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Transportation Fuels from Biomass: An Interesting, But Limited, Option

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Foreword

"America is addicted to oil," the President proclaimed in his State of the Union speech on January 31, 2006. Since then, and with the continued high prices of crude oil and gasoline, there have been a flood of proposals, each promising energy independence for the United States. Foremost among these are calls to make greater use of ethanol.

The Department of Energy's Energy Information Administration projects that the United States will need almost 50% more energy in 2030 as we consume today. It also projects that even with more rapid advances in technology, fossil fuels—oil, gas, and coal—will continue to provide 80% of our energy needs. A similar global forecast has been by the International Energy Agency.

The United States is a mobile society and will remain one. For this reason as well as reasons of economic resiliency and national security, it is important that we explore the potential of all energy sources, especially those that can provide abundant and affordable transportation fuels.

Using the products of American agriculture or other sources of biomass for transportation fuel, such as processed vegetable oil, have garnered the most attention, with the President even singling them out for special emphasis in his 4-point energy plan of April 2006. While biomass-derived fuels for transportation offer a rich set of options for substituting petroleum-based gasoline, they are not without their own challenges. The barriers to rapidly expanding the use of ethanol are serious and deserve serious consideration. For instance, the Energy Information Administration forecast assessments show only limited growth in the use of ethanol even under assumptions of high oil prices through 2030. Today, ethanol consumption represents 2.8% of the gasoline we consume. By 2030, daily consumption of gasoline could be as much as 525 million gallons. The U.S. produced only 4 billion gallons of ethanol last year and is projected to produce about 7 billion gallons by 2012. In addition to technical considerations, far greater use of ethanol would require enormous investments in plants, transportation and storage.

The technical capacity to produce gasoline from biological sources predates the automobile. Yet, this method was abandoned when it became apparent that petroleum was a cheaper and more effective source of fuel. Cost differences and the technical immaturity of the more advanced techniques remain significant barriers to expanded use. To date, the recent national discussion, and subsequent media coverage, of a shift to ethanol has not provided a detailed assessment of these costs and technical issues.

This paper reviews those factors, placing them in a context that allows for a fair assessment of their contribution to America's energy future. As a nation, we should rise to challenges but also be mindful of the dangers of exaggerated expectations.

— William O'Keefe, Chief Executive Officer
Jeff Kueter, President

Executive Summary

The recent increase in oil prices, combined with on-going concerns about both oil supplies and carbon dioxide emissions from fossil fuels, have focused attention on the potential use of biomass to produce transportation fuels. The Marshall Institute's review of available information leads us to conclude that conventional and unconventional oil reserves are adequate for many decades to come, and that improved technology will increase our ability to extract these resources. For example, the Department of Energy recently announced that new, carbon dioxide enhanced oil recovery technology could add 89-430 billion barrels to the U.S recoverable oil reserves, which currently stand at 21.6 billion barrels. None the less, we support research on biomass' potential; society benefits when all technological options are fully evaluated and decisions can be made on an informed basis.

Biomass offers a rich set of options for manufacturing substitutes for both gasoline and diesel fuel. Some of these, such as the production of ethanol as a gasoline replacement, or processed vegetable oils (biodiesel) as a diesel fuel replacement, are well-known; others, such as the gasification of biomass to produce either hydrogen for fuel cell vehicles, or synthetic hydrocarbons for conventional vehicles, are more speculative.

While use of ethanol as an automotive fuel dates back to the late 19th century, its use was discontinued after World War II, when abundant supplies of cheap, high octane gasoline became available. Interest in the use of ethanol (a high octane component) as an automotive fuel was revived in the late 1970s as a result of higher crude oil prices and the phase out of lead octane enhancement additives.

In the U.S., ethanol for fuel use is manufactured by fermentation of corn. This technology is well-known, since it has been used for millennia to produce alcoholic beverages. However, it is an energy-intensive technology. Until the mid-1990s, it took more fossil fuel energy to produce ethanol from corn than was contained in the ethanol product. Improvements in both agricultural techniques and ethanol processing have changed the energy balance. Using current agricultural and processing technology, ethanol contains about 36% more energy than the fossil fuel used to produce it. Since most of the fossil fuel energy to produce ethanol comes from natural gas or coal, ethanol use has a larger impact as a substitute for oil.

Since it is currently produced from corn, U.S ethanol supply is limited to a few percent of the demand of gasoline. Ethanol represented only 2.4% of the U.S. gasoline pool in 2004. In its reference case, the Department of Energy's Energy Information Administration (EIA) projects that this share could rise to 5.6% of the gasoline pool by 2030. In its high oil price case, EIA projects ethanol providing 7.3% of the gasoline pool in 2030. While corn-based ethanol has a role to play as a transportation fuel, it is far from a panacea and will not free the U.S. from dependence on either fossil fuels or oil imports. Ethanol currently enjoys a $0.51/gallon subsidy, but even with this subsidy, and current high oil prices, it is more expensive than gasoline.

Price of Corn-Based Ethanol vs. Price of Gasoline

		$/gal
Cost of ethanol in 10 Midwestern states on March 22, 2006		$2.34 – $2.50
Subsidy (American Jobs Creation Act of 2004, PL 108 – 357)		$0.51
Net cost of ethanol		$1.83 – $1.99
Energy Content (BTU/gal):	Gasoline	125,000
	Ethanol	76,000
Gallons of ethanol per gallon gasoline equivalent =		1.6
Price of ethanol per gallon gasoline equivalent		$2.92 – $3.18
Retail price of regular grade gasoline in Midwest, March 20, 2006		$2.50

Since significant amounts of coal and natural gas energy are needed to produce corn-based ethanol, and their prices tend to follow oil prices, ethanol's cost will tend to increase with rising oil prices.

Importing ethanol produced from sugar would increase supplies. However, imported ethanol is subject to a $0.54/gallon tariff, which eliminates any economic benefit for its use. While importing ethanol would reduce imported oil demand, it would not increase U.S. energy self-sufficiency.

Research has been underway for more than 20 years on the production of ethanol from cellulose. This would greatly increase the potential supply of domestic ethanol, since corn wastes, wheat straw, wood byproducts, and specially grown crops, such as switch grass, could be used as feedstock. While there is progress on this technology, it is currently far too expensive for commercialization.

Vegetable oils and animal fats can be processed into esters, known as biodiesel, which can be used as diesel fuel. U.S. biodiesel production totaled 75 million gallons in 2005, about 0.2% of the diesel fuel pool. Currently biodiesel enjoys a $1.00/gallon subsidy, but even so, it is more expensive than conventional diesel fuel. Since it requires fresh or used vegetable oils (e.g. soybean oil) and animal fats (e.g. tallow) as feedstock, its potential supply is highly limited. Biodiesel's potential is so small that EIA did not consider the impact of its use in its 2006 Annual Energy Outlook.

It is possible to gasify biomass to produce either hydrogen for fuel cell vehicles or a syngas that can be converted into synthetic gasoline or diesel fuel for use in conventional or hybrid vehicles. Gasification of biomass to produce hydrogen, combined with capture and storage of the byproduct carbon dioxide, could result in *negative* carbon dioxide emissions. This technology is described in detail in the recently issued IPCC (Intergovernmental Panel on Climate Change) Special Report on Carbon Dioxide Capture and Storage (IPCC, 2005). While all of the individual components of this technology package have been demonstrated on a commercial scale, the entire manufacturing process has not been demonstrated, making its economics speculative. They appear to be in the same range as other proposed technologies for reducing carbon dioxide emissions. Commercial-scale demonstration of biomass gasification, combined with carbon dioxide capture and storage, is unlikely in the short-term as both governments and industry are currently more interested in demonstrating this technology package using fossil fuels as feedstock.

While it is clear that biomass-derived fuels have a role to play in the transportation sector, that role currently is limited by technological maturity, cost, and supply. Studies at both the U.S. and global levels indicate that the technical potential for sustainably-grown biomass is insufficient to provide the energy required by the current transportation system, let alone the significant increase in transport energy demand projected for the future.

Introduction

The recent increase in oil prices, combined with ongoing concerns about both oil supplies and carbon dioxide emissions from fossil fuels, has focused media and political attention on the potential for using biomass as an energy source. As is usually the case when such attention is focused on a new topic, facts, misinformation, wishful thinking and exaggeration get mixed together, and confusion abounds. The goal of this report is to present some of the facts about, and define the areas of controversy over, the use of biomass to produce transportation fuels.

Biomass is humanity's oldest external source of energy, dating back to prehistoric man's first use of fire. And biomass is still an important part of the world's energy system; the use of "traditional" biomass—charcoal, firewood, and animal dung—in developing countries accounts for almost 10% of the world's primary energy supply. However, because the use of these traditional biomass fuels often generates unhealthy levels of indoor air pollution, and is damaging to the environment unless collection of firewood is carefully controlled, efforts are underway to replace them with modern fuels.

Some industries, particularly the pulp and paper industry, depend heavily on wood wastes as an energy source. The use of methane from landfills, which is generated from the decay of biomass, is growing. Biomass is also used in conjunction with fossil fuels for electricity generation in "waste-to-energy" projects. These are niche applications, which depend on the biomass having no other commercial value and being in close proximity to the application. With the exception of the use of landfill methane, the potential for expanding these applications is small.

While biomass can be combusted to provide heat and power for electricity generation or industrial applications, the current interest in biomass is largely focused on its potential to replace petroleum as a source for transportation fuels. Some see this as a critical need since they believe that the production of conventional oil will peak within the next decade, then decline (Campbell, 2003), leading to major economic disruptions. The Marshall Institute rejects this idea for two reasons:

1. The best evidence indicates that oil reserves are adequate for decades to come, and that improved technology will increase our ability to recover oil from known resources (OPEC, 2006). For example, the Department of Energy recently announced that new carbon dioxide enhanced oil recovery technology could increase U.S. recoverable oil resources by 89-430 billion barrels (DOE, 2006). Current proven U.S. oil reserves are only 21.6 billion barrels.

2. Conventional oil is only one of the fossil fuel resources that can be used to supply transportation fuels. The petroleum industry is already using heavy oil from Venezuela and oil sands from Canada to supplement conventional oil resources. Canadian oil sands reserves are estimated at 178 billion barrels, second only to Saudi Arabia's oil reserves (Government of Alberta, 2004). Reserves of these unconventional oil resources are also available in other countries, ensuring many more years of oil supply (WEC, 2001).

Despite the fact that the world is likely to have ample supplies of conventional and unconventional oil for many decades, we still should examine biomass' potential. Society benefits when all technological options are fully evaluated and decisions are made on an informed basis. Current and past biomass research has produced a rich set of options for manufacturing substitutes for both gasoline and diesel fuels, some of which are well-understood, while others are still in the conceptual stage. The biofuels manufacturing process also offers the potential for producing a variety of biomass-based chemicals, just as petroleum refining provides the potential for production of petrochemicals. However, the production of chemicals from biomass is beyond the scope of this paper.

Most of the discussion of biomass-based transportation fuels has focused on the use of either ethanol as a replacement for gasoline or processed vegetable oil (biodiesel) as a replacement for conventional diesel fuel. These two topics are discussed first, followed by a discussion of gasification, a more speculative approach for converting biomass to transportation fuels.

Ethanol from Corn as a Gasoline Replacement

The use of ethanol, the alcohol contained in alcoholic beverages, as an automotive fuel dates back to the 19th century. Henry Ford's first motor car, introduced in 1896, was designed to run on ethanol, and his first Model T, introduced in 1908, was a flexible fuel vehicle that could run on gasoline, ethanol, or a mixture of the two. Until the end of World War II, small amounts of ethanol were blended into gasoline to increase either octane or volume. After the war, use of ethanol in gasoline disappeared due to the availability of abundant supplies of cheap, high octane gasoline. However, interest in using ethanol (a high octane component) as a gasoline blend stock revived in the late 1970s as a result of higher crude oil prices and the phase out of lead octane enhancement additives.

The Clean Air Act Amendments of 1990 required that reformulated gasoline, used in about 40% of U.S. market, contain 2% oxygen. This action, combined with a tax subsidy for ethanol, created another impetus for ethanol's use—ethanol contains one atom of oxygen per molecule (EIA, n.d.)—although the automotive emission reduction requirements of the Clean Air Act could have been achieved without an oxygen mandate (EPA, 2005). The Energy Policy Act of 2005 repealed the Federal oxygen requirement for reformulated gasoline. However, many refiners are expected to continue using ethanol in gasoline because it is a high octane component (EIA, 2006a). In addition, some states (e.g. Hawaii) mandate the use of oxygen and/or ethanol in gasoline (The Hawaii Channel, 2006).

Ethanol-gasoline blends are characterized by the percent by volume of ethanol that they contain. Conventional vehicles can use blends containing 15% or less ethanol in gasoline without modification. If more than 15% ethanol is used, engine modifications are required to compensate for the changes in fuel properties. When these modifications are made, the vehicles are designed to operate on either gasoline or ethanol-gasoline blends. Such vehicles are known as flexible fuel vehicles (FFVs), many thousands of which have been manufactured. The highest concentration of ethanol that can be used in an FFV is 85%; 15% gasoline is necessary to provide sufficient volatility to start the engine. Specially designed vehicles can use higher concentrations of ethanol.

The simplest method for producing ethanol is fermentation of sugar. Starches from grains or potatoes can also be used for fermentation, provided that they are first converted to sugars by treating them with an enzyme know as amylase. Since the fermentation of sugars and starches has been practiced for millennia to produce alcoholic beverages, its technology is well-known.

The production of ethanol by fermentation is a resource-intensive activity. Commercial scale agriculture requires fertilizer and fuel for the farm machinery and equipment used to plant, harvest, and transport the product. Ethanol production also requires energy. Fermentation of corn produces a mixture that is about 8% ethanol in water, a mixture that will not burn and cannot be used as fuel. This "beer" is then distilled, like whiskey, to makes 99.5% pure ethanol. However, the distillation required to produce 99.5% ethanol is also energy-intensive. Only then can ethanol be used as a transportation fuel. The amount of energy needed to produce ethanol is discussed in more detail below.

Theoretically, biomass could be used to supply all of the energy needed to produce ethanol. Biomass could be gasified to produce hydrogen for ammonia manufacture, the most energy-intensive aspect of fertilizer manufacture. Farm machinery could be operated on biomass-derived diesel fuel, and combustion of biomass could supply the energy for ethanol distillation. In the U.S. none of these approaches is economically attractive, and none is used to any appreciable extent; the energy used to make fertilizer, operate farm machinery, and distill ethanol is overwhelmingly supplied from fossil fuels.

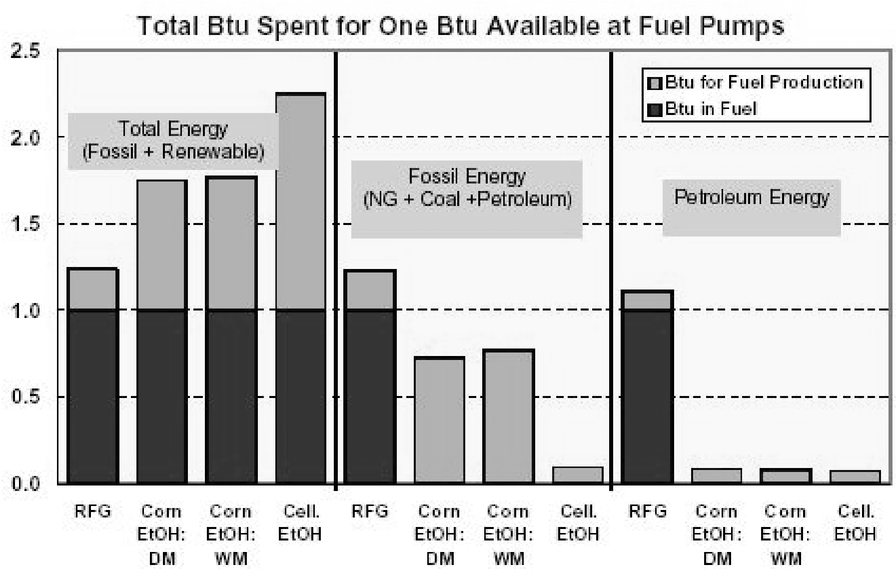
Ethanol is easy to produce, as evidenced by the historic availability of moonshine whiskey. However, simple distillation produces a mixture of 95% ethanol/5% water, which is unsuitable for blending with gasoline. More than 0.5% water in the ethanol can cause ethanol-gasoline blends to separate into two phases the gasoline distribution system, a gasoline-rich phase, and an ethanol-rich phase. If this happens, the ethanol-rich phase will be lost in the "water bottoms" that have to be removed from the system, and the remaining gasoline-rich phase will not longer meet quality specifications. The addition of a third component to the mixture (e.g. ethylene glycol) allows production of ethanol with 99.5% purity, which will ensure that ethanol-gasoline blends can be distributed without phase separation.

Given that the production of ethanol is a well-known technology, which is practiced on a large scale, one would expect that its energy requirements would be well known. However, this is not the case. Transportation fuels, such as ethanol and gasoline, are energy carriers, produced from primary sources of energy such as biomass and crude oil. The production of energy carriers uses energy; how much energy is a subject of on-going debate.

One way of comparing transportation fuel processes is to calculate the ratio of the energy in the transportation fuel to the energy used to produce the fuel, including solar energy for biomass-derived fuels. A more specific version of this calculation looks at the ratio of energy in the transportation fuel to the fossil fuel energy input, and an even more specific calculation considers only the energy from crude oil. The answers provided by these three calculations can be different, and they all depend on how the boundaries are drawn around the process. For example, while there is general agreement that the energy in purchased electricity should be included in the energy balance, there is less agreement about whether the energy used to make the steel in farm machinery and refinery equipment also should be included.

These three ways of evaluating transportation fuels are shown in Figure 1, taken from a study carried out at Argonne National Laboratory (DOE, 2005). BTU stands for British Thermal Unit, the amount of energy needed to raise the temperature of a pound of water by 1°F: RFG, for reformulated gasoline; EtOH, for ethanol; DM and WM, for dry milling and wet milling, two processing technologies for making ethanol from corn; Cell., for cellulose, another potential source of ethanol (which will be discussed below); and NG, for natural gas.

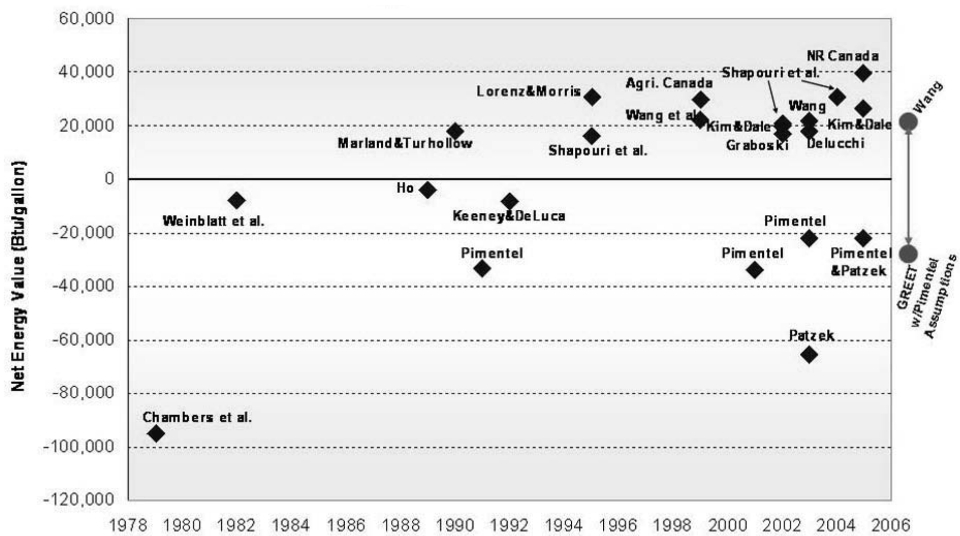
Figure 1



It takes far more *total* energy to produce biomass-derived transportation fuels than RFG, but, as advocates of biomass-fuels are quick to point out, much of that energy is solar energy, which is free and environmentally benign. The more useful comparisons are the amounts of fossil fuel or petroleum energy required to manufacture these fuels. Argonne claims that biomass uses much less fossil energy, particularly petroleum energy, than biomass fuels. Not everyone agrees.

The results of a large number of studies on the fossil energy required to produce corn-based ethanol are presented in Figure 2 (Wang, 2005).

Figure 2 – Net Energy Balance for Producing Ethanol from Corn



Energy balance here is defined as Btu content a gallon of ethanol minus fossil energy used to produce a gallon of ethanol

When corn-based ethanol was first produced for fuel use in the 1980s, almost all studies showed that it required more fossil fuel energy input than the energy contained in the product. Since the mid-1990s, most studies have shown that ethanol produced from corn contains more energy than the fossil fuel used to produce it. A gallon of ethanol contains 76,000 BTU (Low Heating Value, the amount of energy theoretically available for use by an automotive engine). Most recent studies show that ethanol from corn contains about 20,000 more BTUs per gallon than the fossil fuel used in its production. Grabowski (2002) provides the following breakdown of current energy inputs and outputs for corn-based ethanol production:

Table 1 – Energy Balance for Corn-Based Ethanol

	BTU/Gallon
Corn Production and Transportation	21,400
Ethanol Production and Transportation	49,300
Byproduct Energy Credit	-12,900
Net Fossil Energy Inputs	57,800
Energy in Ethanol	76,000
Net Energy Benefit	18,200

Several reasons are cited for the reduction in the energy required to produce ethanol. Corn output per pound of fertilizer has risen by 70% in the past 35 years. This is important because the energy required to produce fertilizer is an important part of the energy input to corn, and therefore ethanol, production. The energy required to process corn into fuel grade ethanol has also declined, between 15,000 and 30,000 BTU/gallon depending on the process used. Finally, the corn not converted into ethanol is a byproduct, known as distillers dry grains and solubles (DDGS), which is used as animal feed. DDGS can displace other animal feeds, which also require energy in their production. The net savings in energy should be taken as a credit, about 16-20%, against the energy used in producing ethanol. Some studies do not consider the energy implications of byproduct production (Wang, 2005).

While most recent studies show a net energy benefit for the production of ethanol, two researchers, Drs. David Pimentel, Cornell University, and Tad Patzek, University of California at Berkeley, disagree (Pimentel and Patzek, 2005). They claim that the production of corn-based ethanol required 29% more fossil fuel energy than is contained in the product. As the bar at the right of Figure 2 shows, Wang got the same results as Pimentel and Patzek when he used their assumptions in his model. Pimentel and Patzek's 2005 paper does not provide details of their energy balance calculations, but many of these are available in a long report available on Patzek's website (Patzek, 2006).

Critics of Pimentel and Patzek claim that they are using old data for energy requirements for ethanol production. In response, Pimentel and Patzek claim that they are using long- term averages for energy inputs. For example, instead of using the lower energy requirement for fertilizer manufacture that the most modern plants achieve, they use higher figures that represent a wider range of plant performance. The same is true for other parameters. Most critically, in some of their published work, they do not take an energy credit for co-products (Grabowski, 2005).

The approach taken by Pimentel and Patzek appears to unduly penalize ethanol produced from corn. It looks backward rather than forward. If ethanol production expands, it will be on the basis of new, more efficient technology, not older, inefficient technology. Use of currently available technology produces a small energy benefit for ethanol production. However, energy balance is only one of the questions about the use of ethanol as a fuel. Two equally important questions are: how much ethanol can be made available and at what cost? These topics are addressed in the next sections.

How Much Ethanol Could Be Produced from Corn?

EIA documents both current energy use and price, and forecasts future energy demand and price. According to EIA and other sources:

- 2004 domestic production plus net imports of gasoline totaled 140 billion gallons (EIA, 2006b).
- EIA's reference case for the future, which forecasts crude oil price to be $57/Bbl in 2030 (2004$), projects U.S. demand for gasoline to grow to 163 billion gallons by 2015 and 191 billion gallons by 2030 (EIA, 2006a).
- Ethanol for gasoline production totaled about 3.4 billion gallons in 2004 (NCGA, 2005), or about 2.4% of the gasoline pool.
- EIA's reference case projects ethanol production to grow to 10.7 billion gallons in 2030, or 5.6% of the gasoline pool (EIA, 2006a).
- EIA's high oil price case for the future, which forecasts crude oil price to be $96/Bbl in 2030 (2004$), projects gasoline demand to be only marginally lower, at 188 billion gallons in 2030, and ethanol production to be 13.8 billion gallons, or 7.3% of the gasoline pool (EIA, 2006a).

EIA's projections are a reasonable outlook for ethanol. It will play a role as a transportation fuel, but it is far from a panacea. It will not free the U.S. from dependence on fossil fuels, nor will it eliminate U.S. oil imports.

Ethanol is often included as part of a broader package of technologies that their advocates claim will achieve U.S. energy independence. One such package is Set America Free's Blueprint for U.S. Energy Security (Set America Free, n.d.). This package calls for using ethanol, methanol, biodiesel, and electricity to power the vehicle fleet, but does not provide any information on the fraction of U.S. transportation energy demand that would be supplied by each of these energy sources. It also claims, without documentation, that fuel additives can enhance the combustion efficiency of gasoline and diesel fuel by 25%. If such additives existed, they would be heavily marketed, especially to truck fleet operators who are very sensitive to fuel costs.

A "blueprint" is usually a transparent document showing how a goal is to be achieved. However, Set America Free's "blueprint" is completely opaque. It provides no detail; only a list of options, all of which have been the subject of intensive R&D, often for decades. Many of them are now being applied or are likely to be applied in the future, but as well-documented assessments, such as the EIA outlook cited above, show, they cannot achieve energy independence or the reverse the growth in oil imports.

How Much Does It Cost to Produce Ethanol from Corn?

As shown in Table 2, even at today's high oil prices, ethanol is more expensive than the gasoline it replaces.

Table 2 – Price of Corn-Based Ethanol

	$/gal	Reference
Cost of ethanol in 10 Midwestern states on March 22, 2006	$2.34 – $2.50	Ethanol Market, 2006
Subsidy (American Jobs Creation Act of 2004, PL 108 – 357)	$0.51	
Net cost of ethanol	$1.83 – $1.99	
Energy Content (BTU/gal): Gasoline	125,000	
Ethanol	76,000	
Gallons of ethanol per gallon gasoline equivalent =	1.6	EIA, 2006c
Price of ethanol per gallon gasoline equivalent	$2.92 – $3.18	
Retail price of regular grade gasoline in Midwest, March 20, 2006	$2.50	

Since ethanol is a high octane component, some of this higher cost is offset by its value in meeting gasoline octane specifications, but even considering this benefit, ethanol is more expensive than gasoline.

Corn-based ethanol is unlikely to become cost competitive with gasoline anytime soon. As indicated above in the discussion of energy balance, there has been considerable improvement over the last 20 years in the efficiency of producing ethanol. With any process, continued efficiency gains are governed by the law of diminishing returns. The easy and most dramatic improvements are achieved early, while later improvements are smaller and more difficult to implement.

Since ethanol production uses a significant amount of fossil fuel energy, an increase in oil prices will not be a major benefit to its cost competitiveness. Directionally, the costs of natural gas and coal, which are the sources of most of the fossil energy used to produce ethanol, will increase in tandem with the price of oil. This means that the cost of production of ethanol will tend to increase as oil prices increase.

The actual price to the consumer is not the only cost of ethanol for consideration. At current production rates, the $0.51/gallon subsidy for ethanol costs U.S. taxpayers nearly $2 billion/year. If ethanol production increases as projected by EIA, this cost will grow to more than $5 billion/year by 2015. Whether this is a cost effective way of increasing U.S. energy supply is a subject for debate.

Are There Alternative Ways of Producing Ethanol?

Two alternatives for increasing the supply of ethanol are frequently discussed: production from sugar and production from cellulose, which are discussed in the next sections.

Ethanol from Sugarcane

Sugarcane yields more sugar, and therefore more ethanol, per acre than corn. In addition, the combustion of sugarcane waste, known as bagasse, for energy in sugarcane processing is well established. As a result, the energy balance for ethanol from sugarcane is far more attractive than the energy balance for ethanol from corn. A recent study indicated that in Brazil, ethanol production produces 8-10 times as much energy as is provided from fossil fuel inputs (Kaltner, *et al*., 2005). Currently, Brazil produces about 3.5 billion gallons/year of ethanol, 90% of which is used domestically. Brazil plans to significantly increase this production. News reports indicate that Petrobras, the Brazilian national petroleum company, plans to export 2.5 billion gallons per year of ethanol by 2010 (MSNBC, 2006).

Currently, ethanol is not produced from sugarcane in the U.S., but the Energy Policy Act of 2005 included $36 million funding for sugar-to-ethanol demonstration grants, and $50 million funding for loan guarantees for sugarcane and sucrose-to-ethanol facilities (Abercrombie, 2006). However, it is unlikely that production of ethanol from domestic sugarcane could make a significant impact on U.S. energy supply. The U.S. has a large sugar industry, currently fifth in the world, but still does not grow enough sugar to meet its own needs (USDA, 2006). A variety of discussions are underway about expanding U.S. sugar production to produce ethanol, but many of these actually focus on using both the sugar itself and the cellulose in bagasse as feedstocks (LSU Ag Center, 2006). Production of ethanol from cellulose is currently uneconomic (see the discussion below). Imports from Brazil and other sugar producing countries could significantly increase U.S. supplies of ethanol, but would do nothing to increase U.S. energy independence. Also, imported ethanol is subject to a $0.54/gallon tariff, which eliminates any economic benefit for its use.

Ethanol from Cellulose

Sugars and starches make up a small part of most plants, even sugarcane. The bulk of plant material is cellulose, hemicellulose, and lignin. Most of the claims of ethanol replacing petroleum in transportation fuels are based on the assumption that these materials, particularly cellulose, can be converted into ethanol. The cellulose could come from corn wastes (often referred to as corn stover), wheat straw, wood waste, or specially grown crops like switch grass. The technology to do this commercially is not now available, and there are substantial hurdles to its development.

Cellulose is a polymer made of 300 to 15,000 glucose molecules. Glucose is a simple sugar and easy to ferment into ethanol. However, converting cellulose to ethanol presents two challenges. First, it is necessary to prepare the cellulose for processing. In plants, cellulose is protected by a layer of hemicellulose, a polymer made up of 70 to 200 more complex sugars, and lignin, a polymer made up of a complex mixture of smaller molecules. The hemicellulose and lignin must be removed before the cellulose can be processed. Second, it is necessary to break the cellulose polymer down into individual glucose molecules.

The Department of Energy's National Renewable Energy Laboratory (NREL) has conducted research on converting cellulose to ethanol for over two decades (NREL, 2005). In NREL's process, plant material is treated with dilute sulfuric acid at moderate temperature and pressure, which breaks down the hemicellulose and some of the lignin polymers. These can then be solubilized in water, leaving behind solid cellulose and the remaining lignin. Cellulose can be broken down into its component sugar molecules using even stronger acids and higher temperatures and pressures, but this degrades the sugars and reduces ethanol yield to uneconomic levels. For this reason, research is proceeding on the use of enzymes, known as cellulases, which will break down cellulose. Such enzymes exist naturally; they allow cattle, termites, and beavers to digest cellulose. NREL has demonstrated a cellulose decomposition process based on cellulases in the laboratory, but the current cost of these enzymes is many times that needed to make this process cost competitive. Further research is underway to lower the cost of the enzymes and to engineer the process, and may eventually yield a commercially competitive process.

Research is also underway at a number of universities in a group known as the Biomass Refining Consortium for Applied Fundamentals and Innovation (CAFI). The Consortium is studying a wide range of topics, including the development of better cellulose pretreatment techniques (Wyman, *et al.*, 2005) and genetically-engineered yeasts for improved ethanol yields (Ho, 2005). There are also a number of private research initiatives to improve ethanol yields, one of the more publicized ones being J. Craig Venter's effort to develop genetically engineered microbes to breakdown and ferment cellulose (Washington Post, 2006).

As indicated in Figure 1, the energy balance for enzyme-based cellulose-to-ethanol processes is much more favorable than for corn-to-ethanol. Much of this favorable energy balance is based on assuming that the lignin and hemicellulose that are not converted into ethanol will be combusted for energy, as is currently done in the pulp and paper industry (Nichols, 2004). The use of biomass fuels also would make the cost of ethanol from cellulose more independent of future oil prices than the cost of ethanol from corn. However, despite these considerations, it is clear that large-scale conversion of cellulose to ethanol is still decades away. EIA assumes small scale production of ethanol from cellulose starting in 2010 in its high oil price case, but only production from corn in its reference case.

Diesel Fuel from Processed Vegetable Oils (Biodiesel)

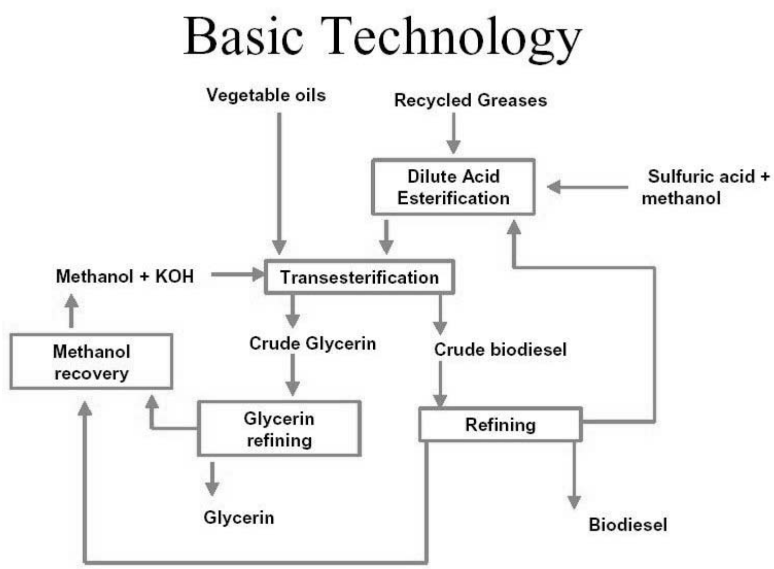
The use of vegetable oils as diesel fuel also dates back to the 19th century. Rudolf Diesel, the inventor of the diesel engine, envisioned it operating on cheap fuels, including vegetable oils. In the first large-scale demonstration of his invention at the 1900 Paris Exposition, the engine was fueled with peanut oil.

While it is possible to operate a diesel on pure vegetable oil, current efforts are focused on vegetable oils that are reacted with methanol to form esters. These processed vegetable oils are usually referred to as biodiesel in the U.S. In Europe they are sometimes referred to as FAME (fatty acid methyl ester). Biodiesel is more stable than the vegetable oils from which it is derived, and can be stored for long periods of time without degrading. Engines operated on biodiesel tend to have fewer emissions than engines operated on unprocessed vegetable oils.

The basic technology for biodiesel production is shown as Figure 3, in a chart developed by the Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE, n.d. a). Conventional diesel engines can be operated on 100% biodiesel or on mixtures of biodiesel and conventional diesel fuel in any proportions.

Biodiesel processes are simple enough that several websites provide detailed instructions on how to produce biodiesel at home (Journey to Forever, n.d.). However, given that the process involves use of methanol and potassium hydroxide (KOH), both of which are dangerous substances to handle, production of biodiesel in your garage is not recommended.

Figure 3



The processing for biodiesel is less energy intensive than the processing for ethanol, and as a result, its energy balance is more attractive. Sheehan, *et al*. (1998) of NREL found that biodiesel processed from soybeans yields 3.2 units of fuel product energy for each unit of fossil energy consumed and that it reduced petroleum use by 95%. Pimentel and Patzek (2005) disagree, saying that production of biodiesel from soybeans requires more fossil energy than it produces, but, as was the case with ethanol, their arguments do not seem persuasive.

While biodiesel is attractive from an energy balance standpoint, it is an expensive and highly limited option. Looking first at price, the Department of Energy's Clean Cities Alternative Fuels Price Report for September, 2005 reported that the average price of 100% biodiesel (B100) was $3.40/gallon, which includes the $1.00/gallon tax credit created by the American Jobs Creation Act of 2004 (PL 108-357). By comparison, the price of conventional diesel fuel was $2.81/gallon (EERE, 2005).

There is less scope for improvement in biodiesel processing than for improvement in ethanol processing. The process is simple, but the feedstock must be either fresh or used vegetable oil or animal fats. While used vegetable oil, e.g. from McDonalds, is a waste product with little value, removing its contaminants is expensive. According to the Department of Energy, the current cost of soybean oil is about $1.50/gallon of biodiesel. Using animal fats or grease can reduce this cost, sometimes to as low as $1.00/gallon (EERE, n.d. b). Since relatively little fossil energy is used in producing biodiesel, its production costs are relatively independent of oil prices.

Raw material supply is also a problem for biodiesel. Oils represent only a small fraction of the vegetables from which they come and animal fat is only a small portion of the domesticated animals that are their source. This limitation of feedstock is evident when U.S. capacity and production are compared. The National Biodiesel Board estimates that the current production capacity for biodiesel is 354 million gallons per year. However, in 2005, only 75 million gallons of biodiesel were produced. (National Biodiesel Board, 2006). This was a dramatic increase from the 25 million gallons produced in 2004. Still, the 2005 production rate represents only about 0.2% of the approximately 42 billion gallons of diesel fuel consumed in the U.S. in 2004 (EIA, 2005a). The potential impact of biodiesel on U.S. energy supply is so small that EIA does not discuss it in the section on ethanol and synthetic fuels in its Annual Energy Outlook 2006. Research is underway on genetic modifications that would increase the oil content of soybeans and other potential sources of biodiesel, but even doubling biodiesel supply would have negligible impact on U.S. energy supply.

How Much Biomass is Available for Energy Use?

Estimating the biomass resource available for energy production is difficult for several reasons.

1. Biomass energy production will compete with the use of biomass for agriculture and forestry products. The demand for agricultural and forestry products will increase as population and wealth increase, and the assumptions made about the rates of increase in those demands will affect how much biomass resource is available for energy use.

2. Most studies assume that some land that is currently not used for commercial agriculture or forestry will be brought into production for energy use. Assumptions about the restrictions on the use of this marginal land, and on its productivity, are critical.

3. Biomass for energy use must be harvested on a sustainable basis if it is to have a long-term impact on supply. For forestry, this means that the rate at which trees are cut down cannot exceed the rate at which new trees are grown. For agriculture, this means growing crops in a way that does not deplete soil nutrients or exceed water availability. Assumptions about sustainable production rates are also critical.

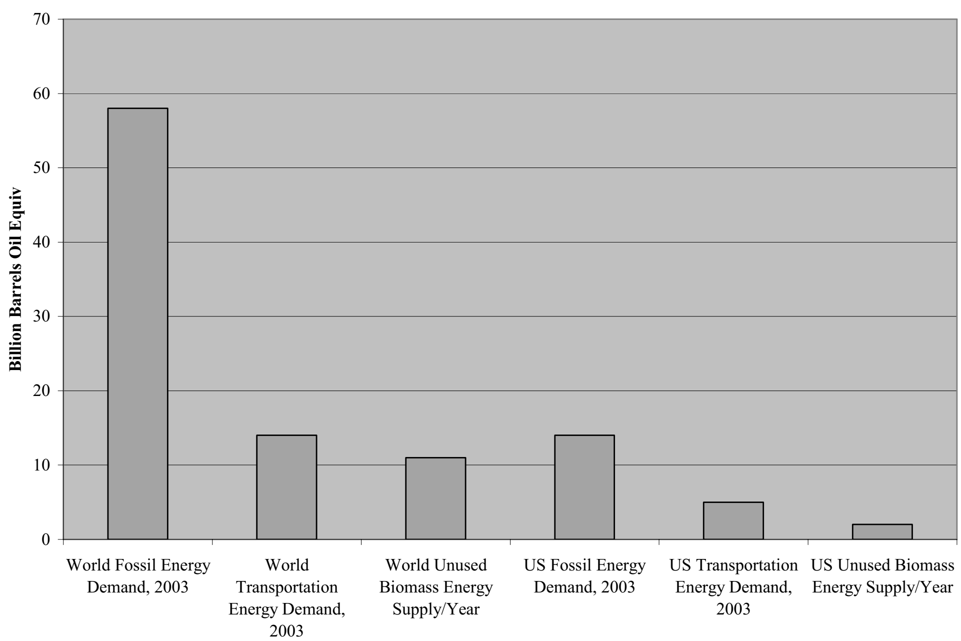
Because of these difficulties, estimates of biomass availability vary widely.

Figure 4 shows the estimated amount of sustainably-grown biomass energy compared with world and U.S. energy demand in 2003, and world and U.S. transportation demand, again in 2003. The data on world energy demand is from the International Energy Agency's Key Energy Statistics, 2005 (IEA, 2005), and the data on U.S. energy demand is from the Energy Information Administration's Annual Energy

Outlook, 2006 (EIA, 2006a). The estimate of world unused biomass energy availability is from Parikka, 2004, based on his survey of the available literature on forest areas and productivity, and on agricultural resources that could be used for energy crops. The estimate of U.S. unused biomass energy availability is from a recent study by the Departments of Energy and Agriculture (Perlack, *et al.*, 2005).

The Parikka and Perlack, *et al.* studies represent balanced approaches to estimating the *technical* potential for biomass availability. Neither study considers what is likely to be economically or politically feasible. Both studies assume that all biomass can be converted into fuels, either because cellulose fermentation is commercially available or because the biomass is gasified and converted into transportation fuels (discussed later in this report). Neither of these processes is currently commercially viable. Both studies also take land availability, food and forestry product needs, and current use of biomass into account, and limit the amount of biomass available for fuel to that which can be sustainably-grown.

Figure 4 – Energy Demand vs. Biomass Energy Supply



Looking both at the world and U.S. energy situations, the Parikka and Perlack, *et al.* studies indicate that there is not enough unused biomass resource to supply current total energy demand, or even transportation energy demand, and that demand will be growing. EIA projects that U.S. transportation demand will reach 7 billion barrels of oil equivalent by 2030 (EIA, 2006a), and world transportation energy demand will reach 24 billion barrels of oil equivalent by 2025 (EIA, 2005b). EIA has yet to publish its global projections for 2030. Unused biomass energy could satisfy less than half the projected global transportation energy demand and less than a third of the projected U.S. transportation energy demand.

A variety of research activities are underway to improve biomass yield (Ragauskas, *et al*., 2006). At present, plants are able to use less than 2% of the light energy they capture to convert carbon dioxide and water into biomass. Any improvement in the ability of plants to use light energy would increase biomass yield. Experiments with genetically modified tobacco were able to increase both photosynthesis rate and biomass production. Genetic engineering is also being used to improve other aspects of the biomass production cycle. Poplar trees genetically engineered to improve their nitrogen metabolism were 41% higher after three years than unmodified control trees. Still other genetic engineering experiments have shown that lignin production can be decreased and cellulose production increased in poplar trees. Since cellulose is the part of the plant's structure that can be converted into sugar and fermented, this approach could increase ethanol yield. These experiments provide exciting research leads. However, they are all still at the laboratory stage and neither their technical nor economic viability has been demonstrated.

Biomass and Carbon Dioxide Emissions

One of the arguments often advanced for the use of biomass is that it will reduce carbon dioxide emissions and the potential for human impact on the climate system. Advocates argue that when biomass is used as a fuel, the carbon it contains is converted to carbon dioxide and emitted to the atmosphere. However, if the biomass is replaced by growing more biomass, this carbon dioxide will be removed from the atmosphere, making the process carbon dioxide neutral. This analysis ignores two factors. First, as documented above, growing biomass and processing it into transportation fuels uses fossil fuels, and results in carbon dioxide emissions. In some cases, as with the production of ethanol from corn, substantial quantities of fossil fuels are used. Second, the claim that the use of biomass is carbon dioxide neutral depends on the biomass being grown in a sustainable manner. Efforts to maximize agricultural biomass fuel production could result in reductions of soil carbon, which translate into carbon dioxide emissions. Efforts to maximize forestry biomass fuel production could result in trees being cut faster than they can be replaced, again leading to carbon dioxide emissions.

Gasification of Biomass: A More Speculative Approach

An alternative to fermentation and processing of vegetable oils and animal fats is to gasify biomass by reacting it with air, oxygen, or steam to create a syngas composed of carbon monoxide and hydrogen, which then can be processed to make either pure hydrogen or hydrocarbons.

The technology to gasify biomass is the same as used to gasify fossil fuels, and is well-known. Using biomass as a feedstock creates both challenges and opportunities.

Currently, the most widespread use of fossil fuel gasification is to produce hydrogen for ammonia synthesis and petroleum refining. Natural gas is the fossil fuel of choice for this process because it has the highest hydrogen content - most of the hydrogen in the feedstock ends up as hydrogen in the product. Using biomass as a feedstock would create materials handling problems, since biomass is not uniform in physical or chemical composition, but these problems can be overcome. The hydrogen produced by this process could then be used in hydrogen fuel cell vehicles.

Currently there is considerable interest in gasification because it produces a byproduct stream that has a high concentration of carbon dioxide, and is a natural candidate for carbon dioxide capture and storage (CCS) technology. Using CCS technology, the byproduct carbon dioxide stream can be permanently stored in a suitable geological formation, e.g., a saline aquifer or a depleted oil or gas reservoir. The carbon dioxide could also be used for enhanced oil recovery. This technology is described in detail in the recently issued IPCC (Intergovernmental Panel on Climate Change) Special Report on Carbon Dioxide Capture and Storage (IPCC, 2005). If sustainably grown biomass were used as the feedstock for gasification in conjunction with CCS technology, the process could result in *negative* carbon dioxide emissions, since the stored carbon dioxide would be replaced by carbon dioxide removed from the atmosphere.

All of the individual technologies needed for production of hydrogen from biomass, and for capture and storage of carbon dioxide, have been demonstrated on a commercial scale. However, they have not been put together in a commercial scale demonstration of the entire process. Economic analyses have been conducted on the process. These indicate that it would be expensive, but no more so than some of the other technologies being considered to reduce carbon dioxide emissions. However, it is unlikely that biomass gasification with CCS technology will be demonstrated in the near future. The current emphasis is on projects that demonstrate the feasibility of gasification plus CCS using coal as a feedstock, e.g. DOE's FutureGen program (DOE, 2003).

While the technology to manufacture hydrogen is well-understood, there are many other problems that would have to be solved before hydrogen could be used as a transportation fuel. Hydrogen fuel cell vehicles are still at the laboratory stage. Their cost is still far too high, and they use too much platinum to be practical. To be practical as a vehicle fuel, hydrogen would have to be distributed to, and stored at high pressure (about 5,000 pound per square inch, more than 300 times atmospheric pressure), at a large number of refueling stations around the country. It would then have to be dispensed, again at high pressure, to vehicles. Handling large volumes of this highly flammable gas at high pressure creates a host of safety challenges that have yet to be addressed. Research on all of these issues is being carried out in the automotive and energy industries, and by a number of governments. The U.S. government program is the FreedomCAR and Fuel Partnership, which has as a goal the development of hydrogen vehicle and refueling technology to a point that would allow commercialization decisions to be made in 2015 (DOE, 2004). Actual commercialization would occur at a later date.

Because of the unresolved problems in using hydrogen as a vehicle fuel, there is also interest in creating synthetic hydrocarbon fuels from biomass. The hydrogen and carbon monoxide in the syngas created when biomass is gasified can be reacted to form hydrocarbons in what is known as the Fischer-Tropsch reaction. Germany used this approach to manufacture jet fuel during World War II, and South Africa has used it to produce liquid fuels from coal for more than 50 years. The Fisher-Tropsch reaction forms straight chain hydrocarbons, which make better diesel fuel than gasoline, but further processing can convert the straight chain hydrocarbons into gasoline (EPA, 2002). Under idealized conditions, using Fisher-Tropsch chemistry could result in a carbon dioxide neutral fuel, but since there would be no excess carbon dioxide to be stored, it could not result in negative carbon dioxide.

Conclusions

- Biomass-derived transportation fuels can play a limited role in U.S. energy supply.
- Using currently available technology, corn-based ethanol uses about 20,000 BTU/gallon less fossil fuel energy than is contained in the product. However, corn supply limits this process to a small percentage of projected U.S. gasoline demand. The current price of corn-based ethanol is higher than the price of the gasoline it replaces, and since significant amounts of fossil fuel energy are used in its production, its price will tend to rise with increased oil prices
- The production of ethanol from sugarcane uses less fossil fuel energy than the production of ethanol from corn. U.S.-grown sugarcane is not currently used to produce ethanol and it is unlikely that it will be a significant source of ethanol in the future. Importing sugarcane-based ethanol could significantly increase ethanol supplies, but would do nothing to improve U.S. energy independence.
- Successful commercialization of a cellulose-to-ethanol process could greatly expand ethanol supply since it would allow use of a wide range of biomass (corn wastes, wheat straw, wood chips and specially grown crops such as switch grass) as feedstocks. Research is underway in government, university, and private laboratories on a variety of processes, but all are currently uneconomical, and large-scale commercialization cellulose-to-ethanol appears to be decades away.
- Vegetable oil and animal fats can be processed into biodiesel, which can be used in blends of any proportion with conventional diesel fuel. Biodiesel is more than $1/gallon more expensive than conventional diesel fuel and its supply is highly limited. It made up only 0.2% of the diesel fuel pool in 2005.
- Gasification of biomass to produce either hydrogen for fuel cell vehicles or a syngas that can be processed into synthetic gasoline or diesel fuel is technically feasible, but has never been commercially demonstrated. Production of hydrogen from biomass, coupled with carbon dioxide capture and storage technology, could result in negative carbon dioxide emissions. Economic studies indicate that this

technology package would be expensive, but no more so than some of the other technologies being suggested to control carbon dioxide emissions.

- While estimates of the amount of fuel that could be produced from biomass vary significantly, they all agree that we cannot supply all of the world's energy needs, or even the transportation sectors energy needs, from biomass.

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May 2006