Chapter 18

BIOFUELS AND BIOMATERIALS

1. Substitution of Biofuels

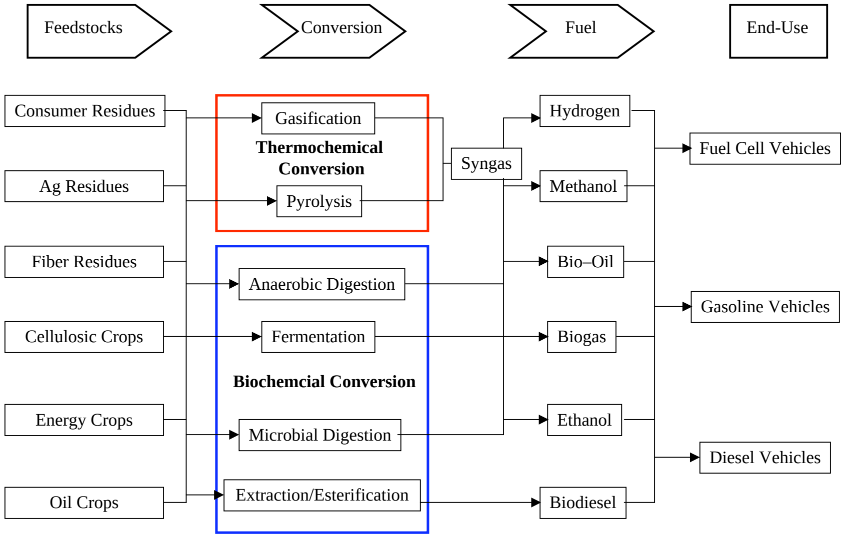
Our *Conventional Wisdom* (*CW*) scenario reveals that using existing technology, biofuels remain economically unattractive compared to oil, with only 0.03 net Mbbl/d (0.06 q/y) competitive on the short-run margin with EIA's $26/bbl oil and 0.6 net Mbbl/d[1] (1.3 q/y) available at a price below $35/bbl-equivalent[2] ($0.75/gal-gasoline-equivalent.) However, the *State of the Art* (*SOA*) analysis demonstrates that when today's known technologies and improvements are fully implemented, biofuels actually become cheaper than oil-based transportation fuels: 4.3 net Mbbl/d (9.2 q/y) can be produced for less than $35/bbl-equivalent ($0.75/gal-gasoline-equivalent), 3.7 Mbbl/d of which is competitive with EIA's short-run margin of $26/bbl. This suggests substitution of 13% of EIA's projected 2025 oil demand before (or 18% after) fully applying oil's end-use efficiency potential.[3]

The National Research Council predicted in 1999 that 1.6 Mbbl/d from biofuels could be feasible and profitable by 2020 and 8.1 Mbbl/d by 2100.[4] Our *SOA* analysis leads us to believe that 4.3 Mbbl/d will be possible by 2025, almost three times greater than the NRC prediction for 2020. This difference between our findings and the NRC's is caused by the same technological breakthroughs that make *SOA* biofuels production so greatly exceed the *CW* finding that older methods like classic corn-ethanol production can profitably provide only 0.6 Mbbl/d in 2025, not much above actual 2003 production of 0.13 Mbbl/d.[5] The NRC and *CW* findings rely on assumptions that do not include new technologies that have lower capital and operating costs and double the yield. On a global scale, a 2004 IEA biofuels report estimates that "…a third or more of road transportation fuels worldwide could be displaced by biofuels in the 2050–2100 time frame."[6] And a study for DoD of how to relieve U.S. oil dependence recommended a large-scale initiative in cellulosic biomass.[7]

The use of biologically based materials as raw materials for industry is an idea that has been around for quite a long time. In fact, when the U.S. Department of Agriculture was established by Abraham Lincoln in 1862, its motto declared, "Agriculture is the foundation of manufacture and commerce".[8] However, biofuels' struggles against petroleum date back to the same period (1862–1864), when the ethanol industry produced 90 million gallons each year to fuel the Spirit Lamps of America.[9] Kerosene from Pennsylvania oil was just hitting the market when the Internal Revenue Act passed a $2.08/gallon tax[9] on alcohols to help fund the Civil War. The tax was intended to be applied to beverage alcohol, but was applied to all forms without a specific exemption. This priced ethanol well above kerosene (taxed at $0.10/gal)[10] and effectively out of the fuels market. That was the first of many battles between ethanol and oil.

The farm ethanol industry emerged again in the United States during the early 1900s, the 1920s, and especially in the 1930s during the Great Depression. It was endorsed by Alexander Graham Bell, backed through Henry Ford's Farm Chemurgy program, and was considered the obvious fuel of the future by most engineers, especially GM research director Charles Kettering. However, in 1924 leaded gasoline was introduced by the Ethyl Corporation, a joint GM-Standard Oil venture, effectively knocking farm ethanol out of the competition. Ethanol would spring up again as vital during World War II with 600 million gallon/y in production.[11] After the war, however, political and economic pressures wiped out the industry and kept it dormant until the next national crisis triggered by the Arab oil embargo 34 years later.

Figure 18–1—Biofuels Flow Chart



The potential uses for biomass as a source of energy are numerous, as can be seen in Figure 18-1. Biomass can be used directly to produce heat or electricity through combustion, either as a stand-alone fuel or through co-firing with coal. Presently, this is the most common use of biomass in the United States; wood and wood-waste combustion for process heat and electricity provided 2.4 quads of energy in 2000.[12] The term “biofuels” usually refers to liquid mobility fuels, including alcohols, esters, and ethers. The two most commonly discussed biofuels in the U.S. are ethanol and biodiesel, both of which can provide significant oil displacement.

Ethanol

Ethanol production in the United States achieved an all-time high in 2003, totaling 2.8 billion gallons (0.3 quads), largely in response to increased demand resulting from the phase out of MTBE as a gasoline oxygenate.[13] Most U.S. ethanol is produced by fermenting sugars derived from the starch in corn kernels. Corn ethanol can be produced via two processes, wet and dry milling, both of which produce valuable coproducts including high-value feed supplements. However, growing corn by the dominant method is resource-intensive, and the kernels represent only half of the energy contained in the corn plant, leading to a low ethanol conversion (see Table 18–1 below). Most available biomass materials are composed of cellulose, hemicellulose, and lignin rather than starches as in corn. These lignocellulosic biomass feedstocks represent a large potential source of biofuels and are currently being developed at pilot and even commercial scale.[14] After pretreatment, the cellulose and hemicellulose are hydrolyzed into their component sugars, glucose and xylose. These sugars can then be hydrolyzed into ethanol via either traditional acid hydrolysis processes or enzymatic hydrolysis.

Major breakthroughs that have occurred with enzymatic hydrolysis include simultaneous saccharification and fermentation, and the ability to simultaneously ferment both five- and six-carbon sugars through the use of genetically engineered enzymes. The costs of these enzymes are being decreased as reported by Novozymes and NREL in a recent press release: "…the two partners have been able to reduce the cost of the enzyme part of the biomass-to-ethanol process from above 5 U.S. dollars to below 30 U.S. cents per gallon of ethanol."[15] These biochemical conversion processes have achieved significantly improved yields over the past few years (greater than 100 gallons of ethanol per ton of biomass).

As an alternative, thermochemical conversion processes are now showing tremendous potential for advancing yield improvements. Pyrolysis and gasification processes both heat biomass in a low-oxygen environment to decompose the feedstock into a carbon-monoxide-and-hydrogen-synthesis gas (syngas)—a classical process for coal and even wood (which fueled many northern European cars during World War II). Syngas mixes more readily with chemical catalysts than do solid fuels, thereby leading to higher ethanol conversion rates. The Fischer-Tropsch process, which is also used to make high-quality liquid fuels from coal (chiefly in South Africa) or from natural gas (in Indonesia and Qatar), is a well established method, though not the only way, to convert from syngas into mobility fuel—in this case biofuel because it came originally from biomass.

Brazil's experience with ethanol as a gasoline substitute represents the most successful program worldwide: it produced 3.2 billion gallons in 2003, both to fuel a four-million-vehicle fleet that runs on pure ethanol and for the nationwide gasoline supply (all of which is blended with 25% anhydrous ethanol).[16] Brazil's federal government chose in 1975 to reduce dependence on foreign oil imports, which were hurting the country's trade balance, by encouraging the production of ethanol as a gasoline substitute. The Brazilian government provided three important drivers: guaranteed purchases by the state-owned oil company Petrobras, low-interest loans for agro-industrial ethanol firms, and fixed gasoline and ethanol prices where neat ethanol sold for 59% of the government-set gasoline price at the pump.[17] As of 2004, the ethanol industry accounts for nearly 700,000 jobs, relatively few of which are seasonal. An official evaluation of Brazil's ethanol program found that it drove total 1975–89 investment in the agricultural and industrial sectors totaling US$4.8 billion (2000 US$) and reduced oil imports during 1975–2000 by US$42.5 billion.[18]

Brazil's sugarcane-based ethanol has the lowest cost per gallon worldwide as the result of efficient agricultural and industrial processes, and a favorable energy balance in the alcohol production. In recent years, the retail price (excluding taxes) of hydrous ethanol has been lower than that of gasoline per gallon, and has even been cheaper than gasoline—and has matched our 2025 cellulosic ethanol cost—on an energy-equivalent basis for some periods during 2002–04.[19]

With such a mature sugarcane-ethanol industry, Brazil is gearing up for ethanol exports that could reach 9 million tonnes a year by 2010, over half of it to Japan (the world's largest ethanol importer in 2003) and a sixth to the U.S. The main obstacles are the import tariffs designed to protect existing ethanol industries. The U.S. charges 54¢/gal, raising ethanol's landed East Coast price from $1.00 to $1.54/gal, and Europe charges 38¢/gal, but the U.S. tariff wall is leaking. Cargill proposes to dehydrate Brazilian ethanol in El Salvador for tariff-free export to the U.S. under an exception in the Central America Free Trade Agreement, despite heavy opposition from the U.S.

corn lobby. Peru is about to open a 25–30,000 bbl-ethanol/d export facility that would be tariff-free under the Andean Trade Preference Act. And China is exploring major investments in Brazil to produce both ethanol and castor oil or biodiesel for shipment to China.[20]

Table 18–1—Energy Balance: Corn vs. Switchgrass[21]

Energy Balance for Ethanol Production (EJ)

	Feedstock	
	Corn	**Switchgrass**
Harvest	**10**	**10**
Handling Losses	1.0	1.0
Ethanol Out	**4.5**	**4.3**
Biomass to Ethanol Conversion	45%	43%
Energy Inputs		
Farm Energy	1.3	0.6
External Process	0.0	0.0
Energy	2.5	0.0
Transport to Market	0.1	0.1
Co-product Credit	-0.8	0.0
Net Energy Inputs	3.1	0.7
Net Energy Out	**1.4**	**3.6**
(Net Energy Out = Ethanol Out - Net Energy Inputs)		
Net Conversion	**14%**	**36%**
(Net Conversion = Net Energy Out/Harvested Biomass)		

U.S. ethanol production, by comparison, has historically fermented sugars from the starch in corn, which has a lower ethanol yield and requires considerable energy, fertilizers, pesticides, and irrigation.[22] In addition, most of the energy required for ethanol production from corn comes from fossil-fuel-based energy (83% from coal or natural gas).[23] Cellulosic biomass (forest and agricultural residues, urban wood waste, and dedicated energy crops) is less energy-intensive and can actually help stabilize soils and reduce erosion. The main impact on processing is that the sugars in cellulosic biomass are more tightly bound with hemicellulose and lignin. The process therefore requires these sugars to be released for fermentation, usually through pretreatment using steam and acid.

A comparison of the energy balance of ethanol from corn and switchgrass (a particularly promising cellulosic biomass feedstock) can be seen in Table 18–1. The net energy value (NEV = energy output – lifecycle energy required for production) for modern corn ethanol production is 21,105 BTU/gal; compared to 68,000 BTU/gal for cellulosic ethanol—80% of ethanol's HHV (Higher Heating Value) energy content of 84,600 BTU/gal,[24] implying a 5:1 net energy gain, nearly as good as an inefficient oil refinery. The large NEV difference is due to a higher percentage use of the carbon to produce ethanol from cellulosic feedstocks, lower energy (fossil energy in particular) requirements to produce the cellulosic biomass, and more electricity produced as a coproduct by burning lignin, much as pulp mills often power themselves by burning lignin-rich "black liquor" and other wastes.

The low fossil energy inputs needed to produce ethanol, particularly from cellulosic biomass, have a large impact on greenhouse gas (GHG) emissions. According to a study by Argonne National Laboratory,[25] E85 fuel (85% ethanol and 15% gasoline) reduces GHG emissions by 68–102% per vehicle-mile traveled[26] while reducing oil use by 70–71% and fossil fuel use by 70–79%. In its *Well-to-Wheel Energy Use* study, General Motors found that CO_2 emissions could be reduced by 68% by using ethanol vs. gasoline.[27]

Biodiesel

Soybeans are the most common U.S. biodiesel feedstock, but biodiesel can also be derived from waste cooking oils, vegetable oil, tallow, and lard. Biodiesel is produced through a chemical process called trans-esterification, whereby the vegetable oil is reacted typically with an alkaline catalyst such as potassium hydroxide or sodium hydroxide to give an alkyl ester (biodiesel) and glycerin. According to the National Biodiesel Board, the U.S. produced approximately 25 million gallons of biodiesel in 2002 for use in diesel engines, either neat (B100) or in blends (e.g., B20, a blend of 20% biodiesel and 80% standard diesel). The fuel is currently being used in over 200 vehicle fleets at a 20 percent blend or higher. The Pentagon bought nearly a million gallons of biodiesel in FY2002. Biodiesel's potential as a replacement fuel is significant, and many economists believe that biodiesel has the potential to replace 2–5% of the diesel now used for transportation in the U.S. Most biodiesel researchers agree, however, that it would be difficult to replace more than 10%[28] because of feedstock limitations.

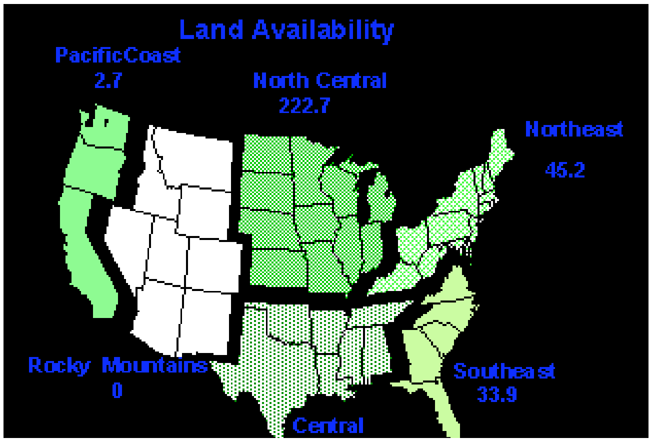
Production of biodiesel has flourished in Europe, with total production for the European Union totaling 430.5 million gallons for 2003 according to the European Biodiesel Board. Germany and France are the leading producers, accounting for 214.6 Mgal and 107.2 Mgal respectively in 2003.[29] The EU has encouraged this aggressive growth by reforming the 1992 Common Agricultural Policy to incentivize non-food crop production in order to eliminate agricultural surpluses, and by adopting a 90% tax exemption for biodiesel.[30]

As part of the U.S. Environmental Protection Agency's Fuels and Fuel Additives registration program, biodiesel emissions data were collected from three different diesel engines. Compared to standard diesel fuel, average emissions decreased by 84.4% in unburned hydrocarbons, 40.5% in carbon monoxide, and 38% in particulate matter, while nitrogen oxides increased by 9.6%.[31] The National Renewable Energy Laboratory (NREL) performed a Life Cycle Inventory on biodiesel and found that biodiesel provides 3.2 units of energy for each unit of fossil fuel energy consumed in its life cycle. In addition, net CO_2 production is reduced by 78%, and biodiesel is virtually free of sulfur and aromatic hydrocarbon.[32]

Biodiesel adoption is not without its barriers, however. Cost continues to be an issue, mainly because its feedstocks can be costlier than standard diesel fuel (although it is possible to get paid to remove some waste streams). Feedstock costs can account for 80% or more of the total cost, and while the cost of the additional raw materials used to essentially cancel out with the credit from glycerin production, the recent collapse of the glycerin market has greatly impaired biodiesel economics.[33] Biodiesel also has a higher cloud point and cold filter plugging point than diesel fuel, which can lead to problems in cold weather, but this can be mitigated by chemical additives or by using a lower biodiesel blend. Biodiesel does tend to oxidize more readily than standard diesel fuel, but a six-month storage life can usually be expected without problems. (Refined petroleum products have a longer but not indefinite shelf life.)

2. Biofuels feedstocks

Acres of U.S. Cropland Suitable For Growing Dedicated Feedstocks[34]

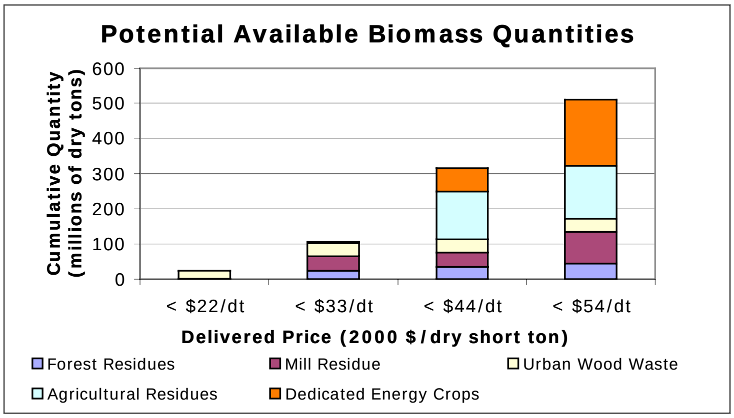


A transition to biofuels as a substitute for petroleum-based transportation fuels will require millions of acres for biomass production. However, the land is available without compromising other national needs. The forestry industry within the U.S. encompassed 504 million acres of timberland in 1997, defined as available forestlands that are not reserved (2000).

Agriculture covered 327 million acres in 2003 (USDA 2003). In fact, the U.S. has the highest per-capita amount of arable land in the world—1.73 acres/person, vs. 0.99 acres/person for other developed countries.[35] The agriculture and forestry industries together occupy 37% of the total United States land area. The Conservation Reserve Program (CRP), which makes annual rental payments to farmers in return for conversion of cropland to vegetative cover, currently represents an additional 35 million acres of arable land that is not in use (CRP March 2004).

Based on this available acreage, Oak Ridge National Laboratory (ORNL) studied biomass feedstock availability in 2000.[36] This report served as a foundation for our supply-curve analysis. Feedstocks were classified in five categories: forest residues, mill residues, agricultural residues, urban wood wastes, and dedicated energy crops. Based on state-by-state data, ORNL estimated that 510 million dry tons of biomass could be generated and delivered each year at a price below $54/dry ton (2000 US$).

Cumulative Biomass Supply (2000 ORNL Estimates)[37]

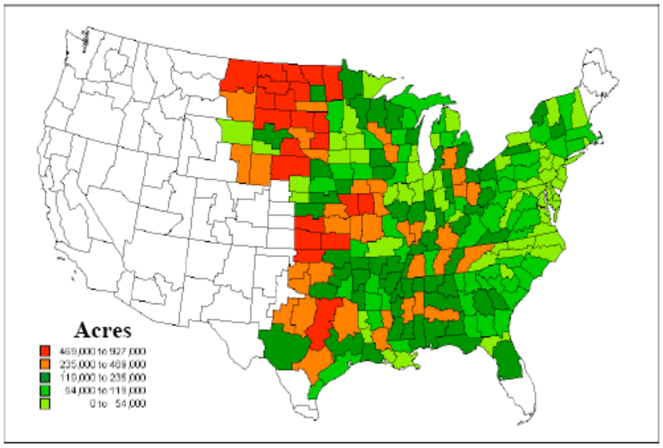


Forest residues include logging residues and sales of rough, rotten, and salvable dead wood. Total supply was calculated to be 45 million dry short tons (dt, 2000 lb/ton) with prices between $33 and $54/dt. Mill residues are classified by type and include bark, coarse residues (chunks and slabs), and fine residues (shavings and sawdust). Most mill wastes are currently used for fuel or as an input for other products because they are fairly uniform and concentrated in one location. Price per dry ton ranged from $22 to $54 and represented a total of 90 million dt/y. Quantities for agricultural residues (leaves, stalks, etc.) were estimated for corn stover and wheat straw and totaled 150 million dt/y at prices of $33–54/dt. Other studies of agricultural residues include additional crop types, bringing the total estimate up from 150 to 280 million tons of waste biomass (though not included here).[38] Urban wood wastes include household wood wastes and yard trimmings, pallets, wood packaging, that typically end up in landfills. ORNL estimated that 37 million dt/y are available at prices of $22–33/dt. Dedicated energy crops include perennial grasses such as switchgrass and short-rotation woody crops such as hybrid poplar and willow. Currently, dedicated biomass crops are not grown on a commercial scale in the U.S. but represent a significant potential energy source if prices can become competitive with current alternative uses. ORNL estimated energy crop quantities at 188 million dt/y at prices of $42–54/dt.

ORNL's energy crop data was generated using POLYSIS, an agricultural sector model that includes all major agricultural crops. The analysis estimated quantities of energy crops that could be produced at a profit at least as great as could be earned producing traditional crops on the same acres. Energy crop production was limited to areas climatically suited for their production (the Rocky Mountain region and Western Plains were excluded). Under the model's Production Management Scenario, 188 million dt/y of bioenergy crops could be grown on 41.9 million acres—23.4 million acres replacing land planted to traditional crops, 12.9 million acres from the

CRP, 3.5 million pasture acres, and 2.1 idled acres.[39] Therefore, dedicated energy crops are predicted to impact current crop production, but only minimally by replacing 6.2%.[40]

Figure 18–2—Profitable Acreage For Energy Crop Production[41]



While dedicated energy crops are not currently being grown on any commercial scale, the U.S. Department of Energy believes that these crops could play a significant role in reducing the nation's dependence on foreign oil while strengthening the U.S. agricultural economy. Since 1991, the Bioenergy Feedstock Development Program (BFDP) has been focusing its herbaceous crop research on switchgrass, a fast-growing perennial grass native to the Great Plains. Long-term yield studies have been performed at 18 sites with annual yields as high as 10 dt/acre, but on a commercial scale, it is expected that yields of 7 dt/acre are more reasonable.[42] For comparison, hay yields in Alabama average about 2.5 dt/acre.[43] Switchgrass can be harvested once or twice a season using standard haying equipment with optimal timing depending on location. Switchgrass has an extensive root system, which improves soil quality by increasing filtration and nutrient-holding capability, and also reduces soil erosion. Because of these qualities, switchgrass may represent an alternative use for the 35 million often erosion-sensitive acres that farmers are paid to keep idle under the Conservation Reserve Program. Hybrid poplar and willow, with annual yields around 10 tons/acre, represent other prospective dedicated energy crops that are being evaluated by the BFDP.

Data for the biodiesel feedstocks was taken primarily from the *2002 Oil Crops Situation and Outlook Yearbook.*[44] Reported values for 1999–2002 were averaged and added to potentially available waste streams. Total supply was estimated at 18.3 million tons of oil/year at a weighted average price of $0.13/lb.

Table 18–2 – Biodiesel Feedstocks

Feedstock	Tons/y	$/lb
Soybean	9,190,500	$0.15
Inedible Tallow	1,917,500	$0.12
Grease Trap Waste	1,835,204	$0.00
Yellow Grease	1,270,526	$0.09
Corn	1,227,000	$0.17
Edible Tallow	902,000	$0.13
Lard	535,500	$0.14
Cottonseed	440,000	$0.18
Sunflower	438,441	$0.19
Canola	310,667	$0.17
Peanut	105,167	$0.36
Flaxseed/Linseed	108,833	$0.37
Safflower	42,500	$0.72
Total	**18,323,838**	**$0.134**

Overall, based on conservative yields, Oak Ridge National Laboratory reported that sufficient bioresources are available to supply at least 8.5 quads/y of bioenergy.[45] The Battelle Memorial Institute calculates a similar number, ~9.5 quads/y, of biomass energy that could be produced at an intermediate price without significant changes to the U.S. agriculture industry.[46]

Biofuel development must not exacerbate, but if soundly pursued could help ameliorate, two problems common in farming, ranching, and forestry.[47] The first is unsound practices that deplete topsoil, biodiversity (especially in soil microbiota), groundwater, and rural cultures. The second, due largely to distorting subsidy patterns and to lax antitrust enforcement against giant grain dealers and packing houses, is unhealthy market concentration and near-monopsony, so by 2002, 62% of agricultural goods came from just 3% of farms, whose margins continued to head toward zero.[48] Driven by a combination of customer food-safety concerns, soil erosion, litigation, primary-producer economic desperation, market innovations, and large-scale monoculture's increasing risks, a quiet but pervasive grassroots shift away from monocultural cropland, rangeland, and woods is beginning in land-grant universities, extension offices, and farms, ranches, and forest operations around the country.

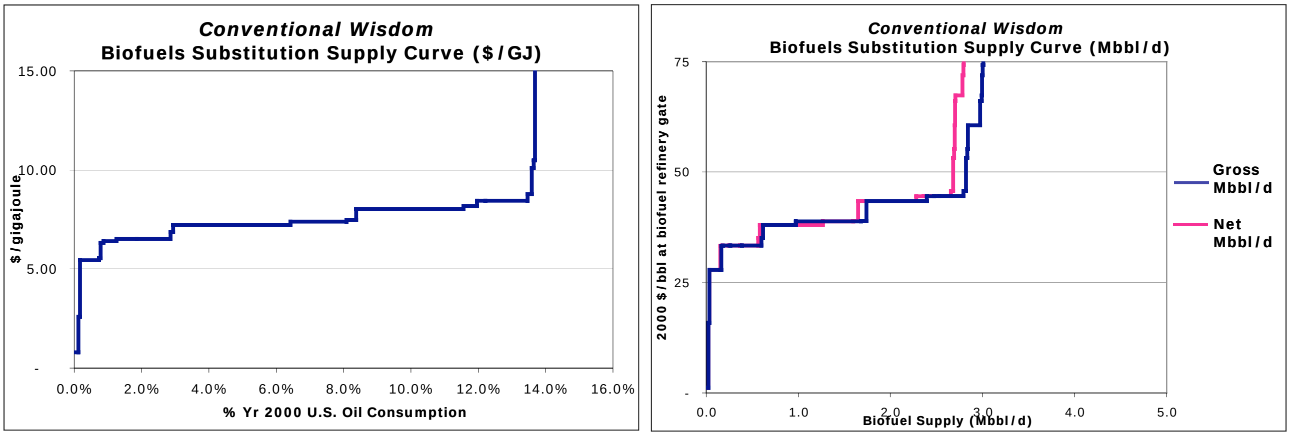
In general, treating soil like dirt is proving less profitable and durable than treating it as a biotic community—an extraordinarily valuable form of natural capital to be productively used and reinvested in. Highly integrated "Natural Systems Agriculture" is proving that letting free ecosystem services sponsor fertility and crop protection can match or beat the yields, margins, and risks of practices based on chemical or genomic artifice. Properly grown feedstocks can even *reverse* CO_2 emissions by taking carbon out of the air and sequestering it in enriched topsoil whose improved tilth can boost agronomic yields.[49] It would be as unrealistic to assume that biofuels will automatically solve any of the basic problems of contemporary agriculture as to imagine that farming and forestry reforms will spontaneously triumph over deeply entrenched practices and concentration trends, which are both reinforced by and reinforcing current public policies. But at a minimum, biofuel efforts should be designed around recommended practices, and could greatly benefit from the new nature-mimicking methods' inherent and increasing advantages. It is as important for imported as for homegrown biofuels that the way their feedstocks are produced should enhance, not degrade, biotic productivity. Industry standards of practice, analogous to those now spreading through the world's timber industry, should thus be designed into international biofuels trade from the start.

An additional feedstock considered is offal and other animal processing wastes using a recently industrialized thermal depolymerization process that could produce 0.05 Mbbl/d of bio-oil, from $20/t feedstocks, at prices as low as $13.20/bbl. One such process, owned by Changing World Technologies, [50] is analogous to the delayed-coker technology used in oil refining, and has recently been extended to handle many other forms of waste, including feedlot manure, municipal solid waste, sewage sludge, used tires, and automotive shredder fluff. Other such technologies are possible. Successful commercial application of this technology to such diverse feedstocks (not included in our analysis) could potentially produce up to an additional million or so barrels per day of biobased oil or two quadrillion BTU/y of other energy forms, effectively closing the loop on some major waste streams. Some of the feedstock streams, of course, have competing uses, and the competitive-market economics have many uncertainties, so we haven't included these resources in our supply portfolio. On the other hand, some waste streams now incur tipping fees or other disposal costs, making their bio-oil economics potentially favorable. Further European-style restrictions on refeeding animal wastes to animals would increase the U.S. waste streams requiring and paying for disposal.

3. *Conventional Wisdom*

Our *Conventional Wisdom* scenario predicts that 0.6 net Mbbl/d (1.3 quads/y) could be produced using existing technology for under $35/bbl-equivalent ($0.75/gallon of gasoline equivalent) as displayed in Figure 18–3 below. However, our analysis shows that on this scenario's assumptions, government subsidies would still be required to make investments in this technology financially attractive. Current federal subsidies (for corn ethanol), not included in these calculations, are valued at $0.53/gallon but currently are due to phase out in the next few years.[51]

Figure 18–3—*CW* Biofuels Supply Curve ($/GJ and Mbbl/d)



Feedstock availability in our model was primarily[52] based on Oak Ridge National Laboratory's 2000 state-level analysis,[53] described above, and the 2002 *Oil Crops Situation and Outlook Yearbook.*[54]

The ethanol process was modeled using co-current dilute acid prehydrolysis of the lignocellulosic biomass with simultaneous enzymatic saccharification of the remaining cellulose and co-fermentation of the resulting glucose and xylose to ethanol.[55] An ethanol conversion rate of 112 gallons of ethanol per dry ton of biomass[56] was assumed across all applicable cellulosic feedstocks. The process was modeled using an ethanol production facility with a capacity of 87.5 million gallons/year with a total capital cost of $166.7 million (2000 $).[57] Annual fixed operating costs were assumed to be $7.7 million and net variable operating costs were $0.12/gallon of ethanol (operating cost minus electricity credit).[58] A conversion of 1.23 gallons of ethanol per gallon of gasoline[59] was used for conversion to equivalent barrels of crude oil.

Table 18–3—*CW* Sample Ethanol Supply Curve Calculation

CW ETHANOL CONVERSION	Value	Units	Conv/Assump	Source	Page
Conversion Rate	112	gallons/dry short ton		21	63
Ethanol Produced	2,468,517,856	gallons			
Gasoline Equivalence (in terms of vehicle fuel economy)	1.23	gal ethanol/gal gasoline			
Equivalent Gasoline Produced	2,004,831,462	gallons			
Equivalent Crude Oil Produced (GROSS)	43,206,085	barrels	gallons to barrels		
Oil sourced Energy Use in Production	2,719	Btu/gal ethanol		11	16
Combustion Efficiency Gain	20%	%		79	875
Net Energy Production	238,582,392	Million Btu	ethanol to HHV Btu		
Net Energy Production	251,728,282	Gigajoules	mBtu to gigajoules		
Unit Capacity	87,500,000	gal/year per plant		21	63
Unit Capital Cost	166,704,365	$/plant	$1997 to $2000	21	63
Capital Cost	4,703,002,302	$			
Capital Life	20	years	Off-Oil Standard		
Real Discount Rate	5%	%	Off-Oil Standard		
Capital Recovery Factor	0.08				
Feedstock cost	480,304,124	$			
Unit Fixed Operating Cost	7,686,225	$/plant	$1997 to $2000	21	52
Unit Operating Cost	0.197	$/gal ethanol	$1996 to $2000	21	51
Unit Electricity Credit	0.077	$/gal ethanol	$1996 to $2000	21	51
Total Net Operating Cost	512,364,001	$			
Cost per Unit Ethanol Produced at the Refinery Gate	0.56	$/gallon ethanol			
Cost per Unit Gasoline Equivalence at the Refinery Gate	0.68	$/gallon gasoline			
Short Run Marginal Cost of Refining	0.09	$/gallon	Oil to Gasoline		
Transportation Cost to Oil Refinery for Blending	0.01	$/gallon			
Approx Cost per Unit Barrel Oil Equivalent (GROSS)	27.86	$/barrel	gallons to barrels		
Cost per Unit Net Energy Produced	5.44	$/Gigajoule			

Biodiesel was modeled as transesterification of vegetable oil with methanol and sodium methylate to a methyl ester followed by acid washing to refine the biodiesel product, and additional purification of the glycerin byproduct with hydrochloric acid. A conversion rate of 1 gallon of biodiesel per 8.39 lb of oil was used for all suitable feedstock streams.[60] Capacity was assumed to be 13 million gallons of biodiesel per year at a total capital cost of $18.2 million.[61] Fixed annual operating costs of $1.9 million and variable operating costs of $0.11 were included, as was a $0.27 per gallon coproduct credit for glycerin.[62] Diesel fuel equivalence was calculated at 1.10 gallons of biodiesel per gallon of standard diesel fuel.[63]

CW BIODIESEL CONVERSION	Value	Units	Conv/Assump	Source	Page
Conversion Rate	8.39	lbs oil/gallon of biodiesel		69	1
Biodiesel Produced	302,866,627	gallons	short tons to pounds		
Diesel Equivalence (in terms of vehicle fuel economy)	1.10	gal biodiesel/gal diesel		55	1
Equivalent Diesel Produced	275,333,297	gallons			
Equivalent Oil Produced (GROSS)	6,584,036	barrels	gallons to barrels		
Oil sourced Energy Use in Production	2.96	MJ/kg biodiesel	Kg oil to MJ	60	166
Energy Produced	38,223,586	Million Btu	gal biodiesel to Btu		
Net Energy Production	36,833,065	Gigajoules	MJ/kg*gal*density		
Unit Capacity	13,000,000	gallons biodiesel/year		62	49
Unit Capital Cost	18,159,516	$/plant	2002 to 2000	62	47
Capital Cost	423,070,096	$			
Capital Life	20	years	Off-Oil Standard		
Real Discount Rate	5%	%	Off-Oil Standard		
Capital Recovery Factor	0.08				
Feedstock cost	223,406,733	$	short tons to pounds		
Unit Fixed Operating Cost	1,914,960	$/plant	2002 to 2000	62	49
Unit Operating Cost	0.11	$/gallon biodiesel	2002 to 2000	62	49
Unit Glycerine Credit	0.27	$/gallon biodiesel	2003 to 2000	80	81
Total Net Operating Cost	(4,660,699)	$			
Cost per Unit Biodiesel Produced	0.83	$/gallons biodiesel			
Cost per Unit Diesel Equivalence	0.92	$/gallon diesel			
Short Run Marginal Cost of Refining	0.09	$/gallon	Oil to Diesel		
Transportation Cost to Oil Refinery for Blending	0.01	$/gallon			
Approx Cost per Unit Barrel Oil	35.08	$/barrel oil			
Cost per Unit Net Energy Produced	6.86	$/Gigajoule			

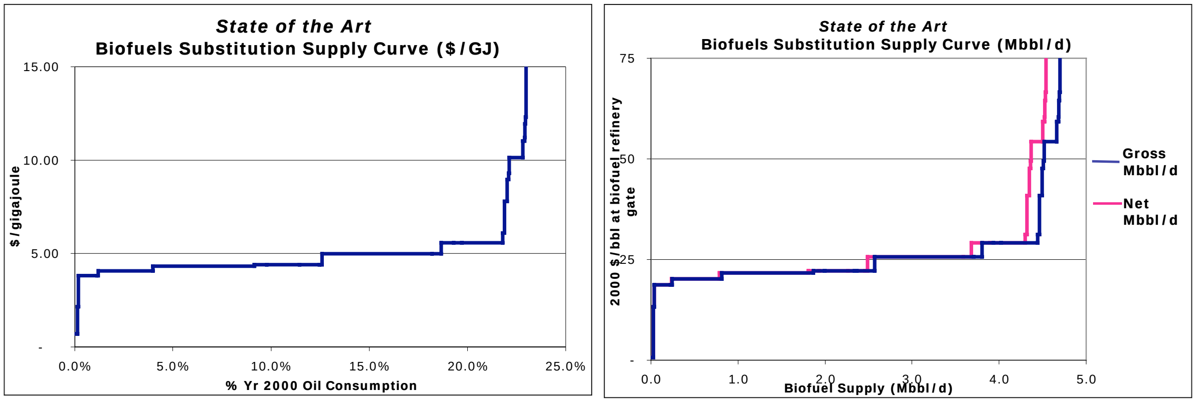
Table 18–4—*CW* Sample Biodiesel Supply Curve Calculation

Each of the processes drew from common assumptions on feedstocks (for each applicable feedstock) and the conversion process that produced the maximum amount of energy was selected along with its corresponding price for incorporation into the supply curve. Each of the $/bbl-equivalent prices represent short-run available refiner acquisition cost (RAC),[64] assuming delivery costs to retail vendors will be similar to those from oil refineries.

4. *State of the Art*

As can be seen in the charts below, the *State of the Art* analysis results in a much larger and cheaper potential than the *Conventional Wisdom* scenario. Our analysis predicts that 4.3 net Mbbl/d (9.2 quads/y) will be available for under $35/bbl-equivalent ($0.75/gallon gasoline equivalent) based on conversion and technology improvements, 3.7 Mbbl/d of which will be competitive with EIA’s short-run marginal cost of $26/bbl. Therefore, after fully implementing *State of the Art* end-use efficiency improvements, 18% of the remaining U.S. oil dependence could be profitably displaced by unsubsidized biofuels.

Figure 18–4—*SOA* Biofuels Supply Curve ($/GJ and Mbbl/d)



The difference between small, subsidized oil displacement in *CW* and large, unsubsidized displacement in *SOA* is the technologies used to convert the same feedstocks to the same biofuels. Throughout this report, our *State of the Art* scenario depicts technologies that were sufficiently developed at the time of writing to be confidently expected as timely and competitive market entrants. Technologies that fit this description were included into the biofuels analysis and described below.

Our *SOA* scenario adopted the Pearson Gasification Process for ethanol production. This process has demonstrated the capacity to produce more than 180 gallons of ethanol per dry ton of biomass,[65] vs. the historical chemical-fermentation yields of fewer than 100 gal/dt using mostly corn. Pearson Technologies (PTI) of Mississippi has developed a unique technology that gasifies biomass in the absence of oxygen to produce syngas that is reacted with a proprietary catalyst in a Fischer-Tropsch synthesis loop to produce ethanol. This technology vastly increases the kinds of materials that can be used as feedstocks and uses more of the available carbon than fermentation processes, while retaining the higher conversion rates and keeping costs of ethanol production below those of existing technologies. The Pearson process was modeled as a 96-million gal/y plant with a capital cost of $156.6 million, fixed operating costs of $6.6 million, and variable operating costs of $0.076/gallon of ethanol.[66]

Figure 18–5—The Pearson Gasification Process[67]

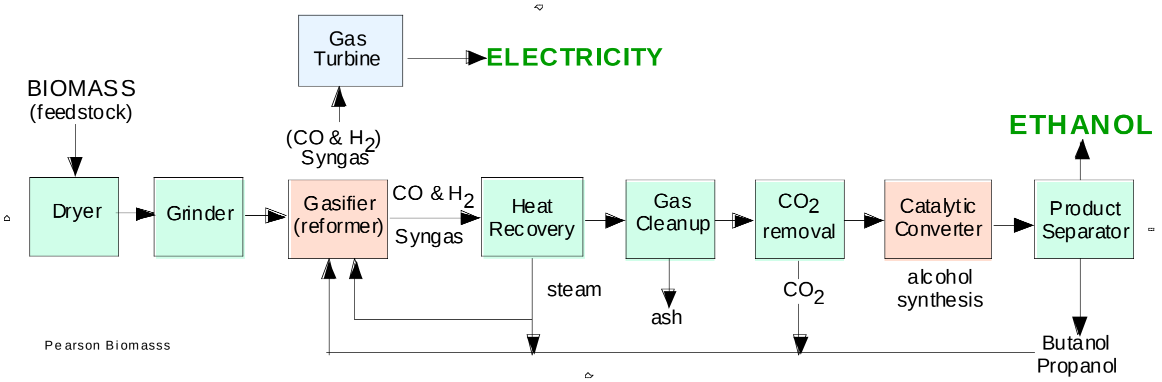


Table 18–5—*SOA* Sample Ethanol Supply Curve Calculation

SOA ETHANOL CONVERSION	Value	Units	Conv/Assump	Source	Page
Conversion Rate	180	gal/ton (short)		77	31
Ethanol Produced	3,967,260,840	gallons			
Gasoline Equivalence (in terms of vehicle fuel economy)	1.23	gal ethanol/gal gasoline			
Equivalent Gasoline Produced	3,222,050,564	gallons			
Equivalent Oil Produced (GROSS)	69,438,350	barrels	gallons to barrels		
Oil sourced Energy Use in Production	2,719	Btu/gal ethanol		11	16
Combustion Efficiency Gain	20%	%		79	875
Net Energy Production	389,811,942	Million Btu	ethanol to HHV Btu		
Net Energy Production	411,290,580	Gigajoules	mBtu to gigajoules		
Unit Capacity	96,000,000	gal/year per plant		78	1
Unit Capital Cost	156,605,538	$/plant	$2003 to $2000	78	1
Capital Cost	6,471,823,097	$			
Capital Life	20	years	Off-Oil Standard		
Real Discount Rate	5%	%	Off-Oil Standard		
Capital Recovery Factor	0.08				
Feedstock cost	480,304,124	$			
Unit Fixed Operating Cost	6,548,335	$/plant	$2003 to $2000	78	1
Unit Operating Cost	0.076	$/gal ethanol	$2003 to $2000	77	38
Unit Electricity Credit	0.000	$/gal ethanol		77	38
Total Net Operating Cost	571,171,186	$			
Cost per Unit Ethanol Produced	0.40	$/gallon ethanol			
Cost per Unit Gasoline Equivalence	0.49	$/gallon gasoline			
Short Run Marginal Cost of Refining	0.09	$/gallon	Oil to Gasoline		
Transportation Cost to Oil Refinery for Blending	0.01	$/gallon			
Approx Cost per Unit Barrel Oil	18.77	$/barrel	gallons to barrels		
Cost per Unit Net Energy Produced	3.82	$/Gigajoule			

Biodiesel production technologies will also improve, driving cost per gallon down and conversion rates up. An *SOA* improved conversion rate of 1 gallon of biodiesel per 7.57 lbs of oil was used[68] to account for improvements in the esterification process and improved raw material quality. Plant capacity was held constant at 13 million gal/y but capital cost (2000 $) was reduced to $16.3 million[69] to account for improved processing technology. The glycerin coproduct credit was reduced to $0.27 per gallon of biodiesel to reflect the increased supply and corresponding downward price pressure due to increased volumes of biodiesel production.[70] However, due to feedstock constraint—far less vegetable oil is available than lignocellulosic feedstocks—only 1.1**%** of the *SOA* quantity below $35/bbl (0.8% below $26/bbl) is biodiesel.

Table 18–6—*SOA* Sample Biodiesel Supply Curve Calculation

SOA BIODIESEL CONVERSION	Value	Units	Conv/Assump	Source	Page
Conversion Rate	7.569	lbs oil/gallon of biodiesel		62	49
Biodiesel Produced	335,718,193	gallons	short tons to pounds		
Diesel Equivalence (in terms of vehicle fuel economy)	1.10	gal biodiesel/gal diesel		55	1
Equivalent Diesel Produced	305,198,357	gallons			
Equivalent Oil Produced (GROSS)	7,298,199	barrels	gallons to barrels		
Oil sourced Energy Use in Production	2.96	MJ/kg biodiesel	Kg oil to MJ	60	166
Energy Produced	42,369,650	Million Btu	gal biodiesel to Btu		
Net Energy Production	41,407,969	Gigajoules	MJ/kg*gal*density		
Unit Capacity	13,000,000	gallons biodiesel/year		62	49
Unit Capital Cost	16,343,564	$/plant	2002 to 2000	62	47
Capital Cost	422,063,984	$			
Capital Life	20	years	Off-Oil Standard		
Real Discount Rate	5%	%	Off-Oil Standard		
Capital Recovery Factor	0.08				
Feedstock cost	223,406,733	$	short tons to pounds		
Unit Fixed Operating Cost	1,914,960	$/plant	2002 to 2000	62	49
Unit Operating Cost	0.11	$/gallon biodiesel	2002 to 2000	62	49
Unit Glycerine Credit	0.27	$/gallon biodiesel	2003 to 2000	80	81
Total Net Operating Cost	(5,166,239)	$			
Cost per Unit Biodiesel Produced	0.75	$/gallons biodiesel			
Cost per Unit Diesel Equivalence	0.83	$/gallon diesel			
Short Run Marginal Cost of Refining	0.09	$/gallon	Oil to Diesel		
Transportation Cost to Oil Refinery for Blending	0.01	$/gallon			
Approx Cost per Unit Barrel Oil	31.24	$/barrel oil	gallons to barrels		
Cost per Unit Net Energy Produced	6.09	$/Gigajoule			

5. Whole-Systems Benefits

Our *SOA* analysis finds 3.7 net Mbbl/d of crude displacement from biofuels available for less than $26/bbl-equivalent. As a very rough approximation, if long-run future oil prices remained at $40/bbl, a perpetual output of 1,351 Mbbl/y multiplied by the $14/bbl difference, and discounted at our 5%/y real discount rate would represent a $378 billion present-value investment opportunity.

A transition to biofuels as a substitute for foreign oil imports has obvious benefits to America's environment, economy, and energy security. According to AUS Consultants, Inc., increasing demand for biofuels to 5 billion gallons by 2012 is predicted to have the following effect through that same year:

- improve energy security by reducing crude oil imports by a cumulative total of 1.6 billion barrels
- grow the U.S. economy by cutting our trade deficit by a cumulative $34 billion
- enhance rural economic development by generating more than $5.3 billion in new investment opportunities
- boost employment by creating more than 214,000 new jobs throughout the U.S. economy
- save taxpayer money by reducing direct government payments to farmers by $10.6 billion

Benefits specific to the agriculture industry are also very significant. That same 5 billion-gal/y biofuel output would increase farm income by $4.5 billion/y or $39 billion through 2012.[71] On a community level, an average 40-Mgal/y ethanol plant would have significant positive economic impacts as detailed in Table 18-7 below.[72] Full implementation of RMI's *SOA* scenario (75.2 b gal/y new ethanol production at less than $26/bbl crude equivalent) would thus bring impressive benefits to rural economies.

Table 18–7 — Local Benefits of Biofuel Production ($ in millions)

	40-Mgal/y Ethanol Plant	Full *SOA* Implementation (1,881 40-Mgal/y plants)
One-time Boost to Local Economy	$142	$267,043
Local Economic Base Expansion	$110	$207,241
Full-time Plant Jobs	41	77,104
Economy-wide Jobs	694	1,305,128
Increased Household Income	$19.2	$36,107
State and Local Sales Tax	$1.2	$2,257

Carbon credits represent another potential system benefit and potential source of revenue from the substitution of petroleum fuels with biofuels. The net emission saving from biofuel production and use is equal to the difference between the full fuel-chain carbon intensity of the baseline fuel (e.g., gasoline) and the carbon intensity of the biofuel required to deliver an equivalent amount of engine output power. The carbon intensity of the biofuel includes the carbon content of the fossil fuel used to produce feedstock, transport and convert it to the final fuel carrier, and deliver it to the customer, and also depends on the yield of biofuel per ton of feedstock input.[73]

Assuming that the average rate of net accumulation of carbon in vegetation and soil on the land used for biofuel production is equal to the rate of accumulation for the previous land use, and because we have already accounted for fossil-fuel energy usage in our biofuel conversion processes, it is possible to calculate a first-order approximation of the net emission savings. Our reported net bbl-equivalents of biofuel are already adjusted for energy equivalence (including heat content and combustion efficiency), so the carbon content of displaced fuel is approximately equal to the carbon saved. Our *SOA* estimate of 1.59 billion bbl-equivalents of displaced crude oil per year would eliminate 181 million tonnes of carbon emissions per year.[74] Assuming carbon credit values of $10–50/tonne of carbon, this would reduce the net price per barrel by $1–6/bbl if the value was captured by the grower, increasing net pretax farm income by about $26–128/acre-y.[75] More broadly, "if the carbon removed from the air could be traded for, say, $25/metric tonne—manyfold less than climate skeptics expect—it could earn $9–20 per acre per year for the average U.S. farmer."[76]

Progress towards ozone attainment is another system benefit of the substitution of petroleum transportation fuels with biofuels. The 1990 Clean Air Act required the EPA to set National Ambient Air Quality Standards for pollutants that are considered harmful to human health and the environment. Ozone, which is formed by the combination of nitrogen oxides (NO_x) and volatile organic compounds (VOCs) in the presence of sunlight, was identified as a significant health risk and has both 1-hour and 8-hour standards in place. According to the EPA, 45% of VOCs and 56% of NO_x emissions are produced by motor vehicles.[77] Final designations of nonattainment areas were announced in April of 2004 and final State Implementation Plans (SIP) are due in 2007. EPA officials have estimated the cost of attainment to reach tens of billions of dollars over the next 15 years.[78] However, biofuels' reduced levels of the precursor emissions to ozone represent a profitable path towards a solution for meeting the ozone standards established to protect public health.

6. The Transition

Europe is demonstrating that a transition to biofuels is already achievable through its commitment to biodiesel. Due to high existing fuel taxes on transportation fuels (as high as 74% of the UK's $5.48/gal ($US) price for diesel fuel),[79] European countries have been able to implement partial (UK, France) and even full (Germany, Austria, Italy, Spain) detaxation policies, thereby making biodiesel cost competitive with traditional diesel fuel. In addition, the European Commission Directive of 2003 established reference value targets of 2% energy content of all transport fuel by 2005 and 5.75% by 2010 for biofuels.[80] Subsidy-free cost-effectiveness will continue to be difficult for biodiesel however, as prices for the glycerin byproduct fall with increased supply and increasing competition for feedstocks.

Though possible and already underway, the biofuels transition will have significant impacts on its related industries. Fuel standards will force the development of new relationships among automobile OEMs, engine OEMs, and fuel suppliers in order to evaluate biofuels' impacts on automobile engines and their warranties (such as the Volkswagen/Daimler Chrysler/CHOREN Industries renewable fuels collaboration). European automakers have already approved blends of up to 5% and are currently evaluating blends up to 30%.[81] Retail fuel distribution will likely remain the same but the dominant players in the distribution chain may change. Germany has seen BP and Shell become the dominant distributor of biofuels while independent companies like Greenergy have taken the lead in the UK by selling branded biofuel products through supermarkets and hypermarkets.

7. Biomaterials

Besides replacing transportation fuels with biobased fuels, there is an opportunity to replace petroleum-derived materials and feedstocks with bioproducts. Bioproducts are defined as industrial and consumer goods derived fully or partly from biomass feedstocks. The National Research Council found in 1999 that "a much larger and competitively priced biobased products industry will eventually replace much of the petrochemical industry."[82] Without competing with food, biofuel, or other production needs, the panel found it realistic by 2020 to meet at least 25% of 1994 needs for organic carbon-based industrial feedstock chemicals, and ultimately over 90%. The Biomass Research and Development Technical Advisory Committee, established by the Biomass R&D Act of 2000, believes that production of chemicals and materials from biobased products will increase from 5% (12.3 billion lb/y) of 2001 production to 12% in 2010, 18% in 2020, and 25% in 2030.[83]

Based on these targets, we adopt a linearly extrapolated value of 27% (of 1994 supply) in 2025 from the NRC, or 0.6 Mbbl/d[84] for our *Conventional Wisdom* value. For *State of the Art*, we conservatively estimate 0.9 Mbbl/d[85] of petroleum savings, based on biomass availability consistent with the feedstock findings in our biofuels analysis: 0.9 Mbbl/d represents the unused portion of the available biomass after assuming conversion to biofuels for prices lower than $26/bbl. We assume that feedstock prices, slightly above those needed for competitive biofuels, can compete in the less demanding, higher-margin biomaterials markets.

There are many potential markets for bioproducts, including polymers, lubricants, solvents, adhesives, and pharmaceuticals. Organic chemicals, including plastics, solvents and alcohols, represent the largest and most direct market for bioproducts based on the similar basic composition of carbon and hydrogen (175b lb in 2001).[87] Lubricants and greases are another sizeable market in which bioproducts are beginning to compete (20b lb in 2001).[88] In fact, Sterling Bio-Technologies Corporation's biolubricant made from 100% vegetable oil was named the "2004 World's Best Technology" by the Federal Laboratory Consortium for Technology Transfer, and began commercial production in April 2004. Its ~$1–2/gal price premium in retail drum quantities is expected to drop to approximate parity with production scale.

Table 18–8—Current Industrial Bioproduct Production[86]

Category	Type of Product	Annual Biobased Production (billion pounds)
Starch and Sugars	Polymers, solvents, inks, adhesives	5.4
Oil/Lipids	Lubricants, pharmaceuticals, surfactants	1.6
Forest Derivatives	Soaps, adhesives, plastics	5.3
Total		**12.3**

Base oil, which typically composes 75% of a lubricant, can be mineral oil, synthetic oil, or vegetable oil and is used to impart lubricity to the product.[89] Vegetable oil-based lubricants have the potential to outperform conventional lubricants with higher viscosity, lower evaporation loss, and higher lubricity. The considerable variety of biolubricants now emerging makes it reasonable to target efficiency-plus-biomaterials savings of 19% for *Conventional Wisdom* and 56% for *State of the Art* lubricants in 2025.[90] This represents a *CW* savings of 0.04 Mbbl/d and 0.11 Mbbl/d for *SOA* based on 2000 petroleum supply to lubricants.[91]

The price of bioproducts remains generally high compared to those of conventional products, but there are markets where bioproducts are able to compete economically, and bioproduct output for those successful markets totaled 12.3 billion lb in 2001 (excluding lumber, pulp, and paper). The cost gap continues to narrow, and already a few manufacturers are producing bioproducts on an industrial scale. Cargill Dow is producing 140,000 metric tons of NatureWorks,[93] a wholly biobased polylactide (PLA) fermented from corn, to be used in numerous applications including packaging and fabrics. Metabolix has been working to commercialize fermentation to PHA technology since the early 1990s, and launched its first 50,000-liter/y polymer production site in 2002.[94] DuPont's polymer platform known as 3GT™ (based on 1,3-propanediol and terephthalate) will begin producing Bio-PDO™ corn-derived chemical/1,3- propanediol commercially in 2006.[95]

Table 18–9—Production Costs of Selected Bioproducts ($/lb)[92]

Product	Petroleum-derived	Biobased
Adhesives	1.65	1.40
Acetic Acid	0.33	0.35
Pigments	2.00	5.80
Inks	2.00	2.50
Plastics	0.50	2.00

Biorefineries represent a key price reduction route for bioproducts. This concept operates similarly to a petroleum refinery by taking in multiple types of biomass feedstocks and converting them through a complex processing strategy to a variety of coproducts including biofuels, biomaterials, power, chemicals, and heat. The biorefinery concept is already in use, particularly in the pulp and paper industry, which uses wood to coproduce paper, fiber, chemical, electricity, and steam. Much the same can be said for some modern integrated processing plants for corn and soy feedstocks. Flexibility will be critical in this model to allow the refineries to vary input streams and to produce a changing product slate to meet shifting market requirements.

The market for bioproducts continues to grow, both organically and through policy mechanisms. The Farm Security and Rural Investment Act of 2002, which reauthorizes the Biomass R&D Act of 2000, mandates the purchase of biobased products by federal agencies when practical in order to improve demand for biobased products, spur manufacturing development in rural communities, and enhance the nation's energy security.

Our petroleum savings from bioproduct substitution counts only feedstock substitution, but feedstock energy represents only 43% of the industry's energy use (the other 57% is used in processing).[96] Efforts are being made to incorporate waste and byproducts into the process energy supply, much as they are used in biofuels production (lignin, bagasse, etc). In addition, field-to-factory gate analysis of feedstock and process energy use reveals that process energy use can be significantly lower for biobased plastics than for petrochemical polymers. Fossil energy use can currently be reduced by 20–50% through bioplastic replacement, with estimates of up to 80% for new projects (Cargill Dow).[97] Pure thermoplastic starch requires 65–70% less process energy than polyethylene, though more typical starch/petrochemical blends currently show savings nearer 30%.[98] Therefore, substitution of petrochemical feedstocks is not one-for-one, making our *SOA* substitution value of 0.9 Mbbl/d conservative. It s beyond the scope of this report to estimate how conservative our *SOA* value is.

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[11] This value represents the *net* crude oil equivalent energy that can be displaced by biofuels. The *gross* energy equivalent has been adjusted to account for energy required in the production and transport of the biomass feedstocks, feedstock conversion to biofuels, and biofuel energy equivalence including combustion efficiency adjustments. (These terms are unrelated to the gross and net heat content used in some countries as synonymous for HHV and LHV.)

[2] The price/bbl was calculated by converting $/gal of biofuel into $/gal of standard fuel (gasoline or diesel) at the refinery gate by using the appropriate heat content equivalency. From that value we subtracted the short-run marginal cost (SRMC) of refining and added the transportation SRMC. This value was adjusted for the difference in heat content between the fuel (gasoline or diesel) and crude oil, and was then converted to a per-barrel basis.

[3] The EIA 2025 forecasted petroleum consumption value is 28.3 Mbbl/d and the RMI *SOA* 2025 consumption value equals 20.8 Mbbl/d.

[4] The NRC report stated targeted 10 percent of 1994 levels of liquid fuels from a biobased products industry by 2020, and up to 50 percent of liquid fuels by 2100. (*Biobased Industrial Products: Priorities for Research and Commercialization*, National Research Council, National Academy Press, 1999.) In 1994, petroleum use was 16.265 Mbbl/d (Energy Information Administration, *Annual Energy Review 2002*, Table 5.11—Petroleum Products Supplied by Type, 1949–2002.)

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[5] Smith, S.J., Wise, M.A., Stokes, G.M., Edmonds, J., "Near-Term US Biomass Potential: Economics, Land-Use, and Research Opportunities," Battelle Memorial Institute, Joint Global Change Research Institute, March 2004.

[6] IEA (2004a) predicts a post-2010 price for cellulosic ethanol of $0.19/L or $0.72/gal (IEA 2004a, Table 4.5, p. 78) —higher than our predicted *State of the Art* price of $0.61/gal ethanol ($0.75/gal gasoline-equivalent), or slightly lower if Table 4.6 (p. 79) is correct in labeling the IEA figures as gasoline-equivalents. The IEA price is based on an NREL estimate (as quoted in IEA, 2000, "Liquid Fuels from Biomass: North America; Impact of Non-Technical Barriers on Implementation") that assumed an ethanol conversion rate of 112 gal/ton vs. our *SOA* conversion rate of 180 gal/ton. Substituting the 180 gal/ton rate into the IEA calculation results in a price of $0.57/gal ethanol, which is actually lower than our predicted *SOA* price.

[7] Petersen, J., D. Erickson, & H. Khan. "A Strategy: Moving America Away from Oil." Arlington VA: Arlington Institute. August. www.arlingtoninstitute.org/whatsnew.html.

[8] Armstrong, R. E., "From Petro to Agro: Seeds of a New Economy," *Defense Horizons*, Volume Number 20, October 2002.

[9] Kovarik, William, "The 1920s Environmental Conflict Over Leaded Gasoline and Alternative Fuels," Annual Conference of American Society for Environmental History, March 2003.

[10] Personal communication with Bill Holmberg, May 20, 2004.

[11] Kovarik, William, "The 1920s Environmental Conflict Over Leaded Gasoline and Alternative Fuels," Annual Conference of American Society for Environmental History, March 2003.

[12] Smith, S.J., Wise, M.A., Stokes, G.M., Edmonds, J., "Near-Term US Biomass Potential: Economics, Land-Use, and Research Opportunities," Battelle Memorial Institute, Joint Global Change Research Institute, March 2004.

[13] Smith, S.J., Wise, M.A., Stokes, G.M., Edmonds, J., "Near-Term US Biomass Potential: Economics, Land-Use, and Research Opportunities," Battelle Memorial Institute, Joint Global Change Research Institute, March 2004.

[14] Iogen Corporation press release, "Cellulose Ethanol Is Ready To Go: Iogen producing world's first cellulose ethanol fuel. Iogen Corporation announced today that it is producing the world's first cellulose ethanol fuel for commercial use," April 2004, www.iogen.ca.

[15] Press release dated 26 April, 2004, "Novozymes and NREL report further progress in biomass-to-ethanol project."

[16] Coelho, S.T. and Goldemberg, J., "Alternative Transportation Fuels: Contemporary Case Studies," *Encyclopedia of Energy*, Volume 1, 2004, pp. 67–80.

[17] Coelho & Goldemberg.

[18] Coelho & Goldemberg.

[19] Table 4.4 on p. 77 of IEA 2004 shows that in fact, in mid-2002 and early 2004, Brazilian bioethanol (at approximately $0.72/gal gasoline-equivalent) achieved our 2025 bioethanol price of $0.75/gal gasoline-equivalent.

[20] "Biofuels Trade Policies Stir Controversy," Bio-Economic Research Associates (Bio-era, Boulder, CO), 10 June, 2004.

[21] Adapted from Smith, S.J., et al. A nominal 10% processing and storage loss was assumed for both crops. The assumed yield was 94 gallons of ethanol per dry ton of switchgrass.

[22] MacLean, H.L., Lave, L.B., and Griffin, W.M., "Alternative Transport Fuels for the Future," *Int. J. Vehicle Design*, Vol. 35, Nos. 1/2, 2004, pp. 27–49.

[23] MacLean, H.L., Lave, L.B., and Griffin, W.M., "Alternative Transport Fuels for the Future," *Int. J. Vehicle Design*, Vol. 35, Nos. 1/2, 2004, pp. 27–49.

[24] Wyman, Charles E., "Ethanol Fuel," *Encyclopedia of Energy*, Volume 2, 2004, pp. 541–555. The 21,105 BTU/gal value represents the weighted-average for wet and dry milling facilities. 68,000 BTU/gal is an average value of the 60,000–76,000 BTU/gal range reported for various cellulosic feedstocks.

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[25] Wang, M., Saricks, C., and Santini, D., "Effects of Fuel Ethanol Use on Fuel-Cycle Energy and Greenhouse Gas Emissions," Center for Transportation Research, Energy Systems Division, Argonne National Laboratory, January 1999.

[26] Emissions effects were compared on per-vehicle-mile fuel-cycle petroleum use, greenhouse gas emissions, and energy use of using ethanol blended with gasoline in a midsize passenger car, compared with the effects of using gasoline in the same car. GHG emissions are global warming potential (GWP)-weighted, carbon dioxide-equivalent emissions of carbon dioxide, methane, and nitrous oxide. The greater than 100% reduction in GHG emissions comes from emissions avoided at electric power plants due to electricity generated in the cellulosic ethanol plant. The ranges of values represent wet vs. dry milling ethanol procedures.

[27] General Motors Corporation, Argonne National Laboratory, British Petroleum, ExxonMobil, and Shell, *Well-to-Wheel Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems—North American Analysis* **2**:3–13, Fig. 3.6, June 2001, www.transportation.anl.gov:80/pdfs/TA/164.pdf.

[28] Schumacher, L.G., Van Gerpen, J., and Adams, B., "Biodiesel Fuels," *Encyclopedia of Energy*, Volume 1, 2004, pp. 151–162.

[29] Biodiesel production numbers for the EU are from the European Biodiesel Board (www.ebb-eu.org/states.php) and converted from mass to volume using an assumed density of 0.88 tonnes/m^3 (Coelho, S.T. and Goldemberg, J.).

[30] "Biodiesel Around the World," Canadian Renewable Fuels Association, www.greenfuels.org/bioworld.html.

[31] Schumacher, L.G., Van Gerpen, J., and Adams, B., "Biodiesel Fuels," *Encyclopedia of Energy*, Volume 1, 2004, pp. 151–162.

[32] Schumacher, L.G., Van Gerpen, J., and Adams, B., "Biodiesel Fuels," *Encyclopedia of Energy*, Volume 1, 2004, pp. 151–162.

[33] Personal communication with James Newcomb, May 28, 2004.

[34] Adapted from "Dedicated Feedstocks," Bioenergy Feedstock Development Program, Oak Ridge National Laboratory, www.bioenergy.ornl.gov/papers/misc/feedstock.html.

[35] Armstrong, R. E., "From Petro to Agro: Seeds of a New Economy," *Defense Horizons*, Volume Number 20, October 2002.

[36] Walsh, M.E., Perlack, R.L., Turhollow, A., de la Torre Ugarte, D., Becker, D.A., Graham, R.L., Slinsky, S.E., Ray, D.E., "Biomass Feedstock Availability in the United States: 1999 State Level Analysis," Oak Ridge National Laboratory, updated January 2000.

[37] Adapted from data in Walsh, M.E. et al.

[38] Armstrong, R. E., "From Petro to Agro: Seeds of a New Economy," *Defense Horizons*, Volume Number 20, October 2002.

[39] de la Torre Ugarte, D. G., Walsh, M.E., Shapouri, H., Slinsky, S.P., "The Economic Impacts of Bioenergy Crop Production on U.S. Agriculture," U.S. Department of Agriculture, February 2003.

[40] 23.4 million acres of existing planted crops are replaced with bioenergy crops but the net loss of traditional crop acreage is only 20.5 million acres, or 6.2% of the 1999 total planted acreage of 325.4 million acres (traditional crops are modeled to be grown on additional idle and pasture acreage: de la Torre Ugarte, D.G, et al.).

[41] Figure 18–2 is adapted from Wright, L. and Cushman, J., and assumes up to 42 million acres available for profitable energy crop production at a farmgate price below $44/dt. The data was generated by Wright and Cushman using POLYSIS, an agricultural sector model that includes all major agricultural crops.

[42] Wright, L.L., and Cushman, J., "Biomass Feedstock Research and Development for Multiple Products in the United States," Oak Ridge National Laboratory, Bioenergy Feedstock Development Program, February 2002.

[43] Bransby, David, "Switchgrass Profile," Auburn University.

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[44] Ash, Mark, "Oil Crops Situation and Outlook Yearbook," Market and Trade Economics Division, Economic Research Service, U.S. Department of Agriculture, October 2002, OCS-2002 www.ers.usda.gov/publications/so/view.asp?f=field/ocs-bby/.

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[58] Wooley, Sheehan, and Ibsen, 1999.

[59] The conversion rate of 1.23 gallons of ethanol per gallon of gasoline is calculated as follows: ethanol contains only 67.7% of the heat content of gasoline (84,600 BTU/gal [HHV] divided by 125,000 BTU/gal [HHV]). However, as stated on p. 875 of "Ethanol and Methanol from Cellulosic Biomass" by Wyman, Bain, Hinman and Stevens (1993), "a 20% gain in engine efficiency can be obtained relative to gasoline in a well-designed engine." Therefore, multiplying 67.7% by 1.2 equals 0.812 gallons of gasoline per gallon of ethanol or inversely, 1.23 gallon of ethanol per gallon of gasoline.

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[63] The diesel equivalence factor (1.10 gal biodiesel/gal diesel) was calculated based on the difference in heat content between the two fuels (138,700 BTU/gal diesel divided by 126,200 BTU/gal biodiesel).

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[64] The calculated cost-per-gallon of biofuel was energetically equated to cost-per-gallon of standard fuel, from which the short-run marginal cost of refining was subtracted ($0.093 for gasoline and $0.089 for diesel) and to which the cost of transportation ($0.01) was added. This cost was then adjusted for the heat content as compared to crude and converted to a $/bbl-equivalent value.

[65] Shleser, Robert, "Biomass-Ethanol Perspective and Opportunities," Worldwide Energy Group.

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[74] 1.59 billion bbl-equivalents of crude are equal to 214 billion kg of displaced crude oil (assuming a density of 0.85 kg/L). Assuming that crude oil is 84% carbon, 181 million tonnes of carbon emissions would be saved each year (U.S. Department of Labor, Occupational Safety & Health Administration, www.osha.gov/dts/osta/otm/otm_iv/otm_iv_2.html.)

[75] Assuming a crop yield of 7 tons/acre and an ethanol conversion rate of 180 gal ethanol/ton, 22 barrels of crude equivalent per acre could be replaced each year. Using a 0.85 kg/L density for crude and an 84% carbon content results in a 2.56 tonnes/acre carbon savings. Therefore, assuming a carbon credit price of $10–50/tonne carbon yields $1.16–5.82/bbl-equivalent, or ~$26–128/acre-y.

[76] Hawken, P., Lovins, A.B., and Lovins, L.H., *Natural Capitalism*, Little, Brown and Company, 1999, p. 205.

[77] U.S. Environmental Protection Agency, Office of Air and Radiation, EPA 451/K-03-001, June 2003, www.epa.gov/oar/oaqps/gooduphigh/ozone.html#6.

[78] Doyle, Michael, "Valley Fails New Smog Standard: New Rule Requires Ozone Levels Measured for 8 Hours," *Modesto Bee*, April 16, 2004, Section A, Pg. A1.

[79] The March 2004 fuel price and tax percentage are from www.theaa.com/allaboutcars/fuel and were converted to US$ using the March 2004 exchange rate from www.chartflow.com/ozforex/averageRate.asp?period=mth&ccy1=GBP&ccy2=USD&days=30&amount=1000.

[80] "Directive 2003/30/EC of the European Parliament and of the Council of 8 May 2003 on the promotion of the use of biofuels or other renewable fuels for transport," *Official Journal of the European Union*, L 123/42, May 2003.

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[84] We adopt a linearly extrapolated value of 27% (of 1994 usage) in 2025 from the NRC (*Biobased Industrial Products: Priorities for Research and Commercialization*, 1999). Of the 2.159 Mbbl/d petroleum used as feedstocks other than for asphalt and lubricants in 1994 (EIA *Annual Energy Review 2002*, 2003,

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Table 5.11), 27% would be 0.583 Mbbl/d. Subtracting 0.23 Mbbl/d of savings due to plastics recycling (pp. 94–95 of *Oil Endgame* main report) from the original EIA feedstock demand of 2.075 Mbbl/d in 2025 leaves net feedstock demand in 2025 of 1.845 Mbbl/d, of which 0.583 Mbbl/d is a 32% substitution.

[85] For the 2025 *SOA* biomaterials substitution potential we adopt a conservative 0.9 Mbbl/d—the unused portion of the available biomass after assuming conversion to biofuels for prices <$26/bbl—for a saving of 52% of the forecasted post-efficiency 1.75 Mbbl/d. The 0.9 Mbbl/d value assumes the same energy-conversion efficiency as the biofuels processes for the biomaterials processes, i.e., the remaining biomass feedstocks would yield enough biomaterials to displace ~0.9 Mbbl/d of crude-oil petrochemicals demand.

[86] Paster, M., Pellegrino, J.L., and Carole, T.M., *Industrial Bioproducts: Today and Tomorrow*, Energetics, Inc. for the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Office of the Biomass Program, July 2003, www.bioproducts bioenergy.gov/pdfs/BioProductsOpportunitiesReportFinal.pdf.

[87] Paster, Pellegrino, and Carole, 2003.

[88] Paster, Pellegrino, and Carole, 2003.

[89] Paster, Pellegrino, and Carole, 2003.

[90] The *Conventional Wisdom* 19% represents a 25% conversion of the 75% of lubricants that are base oil to biobased oils. The 56% *State of the Art* value represents a 75% conversion of the 75% base oil.

[91] The *CW* and *SOA* percentages were multiplied by 203,700 bbl/d (Petroleum Products Supplied by Type, EIA *Annual Energy Review 2002* , Table 5.11 showing 166,000 Mbbl/d; scaled out to 2025 by the forecasted growth rate of 1.2% from EIA 2004, Table 11).

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