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PERSPECTIVES

Biofuels: Thinking Clearly about the Issues

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INTRODUCTION

I believe biofuels are one important manifestation of a much larger trend. It appears we are at a crucial "tipping point". The first decade or so of this century may eventually be regarded as the time when global society decided to stop mindlessly consuming our fossil carbon reserves and started thinking about how to rely more on renewable resources, in this case, renewable carbon-based fuels. To manage the transition to renewable fuels successfully, we will have to understand the issues. I offer some perspectives that I hope will help frame at least some of the related issues and help us think more carefully and clearly about biofuels and other petroleum alternatives.

The fundamental reality that we are facing is presented in **Figure 1**. Biofuels (or any other alternative to petroleum) would not be in the position that they are to make a contribution if the price of oil was still about $20 a barrel, as it was for most of the past three decades. We have been on this same upward trend for oil prices since about 1999, and many in the oil industry now talk about a new floor of oil at about $50–60 per barrel for the foreseeable future with the possibility of spikes to $200 a barrel if major upsets occur anywhere in the world's petroleum-trading system. At $20 per barrel, no petroleum alternatives make economic sense, however much sense they may make for national security or environmental reasons. At $50 plus per barrel of oil, many alternatives make economic sense, including some biofuels and particularly cellulosic ethanol.

I have been working on cellulosic ethanol since about 1976, and for most of that time you could not even pay for biomass, the raw material needed for biofuels, let alone the processing costs to convert it into a fuel when oil was $20 per barrel. But it pays to be persistent, and it pays to have a society in which a few people, at least, have the opportunity to think long-term. We are in a fundamentally different era now. Some biofuels are becoming main stream, and alternatives to biofuels and petroleum are undergoing rapid development. Nearly every major oil company has an active biofuels program.

THINKING CLEARLY ABOUT ENERGY

How do we think clearly about energy? One of the key points here is that we do not use energy per se, but rather energy services, or at least what we value is energy services, not "energy" itself. We do not say, "I think I'll burn a few kilowatt hours of coal today". Rather we say "I can't see; I need to turn on the lights". What was valued was the service, the illumination. And we do not say, "I'm cold, I think I'll burn a little bit of natural gas", but rather, "I think I'll just turn on the heater for a few minutes". When we travel to work, we do not say, "I think I'll burn some fossil carbon in the form of gasoline", but rather just get in our cars and drive to work. It is not energy per se but the services that we receive from energy that we value. The energy services we value are *heat* to keep us warm, *light* (electricity) to let us see and to power thousands of gadgets, and *mobility* to transport both ourselves and our goods around.

We have gotten off track before in addressing issues related to energy by thinking we have an "energy crisis". With regard to our dependence on petroleum, we do not have an energy crisis but rather a mobility, specifically a liquid transportation fuels, problem. There are many good reasons for working on other aspects of renewable energy services (heat and light), but the area of society's greatest current vulnerability is in liquid transportation fuels. That is why biofuels are so important. Biofuels are liquid fuels and they are, by and large, "drop in" replacements for either diesel or gasoline. Because biofuels can be widely produced, some of them in large volumes, and are potentially renewable and carbon neutral, they are essentially the only petroleum alternatives that provide potential large-scale economic, national security, and environmental advantages.

Renewably produced electricity is increasingly a future transportation fuel option for the developed world, but it is much less so for the developing world (e.g., China and India), where

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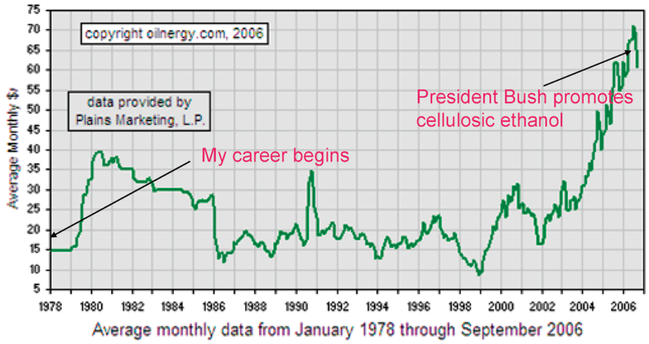

Figure 1. Cost of petroleum 1978–2006.

Table 1. Representative Costs of Energy Provided by Different Energy Carriers, Dollars per Megajoule

energy carrier	energy content[a] (MJ/*X*)	typical market value ($/*X*)	market value ($/1000 MJ)
coal	21500 MJ/ton	40.30/ton	1.87
natural gas	1.086 MJ/ft^3	7.30/1000 ft^3	6.72
petroleum	6120 MJ/barrel	80/barrel	13.10
electricity	3.60 MJ/kWh	0.082/kWh	22.80

[a] EIA 2004 pp 357–386.

the cheap internal combustion engine will be the mainstay of transportation for a very long time. The developing world is also where much of the demand growth for liquid fuels is occurring. As Vinod Khosla, a highly successful venture capitalist and biofuels backer, points out, electric vehicles are "just toys" as far as China, India, and the developing world are concerned. Tata Motors (India) recently announced a new (internal combustion based) subcompact car that will sell for $2500. We are going need liquid fuels for a long time, and biofuels are the only renewable option that I know of to provide these fuels.

BIOFUEL MYTHS: SOME BACKGROUND

There are many myths and misconceptions connected with biofuels that can limit their potential to help end our petroleum addiction. I will discuss briefly several of these myths. One myth is the irrelevant and misleading "net energy" argument (*1*). Net energy in fact offers a very good demonstration of how *not* to think clearly about energy. Many people have heard that ethanol has negative net energy—that it takes more energy to produce ethanol than you get when you burn the ethanol in your car. Net energy is a simple concept with lots of intuitive appeal. We do not like to lose money on our investments. Negative net energy sounds like we are losing our energy investment: less energy out than we put in. But net energy as it has been used in the media and as it is generally understood by the public is both *irrelevant* and *misleading*.

Net energy is *irrelevant* because it falsely assumes that all energy carriers are equally valuable. They are not. **Table 1** shows the cost of energy in dollars per million British thermal units (BTUs, a measure of energy) for several common energy carriers. We are willing to pay about 6 times as much for a million BTUs of petroleum as we are for a million BTUs of coal. Why? Well, try grinding up coal and putting it in your gas tank and see how far you can drive. There is energy in the coal, but it is essentially useless for powering your car. Coal's energy content is simply not as valuable or as versatile as the energy content of petroleum, so it does not command as high a price. Obviously, supply and demand also play a key role in determining prices, as we are seeing with oil now over $100 per barrel.

Net energy is *misleading* because the net energy proponents never compared gasoline's net energy with that of ethanol. Gasoline's net energy is actually worse than that of ethanol, as I will show later. I have critiqued the net energy metric elsewhere (*2, 3*). The interested reader can refer to those accounts for a fuller explanation of why net energy is a very poor, even dangerous metric, to use if we want to think clearly about our oil alternatives.

Another misconception is that biofuels will always be more expensive than petroleum-derived fuels, so we will be stuck in a permanent subsidy for transportation fuels. That might be correct for some biofuels, but it need not happen if we are careful in how we choose among our biofuels. For example, I believe we will be able to produce cellulosic ethanol for much less than $1 per gallon. Any subsidies for biofuels should be temporary and well chosen.

MORE ON ENERGY: ENERGY SERVICES, ENERGY QUALITY, AND STRATEGIC CONSIDERATIONS

Here are some basic facts about the services that we require from energy: heat is largely provided by natural gas and coal. Light is provided by coal, natural gas, hydroelectricity, or nuclear power. Therefore, we have a lot of sources by which we generate electricity and keep warm. But our mobility, our ability to move ourselves and our goods from one place to the other, is almost completely dependent on petroleum. Ninety-seven percent of our transportation needs are provided by petroleum. We are totally dependent on petroleum for mobility. Industrial society literally stops without liquid fuels. Today, that means we stop without petroleum.

Energy has fundamentally different qualities. Another way of saying this is that all BTUs, all ergs, all megajoules, are not created equal. They cannot be perfectly substituted for each other. That is why we value them differently. As **Table 1** shows, a million BTUs of petroleum is worth about 6 times as much as a million BTUs of coal. Thus, one of the fundamental errors in thinking about energy is to simply lump all forms of energy, all energy carriers, as if they were identical. They are not. Any analysis that starts with that premise is wrong at its very core. If you start from a wrong premise, it is almost impossible to come to correct conclusions.

All forms of energy do not have equal strategic importance, either. The United States has huge domestic reserves of coal, hundreds of years of supply at current consumption rates. Natural gas imports are significant, but they are mostly from Canada and Mexico (although we are going to be getting more liquefied natural gas from the Middle East). It is unlikely that Canada and Mexico will cut off natural gas to us—the economies of those two countries are very much tied to our economy. But petroleum supplies have been threatened by exporting states on ideological (nonrational) grounds, and petroleum, like other fossil fuels, is a finite resource. We can argue about when a peak in oil production will occur (*4*), but it is obvious that such a peak must eventually occur. We are burning oil much more rapidly than nature is producing it.

It is simply irresponsible to continue hurtling down this path on which we are completely dependent on a nonrenewable, rapidly disappearing resource, even if it had no national security or environmental drawbacks...as petroleum obviously does. President Bush has said that we are "addicted to oil"...that is true, and it is oil imported from some of the most unstable places on earth. The war on terror may go down in our history as the first war for which we have paid for both sides, as Jim Woolsey, former Director of the CIA has noted. Literally, some of our petro dollars are being shot back at us.

Petroleum dependence undermines our climate security, economic security, and national security, and as bad as oil dependency is for us, it is worse for poor countries without their own oil. You cannot run a modern economy without liquid fuels. If you are an underdeveloped country and do not have petroleum, you have to sell your inexpensive agricultural products on the depressed world commodities market so that you can get a little hard currency to import expensive oil or refined products. You are in the "oil trap", addicted with no way out. Biofuels offer a way out of the oil trap for at least some agriculturally based countries.

DEALING WITH OUR PETROLEUM ADDICTION: ALTERNATIVES TO PETROLEUM

So what can we do to deal with the petroleum problem? We can either decrease demand or increase supply of petroleum alternatives. We should do both. We should implement the best vehicle efficiencies we can, and do it soon, and we should travel smart. The new CAFE standards in the Energy Security Act of 2007 are an important step in the right direction, but better vehicle efficiency alone will not do it all as long as miles traveled continue to increase each year. We also must increase or extend supplies: what are the options there?

We can consider alternative sources of oil. We can process the oil sands of northwestern Saskatchewan and make a very heavy oil that can, with lots of natural gas input, be made into something like petroleum. The United States is importing approximately a million barrels per day of these oil sands products from Canada. Or we can also get an oil substitute from western Colorado oil shale. Or we can make liquid fuels from coal. All of these options are more responsible than continuing to import oil from the world's hot spots, but they are still not great options. All of these options tend to generate lots more carbon dioxide than conventional oil and they are still finite resources—we are postponing but not eliminating the day of transition to more renewable sources. Then there are biofuels, including biodiesel, ethanol from corn, and cellulosic ethanol.

Many myths continue to surround ethanol. The idea that ethanol has a negative net energy is one that I have already mentioned. Net energy is irrelevant and misleading. Second, there is the myth that ethanol's going to drive up food prices. Fuels derived from grains or oilseeds may have a small impact on food prices, but low-cost biofuels will help keep food prices low by reducing transportation costs. For example, the cost of corn affects the price of a few items in the store, but the cost of fuels to move food products around affects the price of literally everything we eat (*5*). I believe, however, that cellulosic ethanol is going to end up reducing food prices because it will reduce animal feed costs and simultaneously help keep transportation costs down. More about this later.

Another myth is that ethanol is bad for the environment. A responsible society will consider its alternatives and conclude that, among the alternatives (ethanol is presently the only real renewable alternative to gasoline), ethanol has the fewest negative impacts and the most positive impacts. Ethanol is not perfect: there is no perfect fuel. But gasoline is even less perfect. So, if we are to make rational choices, we have to know what our options are and compare the good and bad points of each.

Finally, there is the myth that ethanol will always cost more than gasoline. In fact, ethanol from corn costs about $1.20 per gallon to produce with corn at $2 per bushel and about $1.65 a gallon with corn at $3 a bushel. Without subsidies, at current corn prices of around $3.25 per bushel corn, ethanol as a premium (high-octane fuel) is competitive with oil at about $60 per barrel (*6*). Much has been written on the subsidies (now about $0.50 per gallon) that corn ethanol receives, but it is rarely pointed out that gasoline has also been subsidized, both directly by favorable tax treatment and a host of other incentives and indirectly by military expenditures. I will not go into the subsidy issue here, but please recall the importance of making appropriate comparisons. A comparison between ethanol and gasoline is not a comparison between a subsidized fuel (ethanol) and an unsubsidized fuel (gasoline), but rather between two subsidized fuels.

When the technology for producing ethanol from cellulosics matures, and it is going to happen sooner than people think, ethanol will cost around 70 cents a gallon to produce (*7*). This estimate of ethanol production cost includes a 12% return on investment. Cellulosic ethanol will then be competitive with oil at about $25–30 per barrel. It is not likely we will see much oil produced at those prices, except perhaps from the Saudis, the current low-cost producers of oil. The low-cost oil is largely gone, which is why we are in this time of transition, and mature cellulosic ethanol will be able to compete very well with higher cost oil.

COMPARING BIOFUELS AND PETROFUELS

There are three primary fossil fuels: coal, natural gas, and petroleum. Worldwide, about 40% of primary energy needs are met through petroleum. (Coal and natural gas provide about 30 and 20%, respectively.) We are hugely dependent on petroleum. Petroleum, the liquid fossil fuel, is by far the fossil fuel through which we are most vulnerable as a society. It is critical to remain focused on liquid fuels and on petroleum because of that vulnerability. It is important to reduce greenhouse gases and transition away from fossil carbon, but we have to think clearly and make the appropriate comparisons. For mobility, the comparison for any biofuel should be with petroleum products: gasoline and/or diesel.

Fortunately, we can make some comparisons using data published in 2006 by Farrell et al. in *Science* (*8*). Let us do the net energy comparison first. The Farrell data [in Figure 2 of *Science* paper (*8*)] summarize the fossil energy (and other inputs) required to make 1 MJ of gasoline or 1 MJ of ethanol (from corn or from cellulosics). From their data, ethanol's net energy is its energy value minus the sum of all the fossil energy inputs (petroleum, coal, and natural gas) required to make ethanol. On the basis of 1 MJ of ethanol produced, net energy is calculated as $1.0 - (0.04 + 0.28 + 0.41) = +27\%$. By comparison, gasoline's net energy is $1.0 - (1.1 + 0.03 + 0.05) = -18\%$. Gasoline's net energy is *worse* than ethanol's. (As it turns out, the net energy of electricity production from coal or natural gas is even worse than that of ethanol or natural gas...about −200% or so.) Are we going to turn off the lights and stop using petroleum because electricity and gasoline have negative net energies? Of course not. The net energy metric is simply irrelevant and should not be applied to biofuels or to gasoline or to electricity.

Although net energy remains an irrelevant concept, the comparison between ethanol and gasoline is still helpful. We could have been saved much confusion and trouble if the net energy proponents had ever taken a few minutes to compare ethanol's net energy with the net energy of gasoline. Comparisons between our realistic alternatives are absolutely essential for good decision-making. Therefore, what are some useful comparisons? I suggest that two metrics relevant to (1) national

Table 2. Energy Inputs[a] and Greenhouse Gas (GHG) Outputs[b] for Various Fuels

	petroleum	natural gas	coal	other	total	GHG emissions
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	0.08	0.02	−0.02[c]	0.02	0.10	11

[a] Inputs of various energy carriers in MJ per MJ of fuel produced. [b] Greenhouse gas outputs in kg of carbon dioxide equivalents per MJ fuel produced. [c] Credit for coal not consumed due to process residues being burned to provide heat. Data from Figure 2 of Farrell et al. (*8*).

security and (2) climate security be used to compare biofuels with petrofuels. Fortunately, the Farrell data (summarized in **Table 2**) also allow us to make these comparisons.

The amount of oil used to make gasoline versus the amount of oil required to make ethanol (we could call this the petroleum replacement ratio) is an indicator of how much any petroleum alternative reduces our petroleum dependence. From the Farrell data, it takes 1.1 MJ of petroleum to make 1 MJ of gasoline, whereas 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 unit of fuel energy delivered to the customer is huge, approximately (1.1–0.04)/0.04 or about 27-fold. Therefore, if your new car gets 30 miles per gallon of gasoline, on ethanol you are effectively getting (30 × 27) or 810 miles per gallon of oil used. We have *no* other alternative liquid fuel that so greatly increases miles per barrel of oil. This may explain why petroleum companies are beginning to support ethanol and other biofuels. They may see it as a way of stretching their reserves of oil far into the future.

The second suggested metric, the climate security metric, has to do with the reduction in greenhouse gases per unit of fuel energy delivered to the user. A petroleum alternative is not going to help us achieve climate security if it does not significantly reduce greenhouse gases per unit of fuel produced. Corn ethanol currently achieves modest greenhouse gas reductions of about 18% compared to gasoline (Ethanol Today scenario), but new agricultural technologies and new biorefinery operations are reducing greenhouse gas emissions. Cellulosic ethanol will reduce the life cycle greenhouse gas emissions per kilometer driven by almost 90% compared to gasoline—a huge improvement (*8*).

We should mention a few more relevant environmental aspects of ethanol, emphasizing corn ethanol. Soil erosion caused by corn is declining, but it is still an issue. Overall, soil erosion has fallen by about half in the past 20 years or so. There is declining fertilizer use per bushel and declining total use of pesticides and herbicides on corn. It is true that we will probably be planting corn where we should not, given the increased demand for corn for ethanol production. But note again, there is a 95% reduction in petroleum use per mile driven on ethanol, so on this important national security issue of petroleum use, corn ethanol is a big winner—we get a lot of fuel for not much oil consumed. Properly done, cellulosic ethanol can be produced with less erosion, fertilizer, and pesticide inputs than corn. Cellulosic ethanol, done right, can also sequester large amounts of carbon in the soil and reduce nitrogen-related environmental impacts (*9*).

FOOD VERSUS FUEL

Now let us consider the contentious and confusing food versus fuel issue. About 75% of corn consumed is fed to animals, not directly to people. Around 10% of corn goes directly for human consumption, mostly in the form of high-fructose corn syrup and soft drinks. (Maybe we get too much of that kind of "food" anyway.) It is true that pork and poultry prices will increase somewhat as a consequence of increased corn prices...most estimates are that the cost to the consumer will increase about 5–10% due to higher corn prices (*10*). We are probably in a new era of corn in the $4 a bushel region. I think that is a generally a good thing, not the disaster that has been portrayed by some who seem almost hysterical about the issue.

At the end of World War II, corn cost $1.83 a bushel. Does anyone want to go back to the wage rates of that era? Does anyone realistically expect that we should be able to buy a car now for what we were able to purchase a car in 1946, or in 1980 when corn was also $2 per bushel? Then why should corn forever be around $2 per bushel? Largely because of subsidies ("counter cyclical payments") we were stuck for a long time at very low-priced corn. That was good for certain segments of society, agribusiness concerns, and animal feeders, but it was not very good for much of rural America, and it also was not good for poor, agricultural societies around the world. More about that in a moment.

Food grains are primarily wheat and rice. Corn is less important as a food grain but does have a key role as an animal feed. Soy is not a feedstock for ethanol, but for biodiesel, which I do not deal with here. Soybean oil is important in foods, but the protein meal from soybeans is almost entirely consumed by animals. Again, there are no simple sound bites here as far as food and fuel are concerned. It is complicated.

So will people go hungry because of biofuels? This is a controversial issue, but it helps to do some basic math to look at the underlying realities. If we were eating properly, we would consume about 2000 calories and 50 g of protein per person per day. At 300 million people in the country, we require about 205 trillion calories and about 5 trillion grams of protein per year. The three major U.S. crops alone, corn, soy, and wheat, produce 1300 trillion calories and 51 trillion grams of protein per year—about 6 times as much as our basic calorie needs and about 10 times as much as our basic protein needs. (Americans tend to be overweight, but not by that much!)

So what are we doing with the rest of these crops? The answer is that they are going to feed animals. Even most of our grain *exports*, particularly corn, go to feed animals. Our animal population is consuming about 6 times as many calories as our human population and about 10 times as much protein (*11*). Therefore, our land resources or crop acreage go predominantly to produce animal feeds...not human food. In particular, ruminant animals, dairy and beef cattle, consume about 70% of all calories and proteins fed to livestock. Thus, the issue in biofuels is not so much competition with human food, at least in the U.S. context, but rather with animal feed. This analysis would hold, more or less, throughout the developed world. Wealthy societies use land to grow animal feed and then consume animal products: meat, milk, eggs, cheese, etc.

I also believe that a careful, unemotional examination of the facts leads one to conclude that somewhat higher grain prices as a result of biofuels demand, is largely a good thing for the world's poor. As I mentioned earlier, the United States is always challenged in international trade talks to stop subsidizing our agricultural production, to stop exporting artificially cheap grain. If low grain prices are such a great thing for the world's poor, why do their governments ask us to stop making grain cheap? The answer is that by subsidizing grain for so many years to make it artificially less expensive, we have undermined their rural economies. We have helped *to keep* poor people poor. About 80% of those who are "food insecure" (at risk for loss of food supplies) in the world live in rural areas (*12*). If the value of agricultural products rises (for example, because of increased biofuel demand), then more wealth will flow to rural areas around the world. That is a very good thing. Thus, these areas will be *less* at risk of starvation and a whole host of other problems. Bluntly put, they will have more money to enable them to deal with their problems. In contrast, the urban poor (perhaps 20% of the world's total of food-insecure people) are probably somewhat endangered by rising grain prices. However, as their overall society becomes wealthier, it is probably easier for those societies to care for the urban poor or for those poor to find employment. In short, we have got to be careful and thoughtful about these "food versus fuel" issues and not just react with blind emotionalism. Most of us rejoice when we get a raise. Why should we react with near hysteria because the world's farmers get a raise because of increased biofuel demand?

CELLULOSIC ETHANOL AND THE FOOD VERSUS FUEL ISSUE

Focusing now on cellulosic ethanol or other cellulosic biofuels, I believe food production (actually animal feed production) and biofuels will be beneficially linked through the cellulosic biorefinery (*13*). All cellulosic materials have calories "locked up" in their plant cell walls. The key point is that the processing required to unlock these sugars to make cellulosic ethanol can also unlock the sugars for ruminant animal feeds. For that reason, many cellulose-based biorefineries can also be in the animal feed business. This is one important lever to increase food (animal feed) output while simultaneously producing biofuels. In addition, animal feed protein can be coproduced with cellulosic ethanol, particularly from the perennial grasses (*14*). This is a second important lever to increase food (animal feed) output along with biofuel production. I do not have enough space to discuss the potential for animal feed coproduction with cellulosic biofuels, but it is a really important issue.

Thus, we will have a new flexibility in our use of land resources to provide both fuel and animal feed. We can supply our ruminant animals (which consume most of the calories and protein that our land produces) with more digestible cellulosic materials, materials that have been made more digestible by the same biorefining as used for ethanol production, and with plant protein. Land will be used more efficiently to generate food (animal feed) and fuel. There are very interesting opportunities to integrate animal feed, which is primarily protein and calories, with fuel production. I have been working on these ideas for 25 years (*14, 15*), but this is not the place to go into these possibilities in depth.

CELLULOSIC BIOFUELS: FEEDSTOCK AND PROCESSING COSTS

With regard to cellulosic biofuels, here is the fundamental reality again. Oil prices are higher than they have ever been on a sustained basis, and they are not likely to stay down in the future. For large-scale chemical processing for fuels, or in fact any commodity, the only things that matter are the cost of raw material and the cost of processing. **Figure 2** shows the cost of oil in dollars per barrel plotted against the cost of biomass in dollars per ton. We can produce a lot of grass and other cellulosic biomass at $50 a ton and supply it to a biorefinery. The heavy black diagonal line is where the cost in dollars of energy content of the biomass is equal to the cost of the energy

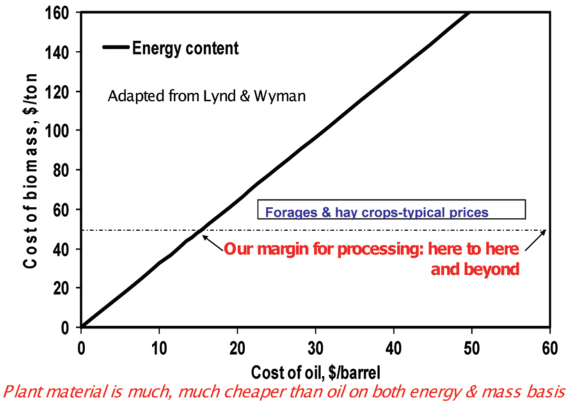

Figure 2. Cost of energy in biomass versus cost of energy in oil.

content of oil. The energy equivalent of biomass at $50 per ton is oil at about $15 per barrel.

When oil was $15 a barrel, the cost of biomass alone made biofuels from cellulosics uncompetitive, but now we are in a different era: oil is around $100 a barrel, and thus quite a margin for processing the biomass to liquid fuel products exists. We have a financial "window" for upgrading the energy content of the cellulosic material by processing it to a liquid fuel. The processing steps can be broadly outlined as *pretreatment* (to open up the cell wall materials for enzymatic attack), *enzymatic hydrolysis* (to convert the cell walls to sugars), and *fermentation* (to convert the sugars to ethanol or other biofuels).

A key point is that about 70% of the total mass of plant material is sugars, again, locked up in cellulose and hemicellulose, as five- and six-carbon sugars (*16*). It turns out that the ethanol fermentation is remarkably good (97% efficient) in converting the energy content of sugars into a liquid fuel, ethanol. If we can efficiently unlock the energy content of sugars (by pretreatment and enzymatic hydrolysis) and then ferment the sugars efficiently to ethanol, we can then significantly lower the cost of biomass processing. Because we also have very competitive biomass raw material prices compared with oil, we can then reasonably expect to build a viable cellulosic biofuel industry.

Reducing processing costs has been done for lots of products (from penicillin to potato chips to computer chips), including products made from oil: gasoline and diesel. In the future, as oil prices continue to rise, the cost of raw material, the biggest portion of the cost of all products made from oil, will rise as well. (This is why gasoline prices swing so wildly with every fluctuation in crude oil prices.) Oil consumption also undermines climate security and national security, as we have seen. Biofuel production is one way of getting ourselves and the rest of the world out of the petroleum trap.

What we have already done to reduce the cost of petroleum refining, we can do again to reduce the cost of biomass refining to fuels. Currently, the cost of processing is relatively large for cellulosic ethanol, about 70% of the cost of making ethanol, with 30% the raw material cost (*17*). There is a lot of opportunity to lower the processing cost. We need pretreatment to open up the sugars and inexpensive enzymes to make those sugars available for fermentation. We also need fermentation organisms to produce the ethanol (or perhaps other biofuels such as butanol). These biomass processing costs can decrease significantly, and reducing the processing costs deserves a high national priority. The United States is spending a billion dollars a day for oil imports. We cannot afford the peril to our national security that our oil addiction causes. If we can sufficiently reduce the cost of biomass processing to fuels, we can enter a new era: domestically produced fuels, large environmental improvements, and opportunities for rural and regional economic development.

REDUCING BIOFUEL COSTS: THE EXAMPLE OF BRAZIL

We have learned from experience that if you focus on reducing processing costs, you can generally find a way. This has been done with semiconductors, which were once very expensive to make but now the processing cost is low, and with penicillin and with so many other goods. As long as the raw material cost is attractive compared to alternatives, we can generally figure out ways to get the processing costs down. The costs of oil as a raw material were so low for so long that nothing could compete with oil. Now the cost of energy in biomass is less than the cost of energy in oil, and our challenge is to get the processing costs down. Brazil provides an example of how this can be done.

Over 25 years ago, Brazil decided to make a liquid fuel, ethanol, from cane sugar. In the years since, they dropped the cost of making ethanol from sugar in Brazil by a factor of about 3. It is now less expensive, on an equal energy basis, to make ethanol from cane sugar in Brazil than it is to make gasoline. Biofuels can and will be less expensive than petroleum if we pursue the right biofuels and stick to our task.

We do not have the climate to grow large amounts of sugar cane in the United States, but we can grow lots of cellulosic biomass—crop residues, wheat straw, rice straw, corn stover (the residue left behind after the corn grain has been harvested), etc. And then there are energy crops: including grasses such as the native American prairie grass switchgrass and woody materials such as willow and poplar planted to be harvested for their energy content, not for food or feed value. There is also a less well-known plant, *Miscanthus*, which can accumulate up to 20 tons of dry matter per acre per year as is. We have not yet turned our agricultural research establishment loose and asked that establishment to "grow as much grass as you can per acre—big rewards and huge markets to the winners, have at it!" So there is lots of upside potential for energy crop yields.

EXAMPLE OF COST REDUCTION FOR CELLULOSIC ETHANOL

In conclusion, I will provide some details about the processing of biomass, including pretreatment and enzymes. I will show one example from my laboratory of the kind of targeted research that might go on to reduce the cost of biofuels. Plant biomass evolved to be difficult for microorganisms to take apart. As a result, trees can last thousands of years, and even straw can hang around for years. We have to get around the barriers Mother Nature has placed in the way of taking apart cellulosic biomass.

My laboratory uses a process called ammonia fiber expansion (AFEX) to remove these barriers (*18*). In the AFEX process, biomass plant material is cooked with hot concentrated ammonia under pressure. When the pressure is released, the ammonia evaporates and is recovered, and the treated biomass is then more available for conversion to sugars. Ammonia treatment tends to minimize sugar degradation that occurs in acid pretreatments. About 98–99% of the ammonia is recovered; the remainder can serve as a nitrogen source downstream for fermentation organisms.

An economic analysis was done of some of the different pretreatments that are being considered for biomass conversion (*19*). The minimum ethanol selling price (MESP) based on the

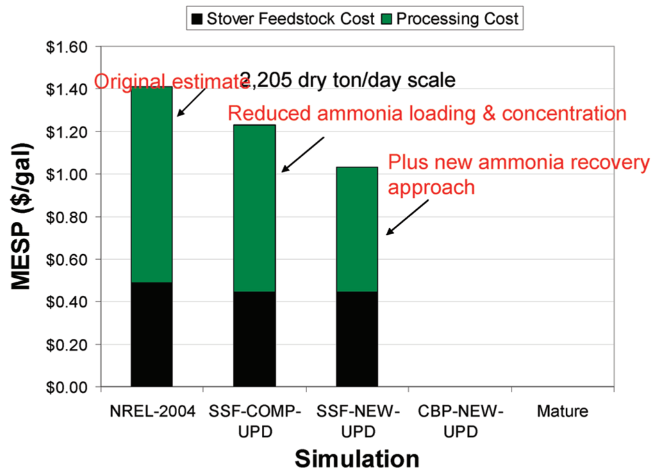

Figure 3. Cost reductions in AFEX processing of biomass.

AFEX pretreatment was about $1.40 per gallon. This comparison showed that, to reduce the costs of the AFEX pretreatment, we needed to use less ammonia (fewer pounds of ammonia added per pound of biomass going through the system), and we needed to recover the ammonia at <100% ammonia concentrations. This involves managing the water in the system, because some of the water in the biomass evaporates along with the hot ammonia when the pressure is released. Finally, we needed a less capital-intensive way of recovering the ammonia (that is, less expensive ammonia recovery equipment and less energy involved in recovering the ammonia). My students and I went to work and we reduced the processing costs. We learned to use less ammonia and to recover the ammonia at lower (<100%) concentrations. The original MESP was $1.40 a gallon, and these two improvements took about 20 cents a gallon off the estimated price, to about $1.20 a gallon. With our colleagues, Dr. Lee Lynd and his associates at Dartmouth College, a novel approach was then taken to recovering ammonia, one that uses a cold water quench to recover recycled ammonia rather than using compressors. That development takes off about another 20 cents a gallon, resulting in around a dollar a gallon estimated ethanol production costs.

A process called consolidated bioprocessing (CBP, in which enzyme production and fermentation are combined in a single organism) provides yet more opportunities for improvement and cost reduction. We are now working with developers of these organisms to integrate CBP organisms into our overall system. Combined with pretreatment improvements, CBP can get us to about $0.80 a gallon ethanol production costs. The ultimate goal is to have a "mature" process by which the cost of processing will be about 30% of the product cost, as with oil today and with semiconductors today, and the cost of raw material at about 70% of the cost to manufacture. That will result in ethanol production costs of about $0.60–0.70 a gallon, including return on investment (**Figure 3**). This can happen much sooner than most people believe. I believe that we will be making tens of billions of gallons of ethanol and perhaps other biofuels from cellulosics in the near future. This is absolutely going to happen, and it is going to happen more quickly than most people realize.

SUMMARY

I hope this brief treatment of the subject helps to explain my optimism that cellulosic biofuels will actually cost less, much less, than fuels from petroleum. Cheap biofuels are going to change the world fundamentally. They will change agriculture fundamentally. They will change our interaction with the environment fundamentally. I believe that, if we are wise and careful, we can shape this enormous transition to simultaneously improve the world's economic and environmental security and provide greater prosperity for rural areas around the world. We need to devise appropriate metrics and policies to ensure that biofuels achieve their potential for economic and environmental improvements. Thus, inappropriate and misleading metrics such as net energy must be discarded. This is a critical time of transition. Our society needs to think clearly and carefully about these interrelated issues.

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The TOC photograph is reprinted with permission of Kurt Stepnitz, Michigan State University Communications.

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