Pimentel and Patzek give the soy meal an energy credit that is only about 15 percent of the input energy. Even using the replacement value measure should lead them a much higher co-product credit. In their 1995 analysis, Ahmed and Morris, using a comparable amount of barley protein as the replacement value, arrive at a co-product energy value more than three times that arrived at by Pimentel and Patzek.[42]

3. The Pimentel/Patzak study assumes that soybean farmers apply 2.2 tons of lime annually on every acre of soybeans they raise. Yet according to Jim Duffield, a senior agricultural economist at the U.S. Department of Agriculture, only 60 percent of soy farmers use lime at all, and one application lasts for up to 10 years. Given that in Pimentel and Patzek's calculation, lime accounts for one third of the energy used for soybean farming, changing this input alone would significantly change their overall conclusion.

4. The authors have seriously misread at least one of their sources. They cite a Department of Energy study as supportive of their conclusion that biodiesel is a net energy loser.[43] They use as evidence the following excerpt from that report, "1 MJ of biodiesel requires an input of 1.24 MJ of primary energy". The quote is accurate. But the authors apparently are unaware that when the cited study refers to "primary energy" it means solar energy inputs as well. Two pages later the study restricts its analysis to fossil energy inputs and concludes, "Biodiesel uses 0.3110 MJ of fossil energy to produce 1 MJ of fuel product; this equates to a fossil energy ratio of 3.215. In other words, the biodiesel life cycle

produces more than three times as much energy in its final fuel product as it uses in fossil energy."

5. With regard to the conversion of cellulosic materials like switchgrass or wood, again it is very difficult to deconstruct the authors' findings. One methodological assumption, however, does stand out. The authors offer no energy credit for the byproduct. In this case the byproduct is the majority of the lignocellulosic feedstock delivered to the processing facility.

When a lignocellulosic material is converted into ethanol, some one third to one half of the feedstock remains unused, depending on whether both the cellulosic and hemicellulosic sugars are converted, or just the former. The material not converted into ethanol contains sufficient energy to make the processing facility self-sufficient. Indeed, many paper mills today use the waste wood from the manufacturing process to supply all of the energy to run their operations. We would expect that ethanol facilities that use wood or other cellulosic materials as their feedstock would do the same.

It appears that Pimentel and Patzek assume this energy-rich material will be thrown away. Correcting for this oversight alone, without changing any of the other numbers in their calculations, would make cellulosic ethanol a very positive net energy generator.

One should note that the same principle that applies to cellulosic feedstocks like wood would also apply to a cellulosic feedstock like corn stover (the stalk, and leaves of the corn plant). There is a modest difference in that with wood and switchgrass, the feedstock is delivered to the plant for processing. Corn stover, on the other hand, requires separate collection and delivery from the corn grain.[44]

Interestingly, the 1981 report by the advisory panel Pimentel chaired estimated the potential of corn stover as an additional feedstock for making ethanol. It concluded that up to 2.5 tons of corn residue could be removed from about 30 percent of the corn acreage without environmental damage. The net energy ratio of doing this is estimated to be nearly 9 to 1. The study was looking to the possibility of converting the residue into ethanol, but if instead it was used to fuel the ethanol production facility it could generate a very substantial net energy output.[45] Several ethanol facilities are today beginning to use wood waste or, in the near future, corn stover, to replace natural gas to meet their thermal energy needs. The net energy ratio in that situation should be well over 2 to 1.

Conclusions

Investigating the energy balance of renewable fuels, indeed, of all fuels, is a worthy endeavor. What puzzles the agricultural community is why biofuels are singled out for such an intense focus on this one issue.

All researchers agree that manufacturers and farmers are becoming more energy and resource efficient, whether in the process of manufacturing equipment or in the raising of crops or producing ethanol. The trajectory is positive and since it is positive, policymakers should focus on what policies could nurture and extend this positive dynamic.

New energy balance studies should focus on the future, not the past. To our knowledge, only three studies have done this. Two were done by my organization, the Institute

Many paper mills today use the waste wood from the manufacturing process to supply all of the energy to run their operations. We would expect that ethanol facilities that use wood or other cellulosic materials as their feedstock would do the same. It appears that Pimentel and Patzek assume this energy-rich material will be thrown away.

A carbohydrate economy, where plant matter is used as a fuel and industrial material as well as for food and feed and clothing and paper, is one that can transform the face of agriculture as well as manufacturing, and change the nature of the global agricultural debate.

for Local Self-Reliance. These studies offered, for biodiesel and corn to ethanol, three estimates: current national average energy use in farming and processing; current state best and industry best energy use; next generation manufacturing and state of the art (organic) farming. Michael Graboski's 2002 study also included a section on projected energy use.

While Pimentel and Patzek's estimates of the energy balance of corn to ethanol appear to be converging with other studies, their estimates of the energetics of biodiesel and cellulosic ethanol differ drastically from other studies. Too little information was provided in their report to understand why this is so. But it leads us to recall that the methodology that Pimentel uses, when applied broadly, has led him to conclude that the planet cannot photosynthetically sustain more than a third of the present population. Both Pimentel and Patzek have concluded, based on their methodology, that all renewable resources combined cannot provide sufficient energy to meet our needs. These are very controversial conclusions. It may be more fruitful to examine these methodological conclusions rather than focus on the methodology's application to a tiny slice of the energy and renewable resource sector.

Many of us believe that biological sources can play an important, perhaps even a crucial role in our future economies. They can replace petrochemicals and other products made from fossil fuels. When coupled with a high efficiency transportation system primarily powered by electricity, they can displace petroleum as an engine fuel.

A carbohydrate economy, where plant matter is used as a fuel and industrial material as well as for food and feed and clothing and paper, is one that can transform the face of agriculture as well as manufacturing, and change the nature of the global agricultural debate. But moving in this direction will require a coherent, long term strategy that cuts across sectors and borders. That means tackling fundamental questions, such as the ownership structure of the agricultural industry and world trade negotiations.

We can't tackle these fundamental questions if we continue to spend an inordinate amount of time and intellectual resources poring over net energy studies. Here is one place where one ancient bit of advice seems particularly apt. Let's not lose sight of the forest for the trees.

NOTES

1 See David Morris and Irshad Ahmed,*The Carbohydrate Economy: Making Chemicals and Industrial Materials from Plant Matter*. Institute for Local Self-Reliance. Washington, D.C. 1992.

2 David Morris, *A Better Way to Get From Here to There: A Commentary on the Hydrogen Economy and a Proposal for an Alternative Strategy*. Institute for Local Self-Reliance. December 2003. An updated and expanded version will be available in October 2005.

3 See David Morris, Op. Cit. Also see Robert D. Perlach, et. al. *Biomass as a Feedstock for a Bioproducts and Bioenergy Industry: The Technical Feasibility of a Billion Ton Annual Supply*. U.S. DOE and USDA. April 2005. The amount of cellulose available is not limited to the amount that can be grown on land. Much more can be cultivated in our abundant seas and lakes and ponds. Some work on growing algae and harvesting them for their oil content has found a very large potential.

4The term carbohydrates is used loosely here to describe plant matter. Carbohydrates do comprise a major portion of plant matter's constituent parts. But there are non-carbohydrate components as well, like proteins.

5 Often the two crops are planted by the same farmer, since corn farmers often rotate soybeans into the planting schedule.

6 The doubling of oil prices in 1979-1980 inspired the federal government to launch a massive effort to reduce our dependence on imported oil. A primary focus was to promote alternative domestically available liquid transportation fuels. This study focused on the comparative viability of making ethanol from corn and cellulose, and making methanol from coal. *Report on Biomass Energy*. The Biomass Panel, Energy Research Advisory Board. U.S. Department of Energy. Washington, D.C. 1981

7 David Pimentel and Tad W. Patzek, "Ethanol Production Using Corn, Switchgrass and Wood: Biodiesel Production Using Soybean and Sunflower", *Natural Resources Research*. March 2005.

8 "Until recently, Brazil had been the largest producer of ethanol in the world. Brazil used sugar cane to produce ethanol and sugarcane is a more efficient feedstock for ethanol production than corn grain. However, the energy balance was negative…" Pimentel and Patzek, Op. Cit. 2005, citing Pimentel and Pimentel, *Food, energy and society*. Colorado University Press. Boulder, CO. Other researchers come to dramatically different conclusions. IC Macedo, "Greenhouse gas emissions and energy balances in bio-ethanal production and utilization in Brazil," *Biomass and Bioenergy* 14:77-81, 1998. Authors found a positive net energy ratio of 9.2 to l. A more conservative analysis by Marcelo E. Dias De Oliveira, et. al., "Ethanol as Fuel: Energy, Carbon Dioxide Balances and Ecological Footprint," *BioScience*, July 2005. Authors found a 3.7 to 1 positive net energy ratio for ethanol from sugar cane.

9 Cornell University news service. July 5, 2005.

10 The study found: corn requires 29 percent more fossil energy than the fuel produced; switch grass requires 45 percent more fossil energy than the fuel produced; and wood biomass requires 57 percent more fossil energy than the fuel produced; soybean plants requires 27 percent more fossil energy than the fuel produced, and sunflower plants requires 118 percent more fossil energy than the fuel produced.

11 An exception to this rule is a recent extended analysis by Patzek and Pimentel. Tad W. Patzek and David Pimentel, "Thermodynamics of Energy Production from Biomass", accepted by *Critical Reviews in Plant Sciences*, March 14, 2005.

12 The best in-depth individual analyses may be contained in two recent studies. Hosein Shapouri, James A. Duffield, Michael Wang, *The Energy Balance of Corn Ethanol: An Update*. U.S. Department of Agriculture, Economist Research Service. Agricultural Economic Report No. 813. 2002; Michael S. Graboski, *Fossil Energy Use in the Manufacture of Corn Ethanol*. National Corn Growers Association. August 2002. Shapouri's contains an excellent table comparing the key assumptions of the leading studies. Graboski's is a very detailed and transparent analysis of all factors, including an excellent analysis of the embodied energy in machinery.

13 David Pimentel and Marcia Pimentel, *Land, Energy and Water: The Constraints Governing*

Ideal U.S. Population Size. Negative Population Growth. 2004.

14 David Pimentel, Xuewen Huang, Ana Cordova, Marcia Pimentel, *Impact of Population Growth on Food Supplies and Environment*. Presented at the American Academy for the Advancement of Science Annual Meeting, February 9, 1996. Citing David Pimentel, R. Harman, M. Pacenza, J. Pecarsky and M. Pimentel, "Natural resources and an optimum human population", *Population and Environment*. 1994.

15 Tad W. Patzek and David Pimentel, "Thermodynamics of Energy Production from Biomass," accepted by *Critical Reviews in Plant Sciences*, March 14, 2005.

16 Graboski, *Op. Cit*.

17 For farm energy, Pimentel's energy input estimates have dropped from about 60,000 Btus per gallon in 2001 to 38,000 Btus per gallon in 2005. Within the ethanol production facility, the energy input estimates have fallen from about 74,000 Btus per gallon in 1991 to 61,000 in 2005.

18 This ratio differs from Pimentel's own of 0.92. There is a typo in the article in that the table has an overall energy input of 11.9 kcal while the text has 11.4 kcal. The text number seems correct, which would lift Pimentel's ratio to 0.98 or just about a breakeven point.

19 Pimentel's net energy ratio is 0.92 while Ahmed and Morris estimated 2.52. Sheehan, et. al. estimated a net energy ratio of 3.2. Irshad Ahmed, John Decker, David Morris, *How Much Energy Does It Take to Make a Gallon of Soydiesel?* Institute for Local Self-Reliance.1996. For a more in-depth and recent report that arrives at a similar conclusion see John Sheehan, et. al., *An Overview of Biodiesel and Petroleum Diesel Life Cycles*. U.S. Department of Agriculture and U.S. Department of Energy. May 1998.

20 Of the 10 other analyses of the energy balance of corn-derived ethanol done since 1989, 8 arrived at a positive conclusion. Ho, in 1989, estimated a 4 percent net energy loss. He assumed a very low 90 bushel per acre yield. Keeney and DeLuca's study, published in 1992, found a small net energy loss. All others found substantial energy gains. S.P. Ho, "Global Warming Impact of Ethanol Versus Gasoline." Presented at 1989 National Conference, "Clean Air Issues and America's Motor Fuel Business." Washington D.C, October 1989; G. Marland, A.F. Turhollow. *CO2 Emissions From the Production and Combustion of Fuel Ethanol From Corn*. Oak Ridge National Laboratory. May 1990; D.R. Keeney, and T.H. DeLuca, "Biomass as an Energy Source for the Midwestern U.S." *American Journal of Alternative Agriculture*, 1992; David Lorenz and David Morris, *How Much Energy Does It Take to Make a Gallon of Ethanol?* Institute for Local Self-Reliance. 1995; Hosein Shapouri, James A. Duffield, Michael Graboski, *Estimating the Net Energy Balance of Corn Ethanol*. U.S. Department of Agriculture, Economic Research Service. Report No. 721. 1995; M. Wang, C. Saricks, D. Santini. *Effects of Fuel Ethanol Use on Fuel-Cycle Energy and Greenhouse Gas Emissions*. Argonne, IL. Argonne National laboratory, Center for Transportation Research. 1999; Levelton Engineering Ltd. and (S&T)2 Consulting Inc. *Assessment of Net Emissions of Greenhouse Gases From Ethanol- Gasoline Blends in Southern Ontario*. Agriculture and Agri-Food Canada. August 1999; Michael S. Graboski, *Fossil Energy Use in the Manufacture of Corn Ethanol*. National Corn Growers Association. August 2002. Hosein Shapouri, James A. Duffield, Michael Wang, *The Energy Balance of Corn Ethanol: An Update*. U.S. Department of Agriculture, Economist Research Service. Agricultural Economic Report No. 813. August 2002; Kim Seungdo, Bruce E. Dale, Allocation Procedure in Ethanol Production System from Corn Grain, *Journal of Life Cycle Assessment*. 2002.

21 Pimentel and Patzek, *Op. Cit*.

22 S.P. Ho, "Global warming impact of ethanol versus gasoline," presented at the 1989 National Conference on Clean Air Issues, October 1989, Washington, D.C.

23 Citizens for Tax Justice, "More corporate giveaways high on congressional agenda". July 22,1997. CalGasoline, "Ethanol is not a suitable replacement for MTBE," September 17, 2002. Croysdale, D. "Belatedly, DNR concedes our air is clean," *The Daily Reporter*. November 6, 2001. Ben Lieberman, "The ethanol mistake: one bad mandate replaced by another." Competitive Enterprise Institute. 2002. National Petrochemical and Refining Association, "NPRA opposes ethanol mandate; asks Congress not to hinder efforts to maintain supply." September 17, 2002.

24 Andrew Ferguson, *Implications of the USDA 2002 update on ethanol from corn*. The

Optimum Population Trust. Manchester, UK. 2003. Also, *Further implications concerning ethanol from corn*. Draft manuscript from Optimum Population Trust. 2004. Carl Hodge, "Ethanol use in US gasoline should be banned, not expanded," Oil & Gas Journal. September 9, 2002. Also, "More evidence mounts for banning, not expanding, use of ethanol in gasoline," Oil & Gas Journal, October 6, 2003. Youngquist, W. *GeoDestinies: the inevitable control of earth resources over nations and individuals*. National Book Company. Portland, OR. 1997. Youngquist's book was not located. A December 1998 article by Walter Youngquist in the *Electric Green Journal* simply cited Pimentel.

25 To generate 1 million Btus of ethanol, about 100,000 Btus of petroleum are used. One million Btus is equivalent to about 8 gallons of gasoline. One hundred thousand Btus is a little less than the energy contained in a single gallon of gasoline. So to make 8 gallons of gasoline-equivalent ethanol requires only 1 gallon of actual gasoline (or diesel) inputs.

26 This paper focuses exclusively on dry mills for processing corn into ethanol. As noted in the main text, the percentage of ethanol coming from wet mills has shrunk from about 80 percent in 1990 to about a quarter today. More than 90 percent of all new ethanol production is produced by dry mills.

27 As noted in the main text, energy used to irrigate corn had been a contentious issue in earlier studies but the differences between Pimentel and others has narrowed significantly.

28 Pimentel's 2001 study, for example, estimated almost 5 million Btus per acre were used for irrigation. The 2005 Patzek/Pimentel study lowered this to .5 million Btus per acre.

29 Michael Graboski's 2002 analysis was chosen for comparative purposes in part because of its thoroughness and in part because it is close in its conclusions to most other post 1992 estimates.

30 A bushel of corn weighs 56 pounds. A bushel of soybeans weighs 60 pounds. Yields (and energy use) per acre vary dramatically from year to year, largely because of weather conditions. Thus most researchers use a 3-year running average yield.

31 In five studies published between 1991 and 2005, Pimentel's ratio of nitrogen used per bushel of corn yield is: 1.24 pounds per bushel (1991); 1.02 (2001); 0.96 (2003); 0.99 (2005). The variations may be reflective of year-to-year cultivation changes due to weather variations.

32 His 2001 and 2003 estimates were about 33,500 Btus per pound of nitrogen while his and Patzek's 2005 study lowered this estimate to 28,872 Btus per pound.

33 For example, his 2003 study estimated processing energy at 59,000 Btus per gallon. His 2001 study estimated 89,000 Btus. See David Pimentel, "Limits of Biomass Utilization," *Encyclopedia of Physical Science and Technology*, 2001; and David Pimentel, "Ethanol Fuels: Energy Balance, Economics and Environmental Inputs," *Natural Resources Research*, 2003.

34 The 2005 article, after a very brief discussion of the value of distiller's grains adds, "Also note that these energy credits are contrived because no one would actually produce livestock and feed from ethanol at great costs in fossil energy and soil depletion."

35 For example, Cornell's press release and Pimentel and Patzek's summary of their most recent study uses a 27 percent energy loss when making biodiesel from soybeans. In the text of the study itself, but not in the tables, the authors note that if a very low coproduct value were taken, the net energy loss would be cut by more than two-thirds, to 8 percent.

36 Morris and Lorenz, *Op. Cit.* estimated a replacement energy value for carbon dioxide capture of 4,000 Btus per gallon of ethanol.

37 For detailed discussions of allocation procedures see Kim Seungdo, Bruce E. Dale, Allocation Procedure in Ethanol Production System from Corn Grain, *Journal of Life Cycle Assessment*. 2002. Also see Hosein Shapouri, James A. Duffield, Michael Wang, *The Energy Balance of Corn Ethanol: An Update*. U.S. Department of Agriculture, Economist Research Service. Agricultural Economic Report No. 813

38 For ruminants like cows, feeding efficiency is dependent on what is called bypass protein, that is, the protein that bypasses the primary digestion process and is absorbed by the animal.

39 Michael S. Graboski, *Fossil Energy Use in the Manufacture of Corn Ethanol*. August 2002.

Graboski also notes, “On average, it appears that DDGS (dried distillers grains with solubles) is superior to corn and soybean meal in terms of energy content for ruminant feeding. In the case of non ruminants, the energy density is lower because non ruminants have a limited ability to utilize fiber as an energy source.” According to G. Aines, et. al, “Distillers Grains,” *University of Nebraska Cooperative Extension Report MP 51*, 1986, the bypass value of distillers grains ranges from 129 percent to 408 percent of soy meal, with a likely value of 200 percent. Graboski also observes that lysine concentration is low in DDGS compared to soybean necessitating lysine supplements for non-ruminants.

40 Graboski, *Op Cit.* Graboski offers an instructive example. Pimentel’s 2001 study cites a 1975 analysis of embodied energy in a center pivot irrigation system (J.C. Batty, et. al, “Energy Inputs to Irrigation” J. Irrigation and Draining Division. American Society of Chemical Engineering. 1975). Apparently Batty estimated that 67.5 million Btus of energy were required to make a ton of steel. A more recent estimate puts the figure at a little more than 19 million Btus, a 72 percent reduction.

41 As noted above, while the article does note the small net energy loss when the soy meal co-product is taken into account, it publicly emphasizes the larger net energy loss of 27 percent that occurs when co-product credits are ignored.

42 Ahmed and Morris, *Op. Cit.*

43 John Sheehan, et. al., *An Overview of Biodiesel and Petroleum Diesel Life Cycles*. U.S. Department of Agriculture and U.S. Department of Energy. May 1998.

44 See J.E. Atchison and J. R. Hettenhaus, *Innovative Methods for Corn Stover Collecting, Handling and Storing and Transporting*. NREL Report. 510/33893. April 2004.

45 The 1981 study concludes that about 3500 pounds of corn residue per acre could be removed from about 20 percent of the land currently used for corn. If a cover crop were planted at the end of the season to enrich the soil during the fall and winter, then all the residue, about 5000 pounds in all, could be removed from about 30 percent of the land. The report estimate that the energy input required for collecting and transporting the corn residue plus the energy required to replace the fertilizer value of the corn residue at about 16 gallons of gasoline equivalent per acre, while an additional 140 gallons of alcohol per acre could be produced. Biomass Panel, 1981. *Op. Cit.*