CHAPTER 14

Biofuels, Biomass, and Other Alternative Fuels

> We don't need oil, and we definitely don't need hydrogen for our cars and light trucks. We don't need new engines, new fuel distribution and storage, and we don't need a lot of money or time to do this. Through three simple inexpensive policy changes we can kick start the transition and reassure investors that there is a long-term market for ethanol, not subject to price manipulation by the oil-producing countries. . . . And this is not an alternative fuel option. It can replace all our oil imports and become the center of our transportation fuels economy. The other impediment, the various politically powerful interest groups also seem to be well aligned. Other objections, like land use, environmental impact and energy balance can be overcome.
>
> Vinod Khosla, April 2006

These words sound like those of a utopian environmentalist, but they come from one of the world's most successful venture capitalists. They would have sounded like a pipe dream as recently as mid-2005, but in 2006 and 2007, similar versions were coming from a variety of unlikely sources, including energy companies, farm groups, environmental organizations, Madison Avenue, and the White House. Combined with increased efficiency offered by lighter hybrid vehicles with plug-in options, these groups argue that biofuels can take a big bite out of oil imports and overall consumption, improving urban air quality, and reducing GHG emissions. Global biofuel production grew by 22% per year in 2005 and 2006. But not all are so optimistic about biofuels. Debate continues about the net energy of biofuels production, the effect of biofuels from food crops on food prices, the prospects for non-food crop biofuels, and the subsidies and import tariffs that affect biofuels markets.

This chapter explores the options for alternative transportation fuels to replace oil. Some of these options are linked to the propulsion technologies discussed in the last chapter, especially flex-fuel vehicles that can use 85% ethanol (E85) or biodiesel blends, and electric drive motors using batteries charged by hybrid engines, plug-in grid, on-site generation, or fuel cells. This chapter gives an overview of alternative transportation fuels and then presents in more detail the opportunities and constraints for fuel ethanol, biodiesel, other biomass energy, as well as natural gas and hydrogen.

14.1 Introduction to Alternative Transportation Fuels

We learned in the last chapter that petroleum fuels 96% of the transportation energy in the United States. Because of the current and long-term problems with oil, there has been considerable talk of switching to alternative fuels since the 1974 oil embargo. But there has been little progress because petroleum products have remained relatively cheap (until recently) and special interests have helped protect the status quo. Today, we see increased attention to alternative fuels, and we do have some experience in several alternatives to help us decide how to proceed.

Let's review the several types of alternative fuels available for use in transportation vehicles:

- **Alternative fossil fuels** include liquefied petroleum gas (LPG), liquefied natural gas (LNG), and compressed natural gas (CNG). Together these were the largest source of energy for alternative fueled vehicles in the United States in 2005 (Table 14.1). These vehicles are modified to use these fuels. Some are "dual-fuel" vehicles that can use both gasoline and the alternative, but unlike flex-fuel vehicles they need two separate fuel-handling systems. Because they have much lower urban air pollutant emissions than gasoline and diesel vehicles, they are primarily used to fuel buses and other large vehicles in metropolitan areas not meeting air quality standards. Once looked upon as a viable option for alternative fuels, price volatility is a growing concern as these fuels tend to follow oil prices.
- **Electricity** used in electric vehicles amounted to less than 0.1% of alternative fuel in 2005, but it has grown considerably since 1995 (Table 14.1). Plug-in, electric, and fuel cell vehicles could greatly increase the use of electricity for transportation.
- **Alcohol fuels** include ethanol and methanol, and these are blended with gasoline in different proportions. E85 is 85% ethanol and 15% gasoline, while E10 or "gasohol" is 10% ethanol and 90% gasoline. Methanol from natural gas was used until the mid-1990s, but little is used today (Table 14.1). Alcohol has less energy content than gasoline; E85 has 27% less energy per gallon, but mileage comparison tests have shown that E85 has 5%–12% less mpg than gasoline. E85 is growing quickly because an increasing number of flex-fuel vehicles are available, and some areas, especially the midwestern states, have expanded the availability of E85. Still most ethanol fuel use has been in E10 gasohol as an oxygenate additive to gasoline to reduce carbon monoxide emissions.
- **Biodiesel** is a distillate or diesel fuel replacement made from biomass oils including vegetable oils, such as soybean or rapeseed; waste vegetable oils; or algae. It is blended with petroleum diesel in blends that range from B-2 to B-100. Still a very small source of fuel, U.S. biodiesel production grew eightfold from 2004 to 2006 and the number of fueling stations quadrupled.

table 14.1 Alternative Fuel and Oxygenate Consumption, 1995–2005

Alternative fuel	1995*	2005*	2005 %
Liquefied petroleum gas	232,701	188,171	5.9%
Compressed natural gas	35,162	166,878	5.3%
Liquefied natural gas	2759	22,409	0.7%
M85	2023	0	0.0%
M100	2150	0	0.0%
E85	190	38,074	1.2%
E95	995	0	0.0%
Electricity	663	5,219	0.0%
Subtotal	**278,121**	**420,776**	**13.2%**
Oxygenates			
MTBE	2,693,407	1,654,500	–
Ethanol in gasohol	**934,615**	**2,756,663**	**86.8%**

* Values for 1995 and 2005 are thousand gasoline-equivalent gallons.
Source: U.S. DOE, Alternative Fuel Database, 2007

- **Other alternative fuels:** Other fuels have more limited availability or are under development. Hydrogen re-formed from natural gas for use in fuel cells and coal-to-liquids, natural gas-to-liquids, and fuels from unconventional oil sands and shales may contribute to future transportation fuels, but they have greater economic and environmental obstacles to overcome than do biofuels or electricity.

Table 14.1 gives the gasoline-equivalent gallons consumed of different alternative fuels in 1995 and 2005. Ethanol amounted to 87% of all alternative fuels in 2005, just about all as an oxygenate additive for gasoline. Oxygenates were mandated in gasoline to reduce carbon monoxide emissions under the Clean Air Act amendments of 1990. Use of methyl tertiary butyl ether (MTBE) oxygenate grew rapidly until the late 1990s when concerns grew over its water pollution problems. California and New York, with a combined 40% of total MTBE consumption, banned its use after January 1, 2004. As a result the consumption trends shown in Table 14.1 have continued. Daily MTBE use has dropped significantly from 2004 to 2006, whereas ethanol use in gasohol increased 30% over the same period. In 2006, EPA lifted the requirement for oxygenate additives.

Although increased use of ethanol in gasohol displaces some gasoline, ethanol's real potential is in E85. Table 14.1 shows significant growth from 1995 to 2005 and this growth continues. The leading state, Minnesota, saw sales of E85 increase from 2.6 million gal (Mgal) in 2004 to 21 Mgal in 2007. Still only 6% of the state's filling stations offer the fuel, and only 5% of the state's vehicles are flex-fuel.

A key issue in the widespread adoption of any alternative fuel is the development of infrastructure for its delivery. Table 14.2 lists the number of alternative-fuel filling stations in the top sixteen states, as well as national totals in 2007 and previous years. With its CNG and

table 14.2 Alternative-Fuel Filling Stations, July 2007

State	CNG	E85	LPG	ELEC	LNG	BD	H_2	ALL
California	184	3	232	379	28	34	23	883
Texas	16	29	556	1	2	45	0	649
Minnesota	1	306	31	0	0	2	0	340
Illinois	14	146	64	0	0	12	0	236
Missouri	7	60	82	0	0	48	0	197
Michigan	13	44	79	0	0	16	2	154
Pennsylvania	29	11	78	0	0	35	1	154
South Carolina	5	46	29	1	0	67	0	148
Indiana	14	84	33	0	0	11	0	142
Colorado	21	26	67	2	0	24	0	140
Ohio	11	34	68	0	0	21	0	134
Oklahoma	51	1	71	0	0	7	0	130
North Carolina	10	9	54	0	0	56	0	129
Wisconsin	16	60	47	0	0	4	0	127
Washington	13	6	56	0	0	32	0	107
Iowa	0	68	24	0	0	13	0	105
Total 2007	**727**	**1166**	**2459**	**444**	**35**	**705**	**31**	**5567**
Total 2006	**732**	**762**	**2619**	**465**	**37**	**459**	**17**	**5091**
Total 2003	**1035**	**188**	**3966**	**830**	**62**	**142**	**7**	**6230**
Total 2000	**1217**	**113**	**3268**	**558**	**44**	**2**	**0**	**5205**

Source: U.S. DOE, Alternative Fuel Database, 2007

electric refilling stations, California has the largest number, but Minnesota leads in E85 stations, Texas leads in LPG, and South Carolina leads in biodiesel filling stations. Whereas most other alternative-fuel stations have dropped in number, E85 and biodiesel stations have increased sixfold from 2003 to 2007. Still the number of alternative-fuel stations is small compared to the 170,000 gasoline filling stations across the country.

Price is also a major issue in the adoption of alternative fuel, and the price of alternative fuels varies among fuels. They are affected by the price of gasoline as shown by the data for 2005 to 2007 in Table 14.3. Although CNG and E85 are the lowest-priced fuels per gallon in Table 14.3, they are usually hard to find. On an energy equivalent basis, E85's price is not as competitive. CNG requires a dedicated or dual-fuel vehicle, and E85 requires a flex-fuel vehicle.

table 14.3 Prices by Fuel, September 2005 to June 2007

	Sept 05 per gal	Feb 06 per gal	June 06 per gal	Oct 06 per gal	Mar 07 per gal	Jun 07 per gal	Jun 07 per gg/de	Jun 07 per MBtu
Gasoline	$2.77	$2.23	$2.84	$2.22	$2.30	$3.03	$3.04	$26.25
Diesel	$2.81	$2.56	$2.98	$2.62	$2.63	$2.96	$2.65	$22.98
CNG	$2.12	$1.99	$1.90	$1.77	$1.94	$2.09	$2.10	$18.18
Propane (LPG)	$2.56	$1.98	$2.08	$2.33	$2.62	$2.58	$3.57	$30.91
Ethanol (E85)	$2.41	$1.98	$2.43	$2.11	$2.10	$2.63	$3.72	$32.21
Biodiesel (B-2–B-5)	$2.81	$2.46	$2.67	$2.75	$2.75	$2.84	$2.55	$22.09
Biodiesel (B-20)	$2.91	$2.64	$2.67	$2.66	$2.53	$2.96	$2.70	$23.43
Biodiesel (B-99–B-100)	$3.40	$3.23	$3.76	$3.31	$3.31	$3.27	$3.22	$27.89

Source: U.S. DOE, Alternative Fuel Price Report, 2007

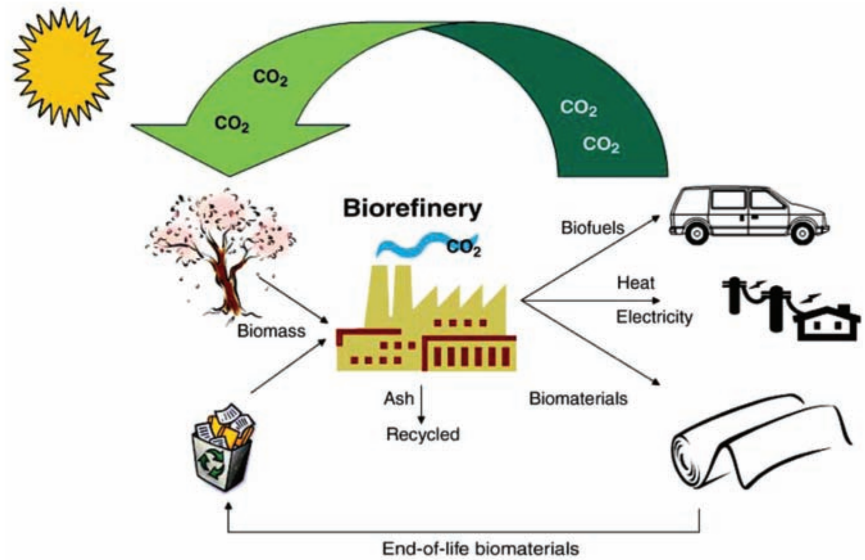
14.2 Prospects and Potential for Biomass Fuels

Have you thanked a green plant today? Of course, we know that through the miracle of photosynthesis, plants are able to absorb solar energy and atmospheric carbon, providing not only the food and materials for all living things, but possibly a significant answer to our economy's energy needs and our environment's need for carbon sequestration. **Biomass** is vegetative and animal waste organic matter that can be converted into useful energy. It includes **solid fuel** like wood and plant residues that can be burned directly for thermal energy or power production. It can be converted to **liquid biofuels** like ethanol and biodiesel that can substitute for gasoline and diesel fuel, or to **gaseous fuels** like methane and **biogas** that can be burned for thermal energy or used in gas turbines to produce electric power.

Figure 14.1 shows the classic carbon cycle with an emphasis on bioenergy. With the sun's radiant energy and atmospheric carbon dioxide (and other nutrients), plants produce physical biomass, which stores the sun's energy. The biomass can be processed in a variety of ways and converted to solid, liquid, and gaseous fuels that can be used for vehicle transport, heat, and power generation, and/or for biomaterials that can be used for building materials, paper, and other products. Processing in a biorefinery usually emits some of the biomass carbon as CO_2 and may require some fossil fuels that also emit CO_2. The end-use combustion of biomass energy also emits CO_2 as the carbonaceous materials are oxidized; and all of this CO_2 ends up in the atmosphere. But biomass combustion is generally considered to be **greenhouse-gas-neutral** because it is part of the contemporary carbon cycle—its carbon recently came from the atmosphere and its carbon emissions are in balance with subsequent absorption by revegetation. Biomaterials can sequester carbon in building materials and other products or can be recycled back to reprocessing for subsequent use.

Biomass energy is the largest source of renewable energy in the world today, and the primary fuel for cooking and heating for nearly half of the world's population. In Africa,

figure 14.1 **The Biomass Energy Carbon Cycle**



Biomass is stored solar energy and atmospheric carbon that can be processed in biorefineries and converted to usable fuels and biomaterials. Combustion releases carbon back to the atmosphere and materials can be recycled. Operating in the contemporary (rather than fossil) carbon cycle, biomass energy combustion is "carbon neutral."

Source: from Ragauskas, et al., *Science 311*:484–489 (2006). Reprinted with permission from AAAS.

biomass contributes about one-half of primary energy; in Asia about one-fourth. Of course, this is mostly traditional firewood and charcoal and is not included in commercial energy markets that we use to monitor energy data. If traditional biomass were accounted for, it probably would make up about 10%–15% of global energy use.

But this extensive use of biomass among the world's poor is also an indicator of poverty. Potentially productive time must be used simply gathering fuelwood and charcoal. Indoor and urban air pollution from wood and charcoal cookstoves is a major health hazard. Both charcoal production and traditional stoves are extremely inefficient, so most of the hard-earned energy is lost. Improvements in stove technology, like the $2 Kenya Ceramic Jiko charcoal stove, can greatly improve efficiency and air quality.

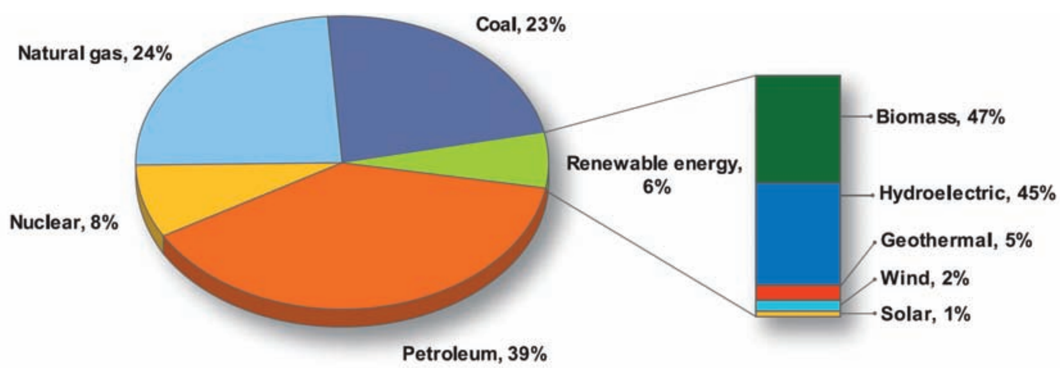
Many think development in poorer countries will come with modern energy systems, but these need not be fossil-fuel based. Wind and photovoltaic power are promising sources in such contexts, but so too is biomass energy as long as it transitions from traditional to more modern applications, such as biomass power plants, fuel ethanol, biodiesel, and biogas from methane digestion.

In the United States, biomass is the largest source of renewable energy today. In 2006, just 7% of U.S. energy came from renewables, and biomass contributed 48% of that, followed closely by hydroelectric power (42%). Hydro's annual contribution fluctuates with precipitation. About half of biomass energy currently comes from residues and pulping liquors in the forest products industry; about 18% from urban wastes and construction residues; about 18% from fuelwood for residential woodstoves and electricity generation; and about 10% from liquid biofuels, mostly ethanol. About 190 million dry tons (Mdt) of forest and agricultural biomass are used for energy. The fastest growing forms of biomass energy are fuel ethanol and biodiesel, liquid products that directly replace petroleum products in transportation. World production of ethanol is growing by more than 20% per year and U.S. production grew by 24% in 2006 to 4.86 billion gallons (Bgal) and another 42% in 2007 to about 7 Bgal. Biodiesel volume is smaller, but its growth rate is even faster. U.S. production increased by 18 times from 25 Mgal in 2004 to an estimated 450 Mgal in 2007. This recent growth in biofuels is not reflected in the 2004 data in Figure 14.2. Before turning specifically to these biofuels, we look at overall potential for biomass.

14.2.1 U.S. Biomass Energy Potential

A number of studies have recently assessed the potential biomass energy production in the United States (e.g., U.S. DOE, 2002; Greene and Mugica, 2005). Perhaps the most comprehensive recent study prepared at Oak Ridge National Laboratory (Perlack, et al., 2005),

figure 14.2 U.S. Biomass Resource Consumption, 2004



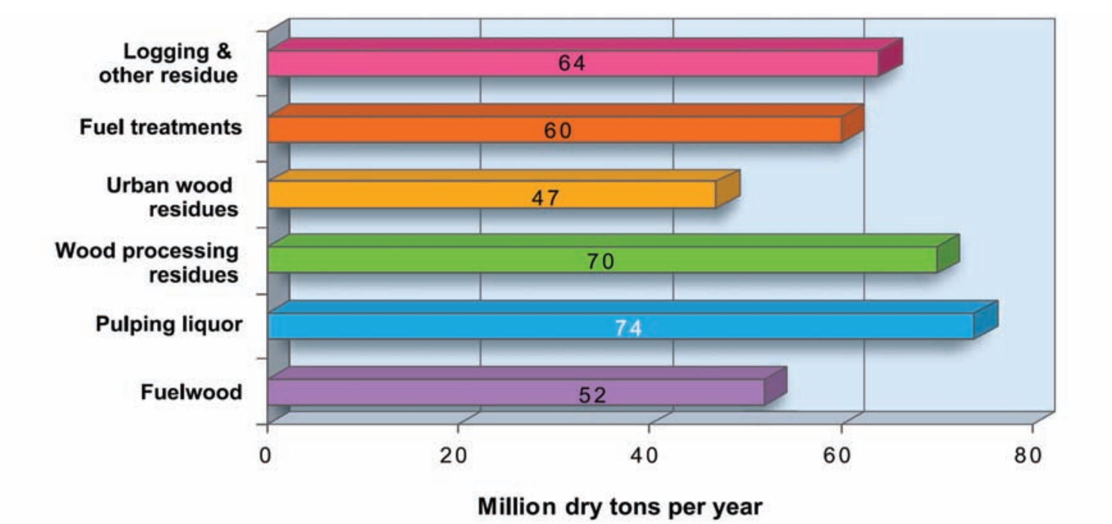
Biomass Consumption	Million dry tons/year
Forest products industry	
Wood residues	44
Pulping liquors	52
Urban wood and food & other process residues	35
Fuelwood (residential/commercial & electric utilities)	35
Biofuels	18
Bioproducts	6
Total	**190**

Source: Perlack, et al., 2005; Oak Ridge National Laboratory assessed the potential of forest and agriculture land resources to sustainably supply biofuels to offset petroleum consumption in the United States. The study found that more than 1.3 billion dry tons (Bdt) per year of biomass energy materials could be produced, which could replace more than one-third of the nation's current petroleum consumption. This includes 370 Mdt on forest lands and 1 Bdt from agricultural lands. A key issue is balancing the need for energy with that for other agricultural products. According to ORNL, these production targets could be achieved while meeting expected food, feed, fiber, and export demands, as well as needs for environmental conservation.

To achieve this potential, we would have to rely on woody, cellulosic fiber from fields and forests. Figure 14.3 shows that forestlands' potential of 370 Mdt includes the 140 Mdt currently used residues generated in the manufacture and use of various forest products and wood for residential space heating. Removal of logging and other residues and fuel treatment thinning are not being fully utilized and can sustainably provide more than 120 Mdt annually. These residues can be recovered from commercial harvest and land-clearing operations, and fuel treatment thinning can be done in conjunction with forest fire hazard mitigation and forest health projects.

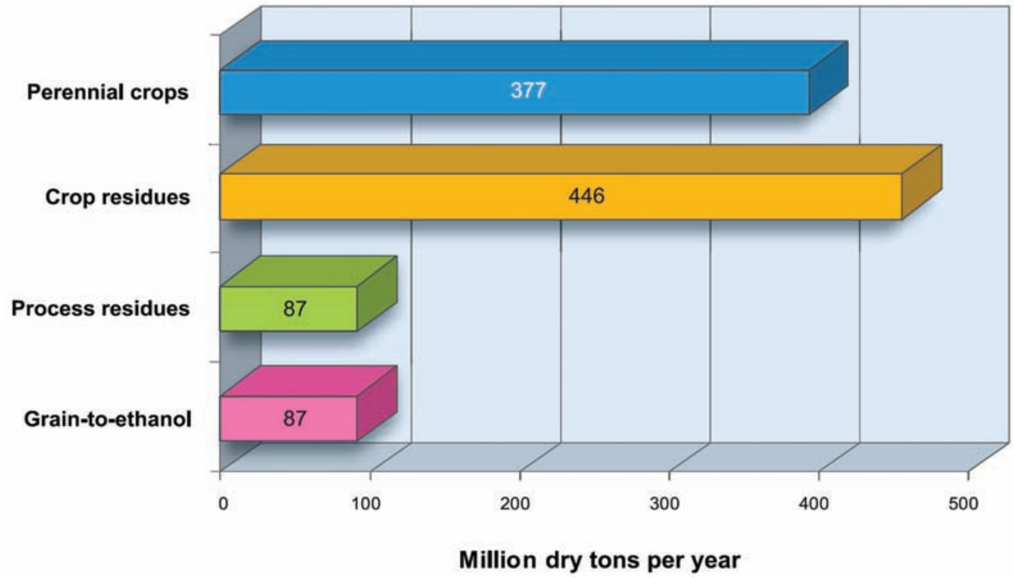
There is much greater potential available from agricultural lands. Figure 14.4 shows that farmland could provide 1 Bdt of sustainably collectable biomass without impacting food, feed, and export demands. This includes 87 Mdt from grains for biofuels and another 87 Mdt from animal manures, process residues, and other residues generated in the consumption food products.

figure 14.3 **U.S. Forestland Biomass Energy Potential**



Fuelwood, pulping liquors, and processing residues are mostly existing uses. Others represent new potential.

Source: Perlack, et al., 2005; Oak Ridge National Laboratory figure 14.4 **U.S. Agricultural Land Biomass Energy Potential**



Grain-to-ethanol and process residues are modest increases above current land use, enhanced by improved yields. Significant new potential comes from perennial grasses/woody crops and residues.

Source: Perlack, et al., 2005; Oak Ridge National Laboratory

The increase in grains for biofuels over current levels is largely due to expected increase in yields and not a diversion from food and export markets. However, the biggest potential increase in agricultural biomass is not from grain crops but from crop residues (446 Mdt) and perennial grasses and woody crops (377 Mdt), or 82% of the total potential.

However, the job of achieving this potential will not be an easy one. It will require

- Increasing yields of corn, wheat, and other small grains by 50%
- Doubling residue-to-grain ratios for soybeans
- Developing much more efficient residue harvesting equipment
- Managing active cropland with no-till cultivation
- Growing perennial crops dedicated to bioenergy purposes on 55 million acres of pasture, cropland, and idle cropland (including Conservation Reserve Program [CRP] lands)
- Using for bioenergy excess animal manure not applied on-farm for soil improvement
- Using a larger fraction of other secondary and tertiary residues for bioenergy
- Developing a large-scale biorefinery industry (Perlack, et al., 2005)

It is important to understand the scale of change necessary to pull off this billion ton growth in biomass energy. Table 14.4 gives the assumptions and scenarios of the ORNL study. All scenarios assume the same agricultural land harvested or reserved as today,

table 14.4 Agricultural Lands Biomass Energy Potential, Three Scenarios

Crop	Acres	Product Yield	Residue Yield	Total Mass	Total Residue	Residue Sustainably Removable	Grains for Bioenergy	Secondary Residues	Total Sustainable Biomass
Million Dry Tons/Acre/Year				Million Dry Tons/Year					
				Baseline					
Corn	69	3.3	3.3	450	225	75	14	6	95
Other crops	244			608	267	38	1	0	39
CRP grasses	25	2	0	51	0	0	0	0	0
Pasture	68	1.5	0	101	0	0	0	0	0
Perennials	0	0	0	0	0	0	0	0	0
Other	42			23	58.5	0	0	60	60
Total	**448**			**1233**	**550**	**113**	**14.6**	**66**	**194**
Moderate Yield without Land Use Change*									
Corn	77	**4.1**	**4.1**	**626**	**313**	**170**	**47**	**8**	**225**
Other crops	235			689	308	**67**	9	1	**98**
CRP grasses	25	2	0	51	0	**25**	0	0	**25**
Pasture	68	1.5	0	101	0	0	0	0	0
Perennials	0	0	0	0	0	0	0	0	0
Other	43			23	73	22	0	75	75
Total	**448**			**1490**	**694**	**284**	**56**	**84**	**423**
High Yield with Land Use Change*									
Corn	77	**4.9**	**4.9**	**751**	**376**	**256**	**75**	12	**343**
Other crops	218			760	359	**173**	12	0	**186**
CRP grasses	15	2	0	31	0	15	0	0	15
Pasture	43	1.5	0	64	0	0	0	0	0
Perennials	**55**	**0.6**	**7.4**	**440**	**409**	**368**	**0**	**0**	**368**
Other	40			62	83	11	0	75	86
Total	**448**			**2108**	**1227**	**823**	**87**	**87**	**998**

* Major changes in bold.
Source: Perlack, et al., 2005; Oak Ridge National Laboratory

448 million acres. The top portion of the table gives the "baseline" of biomass currently available: 194 Mdt. The second portion of the table gives the scenario assuming moderate increase in yields (+30%), no perennials, and no land use change, resulting in 423 Mdt. Finally, the bottom portion gives the high-yield (+50%), perennials, and land-use-change scenario, which yields 998 Mdt. The land use changes involve transfer of some pasture, CRP grasses, and hay acreage to perennials, such as switchgrass.

Of this total potential of 998 Mdt, less than 9% would come from grain crops (mostly corn) and 37% would come from perennial grasses such as switchgrass, 26% from corn stover, and 26% from other agricultural residues, which all could be removed "sustainably" or with minimal impact on soils and waters. Indeed, the future potential of biomass energy depends on our ability to tap these crop residues, grasses, and woody corps, and to convert

figure 14.5 **Perennial Grasses and Crop Residues Are the Key to Increased Fuel Ethanol Production**

(a) Miscanthus

(b) Switchgrass

(c) Corn stover bales in storage

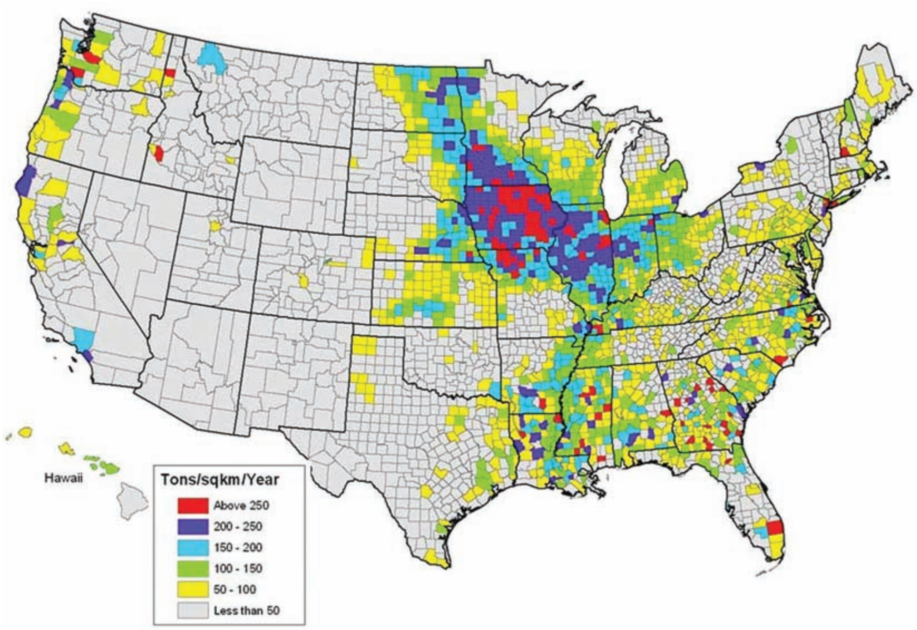
Current U.S. ethanol production uses grain crops like corn, but future production growth must come from crop residues (like the bales of corn stover above [c]) and from perennial grass energy crops (like miscanthus [a] and switchgrass [b]), which combined constitute 82% of ORNL's estimated biomass energy potential.

Sources: a: Miscanthus: photo by Patrick Schmitz, S. Long lab, University of Illinois–UC; b: Switchgrass: photo by Warren Gretz, DOE/NREL; c: Corn stover bails in storage: D. Glasser, NREL, Corn Storer, Approaching its Real Worth, 1999.

them into fuel ethanol economically (Figure 14.5). This is because biofuels from grain crops such as corn and soybeans will never be able to make a significant dent in our oil consumption without impacting food supply and price.

Where in the United States would a biomass energy industry be located? Crop-based biomass would be centered in the country's agricultural heartland, as shown in Figure 14.6 from NREL (2005). The map shows the location of the biomass resource yield (t/km^2/yr)

figure 14.6 **Biomass Resources of the United States**



Resources in tons/sqkm/yr, including dedicated energy crops, residues, municipal wastes.

Source: NREL, 2005

corresponding to the baseline case, including agricultural and woodland residues, municipal wastes, and dedicated energy crops. But conversion to perennial grass-based biomass would broaden the geographic source area beyond the heartland, especially to the southern states that have longer growing seasons. Figure 14.7, from Greene (2004), projects perennial switchgrass production (in 1000 tons per county) in 2030.

14.3 Fuel Ethanol

Humans have been making alcohol for six millennia. Yes, early humans liked beer too. The same fermentation process using microorganisms, mostly yeasts, to convert sugars into alcohol in beer is used to produce fuel ethanol. Another similarity is the current popularity of both alcoholic brews. Fuel ethanol is a replacement for gasoline, can be produced domestically, and has far lower net GHG emissions than gasoline. With higher gas prices, interest has grown among investors, government policy makers, and energy analysts in greatly expanding the production capacity of ethanol in the United States and other countries. World production

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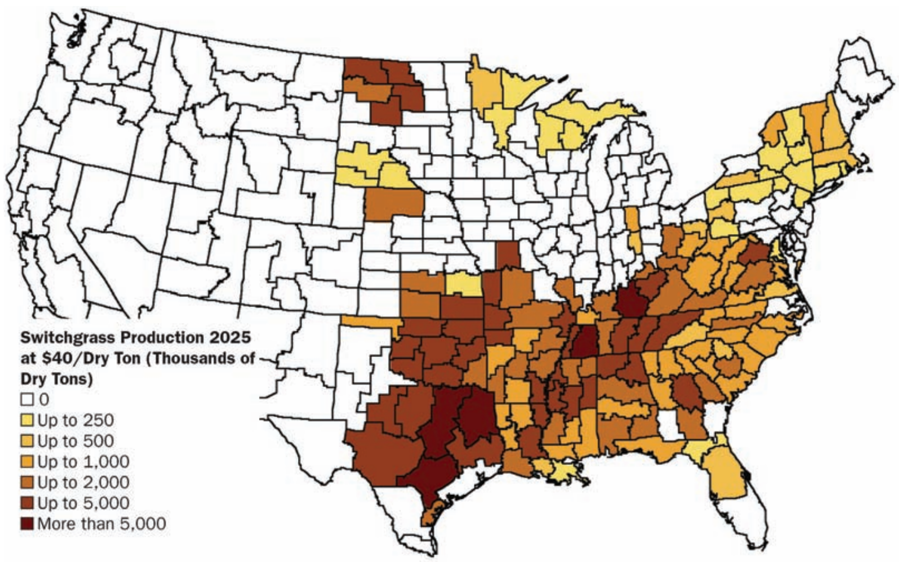
figure 14.7 **Potential Perennial Switchgrass Production in 2025 at $40/dry ton**



Source: Greene, 2004

of fuel ethanol grew from 4.6 Bgal in 2000 to 13.5 Bgal in 2006, or about 22% per year (Figure 14.8). Brazil had been the world leader in ethanol production until 2005 when the United States surpassed it.

figure 14.8 **World Fuel Ethanol Production, 1995–2006**

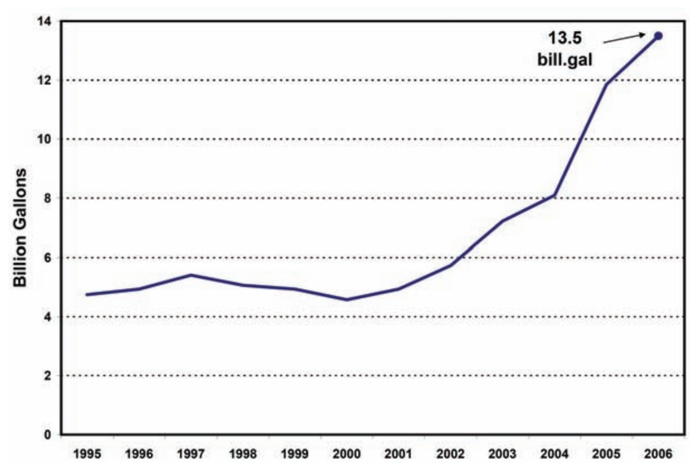
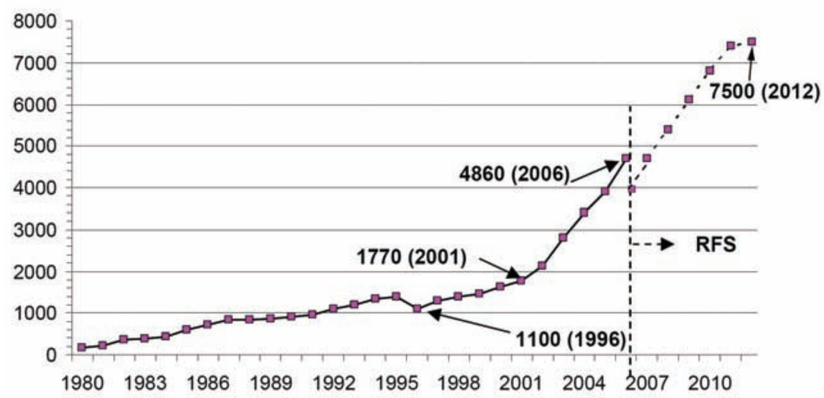


figure 14.9 **U.S. Ethanol Production, 1980–2006, and 2005 RFS for 2006–2012 (million gallons)**



The RFS enacted by the 2005 EPAct was exceeded in its first year (2006). The 2007 act's RFS calls for 35 Bgal by 2022.

The explosive growth of ethanol production in the United States is shown in Figure 14.9. Production grew by 23% per year, nearly tripling from 2001 to 4.86 Bgal in 2006. Production in 2007 is on target to hit 7 Bgal.

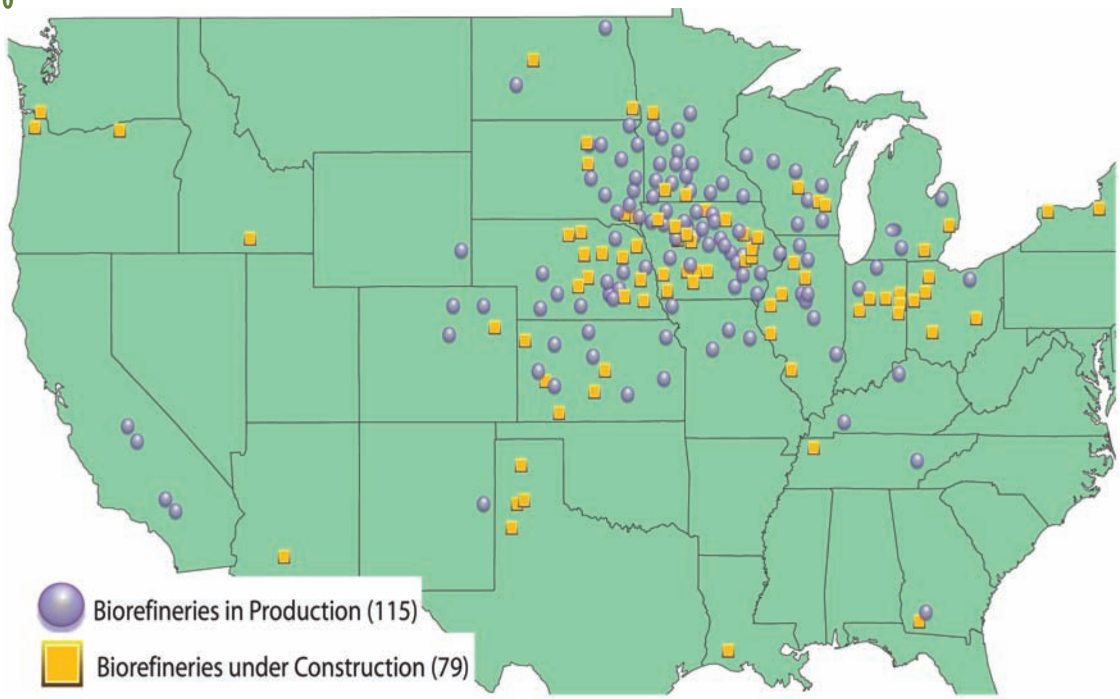
14.3.1 U.S. Ethanol Production Capabilities

This growth is expected to continue, driven in part by the national **Renewable Fuels Standard** (RFS) enacted by the 2005 and 2007 Energy Policy Acts. The 2005 EPAct's RFS requires fuel suppliers to include in their fuel supply a minimum amount of renewable fuels gradually increasing from 4.0 Bgal in 2006 (or 2.7% of total fuel supply) increasing by 0.7 Bgal each year to 7.4 Bgal in 2011 and 7.5 Bgal in 2012 (see Figure 14.9). The 2012 standard is equivalent to a savings of 80,000 bbl/day of petroleum. The act also provided a \$1 billion loan guarantee program for 80% non-recourse loan guarantees for the first four plants up to maximum of \$250 million/plant. And it provided a blender's production tax credit of \$0.51/gal ethanol through 2008. Several states have their own RFS and other incentives for ethanol (see Sidebar 14.1 and Chapter 18).

The 2005 EPAct's RFS provides a minimum production schedule that assures investors and producers of a guaranteed market, and with this assurance the fledgling industry may find its wings. It already has. In its first year, the industry exceeded the standard by 22% in 2006 when it outproduced the 2007 level a year ahead of schedule, and in 2007 production may hit 7 Bgal, exceeding the 2010 RFS. In mid-2007, President Bush called for expanding production at a much faster rate to 35 Bgal by 2017, or 20% of gasoline needs by 2017, his so-called 20-in-10 goal. By the end of 2007, Congress passed and Bush signed the expanded RFS requirement for 35 Bgal/yr by 2022 (see Chapter 17).

With new production capacity under development, this pace of growth may well occur. Table 14.5 shows the fall 2007 ethanol production capacity in the leading states, and Figure 14.10

figure 14.10 Location of Existing and New Fuel Ethanol Biorefineries, October 2007



Source: RFA, 2007

table 14.5 Ethanol Production Capacity* by State, 2007

	Online, 10/07	Under Construction	Total 10/07
Iowa	1863	1495	3358
Nebraska	1018	728	1746
Illinois	881	291	1172
South Dakota	607	378	985
Minnesota	605	498	1102
Indiana	292	556	848
Wisconsin	278	220	498
Kansas	213	295	508
Michigan	214	50	264
Missouri	186	na	186
North Dakota	123	210	333
Ohio	0	529	529
Texas	0	355	355
New York	0	164	164
Other	138	688	826
Total 10/07	**7023**	**6452**	**13,475**
Total 4/06	**4486**	**2049**	**6715**
Total 1/05			**4398**

* Million gallons per year (Mg/yr).
Source: RFA, 2007

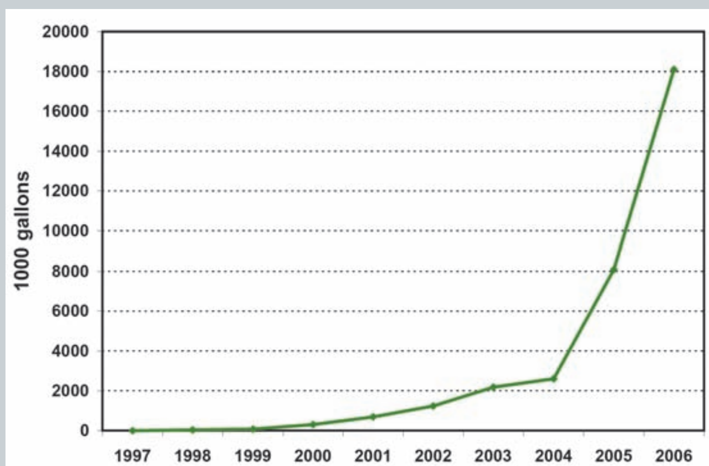
SIDEBAR 14.1

Minnesota: State Promoter of Ethanol Production and E85 Sales

In 1997, Minnesota took a mandate for gasohol sales that applied to the cities only part of the year and extended the mandate to an annual statewide requirement. All gasoline sold in Minnesota was to be E10. There was 97% penetration by 2005. Sales of E85 and the number of stations selling E85 are growing rapidly. In 2007, 21 million gallons were sold, eight times the 2004 sales. The number of fueling stations has grown from 85 in 2003 to 312 in 2007. With ethanol production capacity of almost 600 Mgal/yr in mid-2006, Minnesota is an ethanol exporter. The $1.5 billion industry employs thousands, and the state looks to expand both production and marketing. In 2005, the state approved an **E20 Renewable Fuel Standard,** requiring all gasoline sold in the state to average 20% ethanol by 2010. With its mandatory minimum E10 for all gasoline and rising sales of E85, the state may achieve the standard without any blending to E20. The RFS aims to provide more certainty to investors in the state's ethanol industry.

Minnesota E85 Sales and Stations

	E85 Sales 1000 gal	E85 Stations
2000	301	56
2001	694	65
2002	1244	70
2003	2179	85
2004	2606	101
2005	8085	175
2006	17,934	291
2007	21,400	312



gives their location. Operating and planned capacity doubled between April 2006 and October 2007. In 2007, there were 115 ethanol plants with a total production capacity of 7 Bgal/yr and 79 new plants and expansions under construction, for a total of 13.5 Bgal/yr capacity. There is a strong industrial cluster for ethanol in the Iowa, Illinois, Nebraska, South Dakota, and Minnesota region, with nearly 65% of existing and new capacity, but other states are also adding capacity. Sidebar 14.1 highlights Minnesota's ethanol industry.

This explosive growth is impressive, but 2006 production is still a drop in the bucket compared to U.S. gasoline use (3.5%), domestic oil production (6.2%), and oil imports (2.6%). Currently, ethanol is made primarily from corn in the United States, and it is used primarily as an oxygenate additive in E10 gasohol. To make a greater impact on oil and gasoline markets, three changes in ethanol production and application are needed:

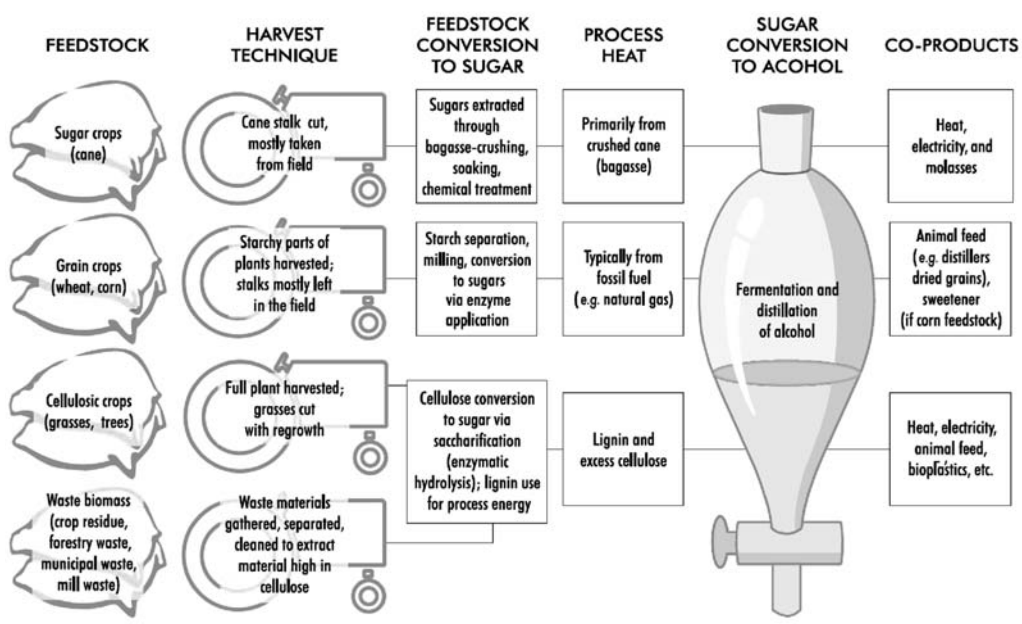
1. Ethanol capacity must continue to grow rapidly to offset a greater proportion of gasoline use.
2. The fuel ethanol market must expand from oxygenate additive to E85 fuel. This requires more E85 production and fueling stations and more flex-fuel vehicles that can use the fuel.
3. Ethanol production must transition from corn-based raw material to cellulosic residues and grasses. This requires production of perennial grasses and residues on the scale of Table 14.4 and further development and commercialization of enzymatic hydrolysis (saccharification) for large-scale conversion of cellulose to ethanol.

Although these developments will take time and investment, many see them as easier, quicker, and less risky than increasing dependence on imported oil or other alternative fuel options such as coal-to-liquids or hydrogen. Before addressing these challenges, let's first look at how ethanol is produced.

The trick in ethanol production is turning biomass materials into readily fermentable sugars. For some feed stocks, such as sugarcane used in Brazil, this production process is straightforward. For others, such as corn and especially cellulosic material, it is more complicated.

The process for four types of feedstock is illustrated in Figure 14.11. The main difference is in the feedstock conversion to sugars. Sugar crops are easy to convert. Grain crops,

figure 14.11 **Ethanol Production Steps by Feedstock and Conversion Method**



Source: IEA, *Biofuels for Transport: An International Perspective,* 2004 such as corn or wheat, require milling, starch separation, and enzymatic reaction. Conversion of cellulosic materials, such as grasses, crop residues, paper wastes, and wood, to fermentable sugars is the most complex. Their sugars are locked in complex carbohydrates (polysaccharides). To free the sugars from the woody lignin requires enzymatic hydrolysis or **saccharization.**

The key to these processes is the **enzymes.** Enzymes are active proteins that catalyze microorganism action to break down complex carbohydrates ultimately into simple sugars. The ease, time, control, and ultimately the cost of these processes depend on effective and often expensive enzymes.

All these processes require energy. Most grain crop conversions use fossil fuels for this process, whereas sugar crop and cellulosic material conversions have residual biomass materials that can be used for process heat, and this enhances the overall energy efficiency of the process.

14.3.2 Ethanol from Corn

Most ethanol from corn uses a dry milling process in which liquefied corn starch is produced by heating ground cornmeal with water and enzymes. The basic process looks like this:

$$\underset{(56\text{ lb})}{\boldsymbol{\mathit{Corn}}} \rightarrow \underset{(32\text{ lb})}{\textbf{Starch}} + \boldsymbol{H_2O} + \boldsymbol{\mathit{enzymes}} + \boldsymbol{\mathit{heat}} \rightarrow \underset{(36\text{ lb})}{\textbf{Sugars}} + \boldsymbol{\mathit{yeast}} \rightarrow$$

$$\underset{(18\text{ lb})}{\textbf{Ethanol}\ (C_2H_5OH)} + \underset{(18\text{ lb})}{CO_2} + \textbf{heat} + \underset{(17\text{ lb})}{\textbf{DDGS}}$$

where the bold italic terms = inputs to the process
DDGS = dried distillers grain solids that have a very high feed value

About 82% of ethanol production in the United States is done using a dry milling process and about 18% is from wet milling. The overall dry milling production process for corn includes the following steps:

1. **Grinding** to the consistency of coarse flour in a hammer mill or roller mill.
2. **Cooking:** Ground corn is mixed with water and two enzymes at high temperature (>120°F) and pressure (10–40 psig), then held at about 180°F–195°F for 4–8 hours. Considerable energy is used in this process and it generally comes from fossil fuels. One enzyme, **alpha amylase**, chemically liquefies the starch polymers into shorter strings, and the other, **gluco amylase** chemically "saccharifies" the short strings into sugars (mostly glucose [$C_6H_{12}O_6$]).
3. **Fermentation:** Sugar "mash" is put in tanks with large amounts of yeast that convert the simple sugars into ethanol, CO_2, and heat.
4. **Distillation:** More heat is added to boil off the ethanol, which is then condensed, separating it from non-fermentable constituents and water.

5. **Dehydration:** The 190 proof (95%) ethanol from distillation still has 5% water, which is removed by more distillation or drying columns.
6. **Fate of non-fermentables:** Because residue materials have feed value, further processing by centrifuge to 25%–40% solids (wet distillers grains with solubles) or by additional drying to about 90% solids (dry distillers grains or DDGS) adds productive and energy value (Kohl, 2003).

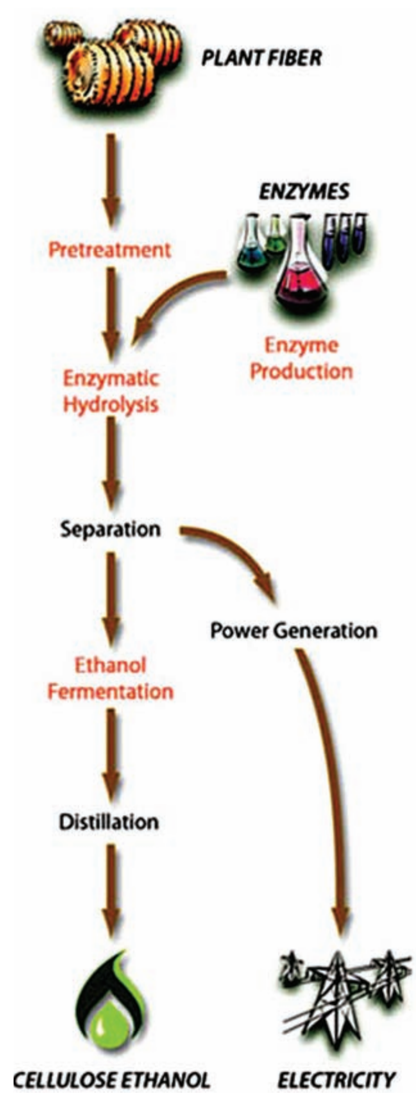
14.3.3 Ethanol from Cellulose

As we learned in section 14.2.1, the biggest potential for ethanol production is not from corn but from cellulosic materials, including

- Crop residues such as corn stover (the stock and husk) and other materials now left in the field
- Perennial grasses such as switchgrass that can be harvested and regrown rapidly without cultivation
- Fast-growing trees such as poplar and willow
- Municipal and other wastes that are high in cellulosic fibers

But the process for converting these materials into ethanol is more complex than it is for corn. They are made up of lignin, hemicellulose, and cellulose. Cellulose molecules are made up of long chains of glucose molecules similar to those of corn but they are encapsulated in lignin. Hemicellulose has long chains of 6-carbon sugars like glucose (called hexose sugars) but also 5-carbon sugars (called pentoses), and these vary depending on the plant. Special enzymes and microorganisms are needed to break down and ferment these different sugars.

figure 14.12 Cellulose Ethanol Process



Source: Passmore, 2006

Acid hydrolysis and enzymatic hydrolysis are two options for freeing the fermentable sugars from the complex polysaccharides in the cellulose; enzymatic hydrolysis is more promising. The overall process has the following steps:

1. **Pretreatment:** To break down the lignin sheath surrounding the cellulose, options include dilute acid, steam explosion, ammonia fiber explosion (AMFE), or organic solvent processes. AMFE uses ammonia under moderate heat and pressure to disrupt biomass components, and it appears to be most promising (Greer, 2005).
2. **Enzymatic hydrolysis or saccharization:** This process converts cellulose to sugars. The key barrier to cost-effective cellulosic ethanol is the high cost of enzymes, but enzyme producers in the biotechnology industry are driving down costs. Iogen, Inc., Arkenol Holdings, Genencor International, Novozymes Biotech, and other companies are active in enzyme development and other processes.
3. **Waste separation:** The lignin must be separated from the fermentable materials. It has high energy value comparable to coal and can be used to generate electricity and heat to power the operation and even feed the grid. This is a significant net energy savings for this process.
4. **Fermentation, distillation, dehydration, and the production of residue feed** materials are basically the same as in the corn-ethanol process.

Commercializing Cellulosic Enthanol: President Bush's 20-in-10 Initiative

In 2007, President Bush announced the goal of making cellulosic ethanol cost competitive with gasoline by 2012 and producing 35 Bgal per year by 2017. This, in conjunction with increased auto efficiency, could reduce gasoline consumption by **20% in 10 years.** In December 2007, this initiative was codified by Congress and extended as a 35 Bgal RFS by 2022. To facilitate this development, under the authority of the 2005 Energy Policy Act, in 2007 DOE announced grants to six companies to build six cellulosic plants in the next four years. The $385 million in grants will leverage private funds for a total investment of more than $1.2 billion. The six companies are as follows:

- Abengoa Bioenergy Biomass of Kansas (11.4 Mg/yr ethanol plus net electricity from corn stover, wheat straw, switchgrass)
- ALICO, Inc. (13.9 Mg/yr ethanol plus net electricity from biomass waste)
- Bluefire Ethanol, Inc. (19 Mg/yr ethanol from green and wood waste)
- Broin Companies (125 Mg/yr ethanol, 25% from cellulosic corn fiber, cobs, and stalks)
- Iogen Biorefinery Partners, LLC (18 Mg/yr ethanol from agricultural residues including wheat straw, barley straw, corn stover, and switchgrass)
- Range Fuels (40 Mg/yr ethanol plus 9 Mg/yr methanol from woody residues and crops)

figure 14.13 Iogen Corporation's Demonstration Cellulose-to-Ethanol Plant in Ottawa

Source: Iogen Corp.

Iogen has a proprietary enzyme used in its 260,000 gal/yr wheat straw-to-ethanol plant in Ottawa, Canada. Its U.S. partnership has attracted funding from Shell Oil, Goldman Sachs, and other investors for its Idaho commercial scale facility.

14.3.4 Ethanol Conversion Efficiencies

The conversion efficiency of biomass energy to ethanol depends on the material. NREL has a biomass feedstock and composition database for several energy crops, residues, and waste. The composition includes C-5 and C-6 polymeric sugars, which determine the theoretical ethanol yield from the material. NREL also has a convenient online calculator that computes the yield for different compositions. See http://www.eere.energy.gov/biomass/ethanol_yield_calculator.html. Table 14.6 gives the ethanol yield for several materials.

Table 14.7 gives current and prospective conversion efficiencies of biomass to ethanol for corn and switchgrass, as well as projected yields per acre. **Gasoline equivalent gallons** (gge) per dry ton and per acre are also given. The projected increase yields (dry tons per acre [dt/ac]) are taken from Perlack, et al., (2005) for corn and from Greene (2004) for switchgrass. Projections of increased conversion efficiency for switchgrass (gallons ethanol per dry ton [gal/dt]) come from Greene (2004). Included in the last two lines are energy credits from coproduction of biofuels (lignin) for generation of power and heat.

Solution Box 14.1 looks at these yields and efficiencies and the ORNL estimate of biomass potential (1.3 billion tons per year [Bdt/yr]) in the context of the 2007 RFS for 2022 (35 Bgal/yr), 2007 production (7 Bg/yr), and current petroleum data. As shown in Table 14.8, this is twenty-one times current ethanol production, three times the 2022 RFS,

table 14.6 Theoretical Ethanol Yield for Feedstock

Material	Yield (gal/dt)	Material	Yield (gal/dt)
Corn grain	124.4	Switchgrass	105.0
Corn stover	113.0	Hardwood sawdust	100.8
Rice straw	109.9	Mixed paper	116.2

SOURCE: NREL Biomass Feedstock Database

one and one-fourth times current domestic oil production, three-fourths of current gasoline consumption, and half of current oil imports.

The immense potential for cellulosic ethanol becomes clear when musing about dedicating production to energy grasses and crops. Solution Box 14.2 considers dedicating all of South Dakota's current farmland to energy grasses and crops. Given expected increases in yields and process efficiencies, South Dakota could become comparable to a member of OPEC in supply of liquid fuel.

14.3.5 Ethanol Net Energy and Greenhouse Gas Emissions

We introduced the debate over ethanol net energy in Chapter 5. The issue was popularized by Cornell University's David Pimental, who has maintained for more than a decade that it takes more energy to produce corn-based ethanol than you get out of it. Others, like USDA's Hosein Shapouri, disputed his claims, and a battle of competing net energy studies ensued. It became clear that the results were a function of the assumptions and data used (see Figures 5.3 and 5.4). While their studies tried to measure total net energy, Michael Wang from Argonne National Lab helped by changing the question: if we care

table 14.7 Current and Prospective Annual Yields and Conversion Efficiencies of Biomass-to-Ethanol

		Biomass to Ethanol Efficiency		
Feedstock and Assumptions	Yield (dt/ac)	gal/dt	gge/dt	gge/ac
Corn (2005)	3.3	124	83	274
Corn, increased yield	4.9	124	83	407
Switchgrass (SG; 2005)	5	50	33	165
SG + improved conversion efficiency (IC)	5	105	69	345
SG + IC + biofuel co-production (BC)	5	117	77	385
SG + IC + BC + increased yield	12.4	117	77	955

* dt/ac = dry tons per acre; gal/st = gallons per dry ton; gge/dt = gallon gasoline efficiency per dry ton; gge/ac = gasoline equivalent per acre

SOURCES: Perlack, et al., 2005; Greene 2004

SOLUTION BOX 14.1

SOLUTION

Putting Ethanol Production Potential in Context

How would the potential ethanol production measure up to current ethanol production, the 2022 RFS, current gasoline consumption, domestic petroleum production, and U.S. oil imports?

Solution:

Let's assume an overall conversion efficiency of 117 gal/dt (77 gge/dt) for energy crops, crop residues, and perennial grasses, and a 0.66 factor for gasoline equivalent.

Biomass production (tons/yr) × fuel yield (gal/dt) =
fuel ethanol (gal/yr) × 0.66 = gasoline equivalent (gge/yr)
1.3 Bdt/yr × 117 gal/dt = 150 Bgal/yr × 0.66 gge/gal = 100 Bgge/yr

How does this potential compare to 2007 ethanol production?

2007 production = 7 Bgal/yr × 0.66 gge/gal = 4.7 Bgge/yr

$$\frac{\textbf{Ethanol potential}}{\textbf{2007 production}} = \frac{\textbf{100}}{\textbf{4.7}} = \textbf{21}$$

table 14.8 Potential Annual U.S. Ethanol Production vs. 2005 Petroleum Indicators

Indicator	Annual Value	Potential Ethanol Indicator
U.S. potential ethanol production	100.0 Bgge	1
U.S. 2007 ethanol production	4.7 Bgge	21
RFS for 2022	30.0 Bgge	3.3
2005 U.S. gasoline consumption	138.6 Bgal	0.72
2005 U.S. crude oil production	78.5 Bgal	1.27
2005 U.S. petroleum net imports	189.4 Bgal	5.3

Sources: Perlack, et al., 2005; Greene 2004

about oil consumption and carbon emissions, not just energy, then shouldn't we be measuring the relative impact of fuel ethanol on those factors? His studies showed corn-based ethanol could displace a considerable amount of petroleum with far less fossil fuel inputs (see Figure 5.3).

SOLUTION

SOLUTION BOX 14.2

Let's Make South Dakota Comparable to an OPEC Member

If South Dakota were to dedicate its 44 million farm acres to energy crops, crop residues, and perennial grasses, what would its annual yield of biomass be at current and expected crop and ethanol yields?

Solution:

Let's assume a mix of corn, residues, and perennial grasses that yields about 4 tons per acre today, and perhaps 10 tons per acre later with greater use of residues and grasses and higher yields. Let's assume an average ethanol yield of 60 gal/dt today and 100 gal/dt tomorrow with more efficient ethanol and energy recovery (after Khosla [2006], and Ceres Company).

South Dakota Biofuel Potential

	Today	Tomorrow
Farm acres	44 million ac	44 million ac
Tons/acre	4 dt/ac	10 dt/ac
Ethanol yield, gal/dt	60 gal/dt	100 gal/dt
1000 bbl ethanol/day	689	2870
1000 bbl gas equiv/day	455	1894

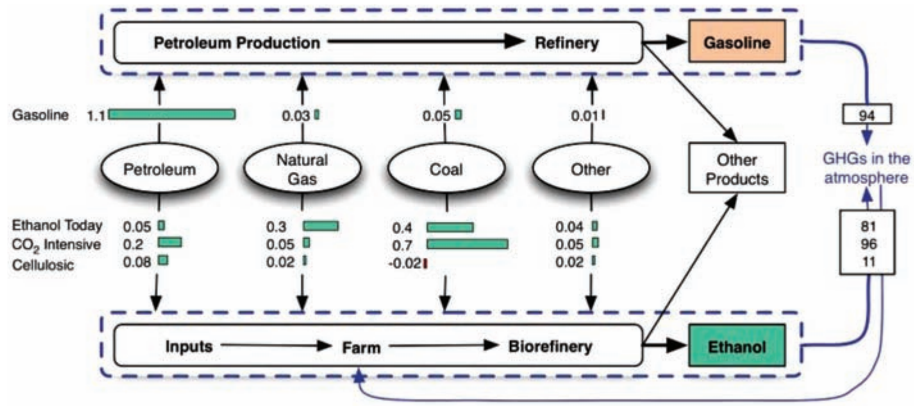
OPEC Oil Production (1000 bbl/day)

Saudi Arabia	9400
Iran	3900
Kuwait	2600
Venezuela	2500
UAE	2500
Nigeria	2200
South Dakota	**1894**
Iraq	1700
Libya	1650

We also discussed a study published in *Science* by the University of California-Berkeley Energy Resources Group (ERG). Using their ERG Biofuels Analysis Meta-Model (EBAMM), the study reviewed six previous net energy and life-cycle studies of ethanol production as well as its own three ethanol scenarios: Ethanol Today, CO_2 Intensive Ethanol, and Cellulosic Ethanol. Their net fossil energy and GHG emissions results were given in Figure 5.4. In Figure 14.14, the energy flows in mega-Joules (MJ) inputs/MJ-fuel and GHG emissions are compared for gasoline (including its petroleum feedstock) and the three ethanol options. Cellulosic ethanol has by far the lowest energy inputs, even negative for coal because of net generation of electricity from lignin by-products, and only 12%–14% of the GHG emissions of gasoline and the other ethanol scenarios (Farrell, et al., 2006).

figure 14.14

Energy flow (MJ input/MJ fuel), GHG emissions (kg CO_2/MJ fuel) from gasoline production and three ethanol scenarios: Ethanol Today, CO_2 Intensive Ethanol, and Cellulosic Ethanol. Cellulosic ethanol requires the fewest energy inputs (0.10 MJ/MJ) and produces the lowest net GHG (11 kg CO_2/MJ).



Source: From Farrell, et al., *Science 311*:506–508 (2006). Reprinted with permission from AAAS.

The UC-Berkeley study prompted a lively online debate among critics and advocates of ethanol fuel (see *Science* online), but the message of the study remained clear:

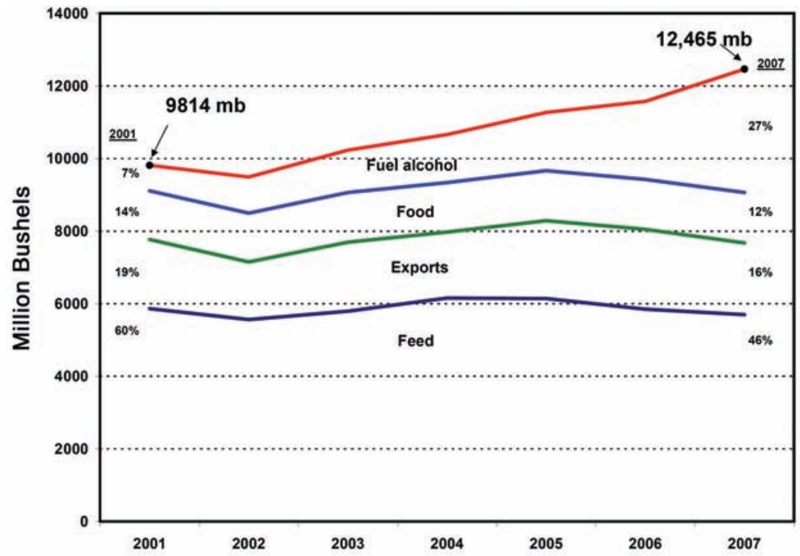
- Corn-based ethanol has considerable petroleum-saving benefits, and small net-energy and GHG emission benefits compared to gasoline.
- Cellulosic ethanol has clear advantages in net energy, petroleum savings, and GHG emission reduction over gasoline and corn ethanol.

14.3.6 Food Crops versus Energy Crops

We can't look at energy production on farms in isolation from food and other agricultural production. In fact, the boom in ethanol production in the United States (Figure 14.9) began to affect the market and price for corn in 2006 and 2007. As shown in Figure 14.15, ethanol use has grown from 7% of U.S. corn supply in 2001 to 27% in 2007. This has prompted world food experts such as Lester Brown (2006) to raise concerns about the effect of corn-based ethanol on food markets. Brown fears that this continuing trend, especially with the growing ethanol production capacity (see Table 14.5), will raise prices and affect exports. The U.S. crop is a major factor in global food markets and a safety net for poor production years in other countries. Indeed, corn prices in the nine primary U.S. markets averaged 66% higher in 2007 than in 2005.

The implications of this changing market are unclear. Farmers welcome the higher corn prices, which have not yet affected food prices significantly in the United States. But at some point, and perhaps soon, the competition between corn for food and feed and corn for fuel will have adverse effects on prices and markets. Significant growth in ethanol fuel production from corn will ultimately be limited by these effects. The growth in ethanol needed to offset petroleum use will have to rely on cellulosic ethanol.

figure 14.15 **Changing U.S. Corn Market, 2001–2007**



Ethanol market has grown from 7% to an expected 27% share of the corn crop, more than the corn export market.

SOURCE: USDA, ERS Yearbook, 2007

14.3.7 Urban Air Quality and Other Environmental Effects of Ethanol

Although gasohol was originally developed to provide oxygen to gasoline to help reduce emissions of carbon monoxide in urban areas, E10 gasohol has a tendency for slightly greater emissions of nitrogen oxides (NO_x) that contribute to the formation of urban smog and ozone. To address this and other urban air quality issues with ethanol, Argonne Lab along with Dartmouth and Princeton universities, conducted a major well-to-wheel (WTW) study of biofuel options (Wu, Wu, and Wang, 2005).

The study compared six biofuel multi-product production options, focusing on cellulosic feedstocks with various forms of combined-heat-and-power (CHP) generation using lignin by-products, including gas turbine combined-cycle (GTCC) and steam power. Some options included Fischer-Tropsch diesel and dimethyl ether production.

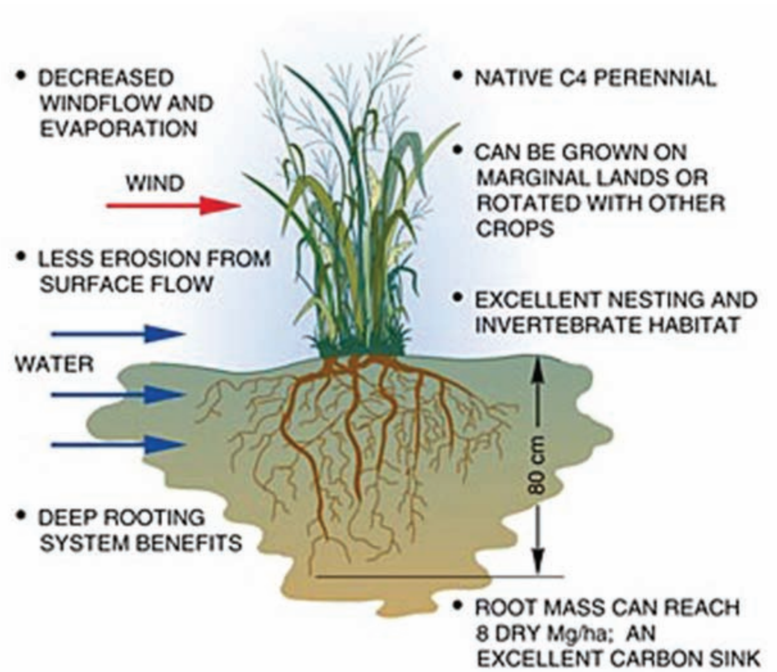
All options showed benefits compared to gasoline and diesel fuel in reducing fossil fuels, petroleum, CO_2 emissions, and urban air pollutants, especially SO_x and surprisingly NO_x. The study concluded: "From a multiple-production perspective, for each unit of biomass, the (ethanol/GTCC) option that co-produces cellulosic ethanol from a consolidated biological process and power from advanced GTCC is the most promising option in that it displaces the greatest amount of fossil fuel and ranks at the top in overall energy and emission benefits among the six options" (Wu, Wu, and Wang, 2005).

Experience with E10 gasohol has shown slight increases in NO_x emissions, but the situation with E85 appears to be different. A 2004 Minnesota study of emissions of E85, E10, and non-ethanol fueled vehicles sheds some light on NO_x emissions. The study tested tailpipe emissions from a flex-fuel Ford Explorer with various fuels, three different brands of E10 (mandatory in Minnesota), non-ethanol gasoline (purchased in Wisconsin), and E85. All ethanol fuel mixes had less total hydrocarbons (THC) emissions than straight gasoline, but two of the three E10 brands had higher NO_x emissions than the non-ethanol gasoline. The E85 test had considerably lower emissions of both pollutants. The air quality benefits of E85, even for NO_x, have also been shown in other studies.

However, Jacobsen (2007) issued a recent caution about the urban air pollution impacts of large-scale use of ethanol due to volatilized ethanol, which is a strong photochemical agent. His work indicates there is alwaays more to know about the effects of potentially beneficial solutions.

Regarding other environmental effects, cellulosic biomass, especially perennial grasses such as switchgrass, has soil and water and carbon sequestration benefits. The perennial grasses are harvested for product but regrow without cultivation or planting. As Figure 14.16 shows, the root system grows deep, holding soil together to reduce erosion and sequestering carbon in its root materials. Perennials provide wildlife habitat, water retention, and wind erosion control, relative to intensive agricultural practices needed for energy crops.

figure 14.16 **Soil, Carbon, and Habitat Benefits of Perennial Switchgrass Grown as an Energy Crop**



Source: Oak Ridge National Laboratory: ORNL-DWG-93-M-8892

These land conservation values make perennial grasses a natural productive use on the nation's CRP lands. CRP currently pays farmers $1.5 billion per year to keep 34 million acres out of production. Most of these lands are highly erodible and not suitable for intensive cultivation but ideally suited for perennial production. Growth and harvest of perennial energy crops on these lands are compatible with the objectives of the CRP program, would contribute to farm income, and would save or shift farm subsidies from keeping land idle to putting it into biofuel production.

14.3.8 Achieving Ethanol's Potential

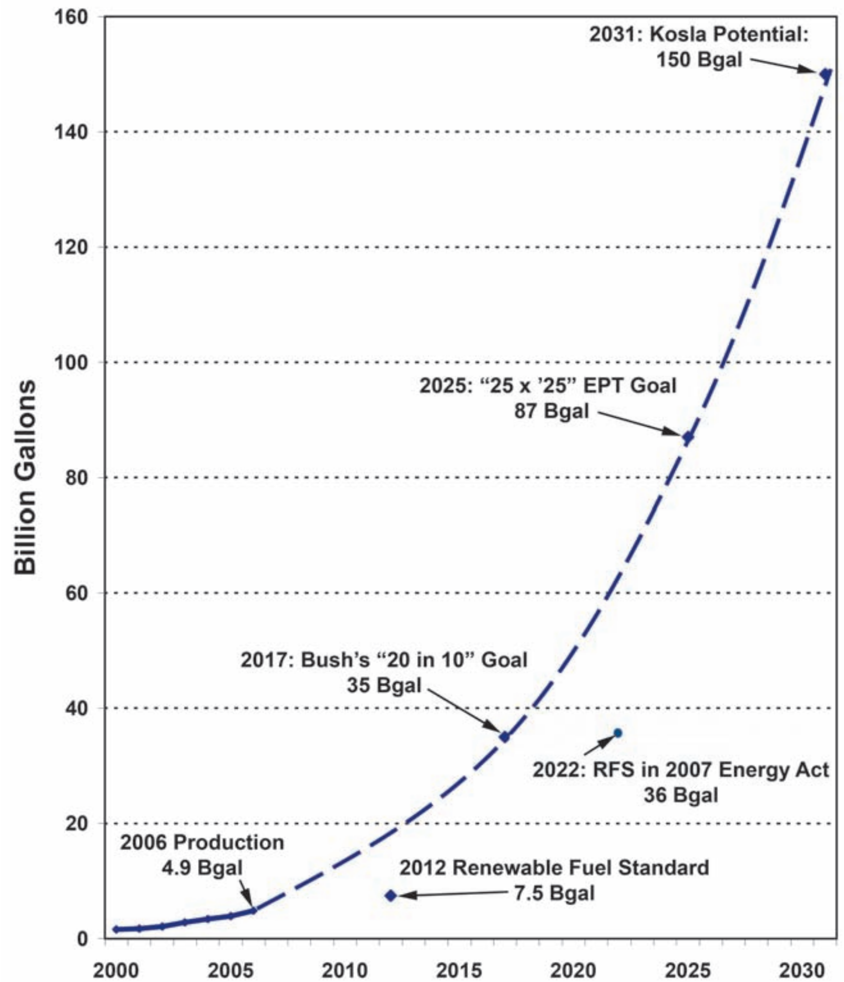
As we have shown, ethanol is now primarily used as an additive in gasohol. If ethanol production capacity, efficiency, and cost improvements meet expected potential, the biofuel can make a significant impact on gasoline consumption, oil imports, and GHG emissions in the years ahead. The market will likely be E85, the 85% ethanol–15% gasoline blend that requires minor changes in existing engines. This requires significant expansion of the agricultural and biorefinery industries dedicated to producing the biomass and processing it to ethanol, as well as the infrastructure to deliver it. This expansion has begun as shown in production (Figure 14.9) and capacity (Table 14.5).

Many are voicing the battle cry for rapid expansion of biofuels, especially E85. These include not only the usual suspects, such as environmental and farm groups, but also not-so-usual ones, such as politicians from all persuasions and notable investors and venture capitalists. Figure 14.17 shows U.S. production through 2006 (4.9 Bgal) and four future visions and goals. They include the following:

a. The 2005 Energy Policy Act Renewable Fuels Standard (RFS): 7.5 Bgal/yr in 2012. At current trends this production will be achieved by 2008 or 2009.
b. President Bush's "20 in 10" goal to achieve ethanol production of 20% of gasoline in 10 years, by 2017. The 2007 Energy Policy Act requires this 35 Bgal/yr by 2022.
c. The increasingly popular "25 × '25" EPT goal to achieve 25% of electric power and transportation fuel energy from renewables by 2025. This goal has been endorsed by half the states and congressional resolutions (see Chapter 3).
d. The vision of Vinod Khosla, the venture capitalist whose words began this chapter. He maintains that ethanol can grow to 150 Bgal/yr by 2031 and displace three-fourths of our gasoline use.

Even if we can expand ethanol production toward these goals by building more biorefineries and dedicating more energy crops and residues, we still need to bring this ethanol to market. As shown in Table 14.2, in 2007 there were only 1100 filling stations that had E85, but the number is growing. More than one-quarter of these were in Minnesota. Stations now generally use the same gasoline tanks and pumps for E85 and regular gasoline. Infrastructure issues seemed to be minor until Underwriters Laboratory (UL) decided in late 2006 not to list gasoline pumps for E85 because of suspected corrosion problems. This created uncertainty about E85 infrastructure and only eighty E85 stations were added between

figure 14.17 **Visions of U.S. Ethanol Production**



Bush's "20 in 10" goal far exceeds the 2005 act's RFS for 2012 and is the same quantity as the 2007 act's RFS for 2022. It is on track with "25 × '25" goal and even Khosla's ambitious goal of 150 Bgal by 2031.

December 2006 and October 2007. But in October 2007, UL completed an exhaustive research effort and announced accepted safety protocol that is expected to clear the way for a huge expansion of E85 stations in 2008.

Minnesota is providing good lessons for the rest of the country in ethanol fueling (see Sidebar 14.1), but more states and more retailers outside the upper Midwest need to provide access to E85 as the market for ethanol and flex-fuel vehicles grows.

In fact, the vehicle market has already outstripped the fuel delivery infrastructure. There are more vehicles that can use E85 than can find a filling station to get it. As discussed in Chapter 13, there are 6 million flex-fuel vehicles (FFV) on the road today that can use both straight gasoline and E85 seamlessly. Thirty-six models of FFV are on the market, almost all made by the U.S. Big Three automakers.

Why would they be making so many if there are so few opportunities to use E85? Well, manufacturers are given a 0.9 mpg credit on their CAFE fuel economy standards for flex-fuel, and they have taken full advantage. No surprise then that the FFV models on the market are mostly large SUVs. See the current list at http://www.fueleconomy.gov/feg/byfueltype.htm.

Although this tactic by automakers has not led to much additional ethanol use, it has put a large FFV fleet on the road, it has given automakers valuable experience in the technology (which is simple and essentially adds no cost), and it positions the U.S. industry for greater sales of FFV. In November 2005, Senators Lugar (R-IN), Harkin (D-IA), and Obama (D-IL) proposed the bi-partisan Fuel Security and Consumer Choice Act, which would require all vehicles marketed in the United States to be FFV within ten years.

In summary, cellulosic ethanol provides an opportunity to produce a majority of our vehicle gasoline consumption and greatly reduce our oil imports within twenty-five years, while helping revitalize rural economies across America. The ethanol fuel can be marketed as E85 in existing infrastructure and used in flex-fuel vehicles that U.S. auto companies have been making for years at no additional cost. With flex-fuel plug-in electric hybrid vehicles, expected on the market soon, consumers have the choice of E85, gasoline, or electric fuel, with the prospect of using zero-urban-emission electric drive in the city and 85% ethanol on the highway, further reducing gasoline use, oil imports, and GHG emissions.

14.4 Biodiesel

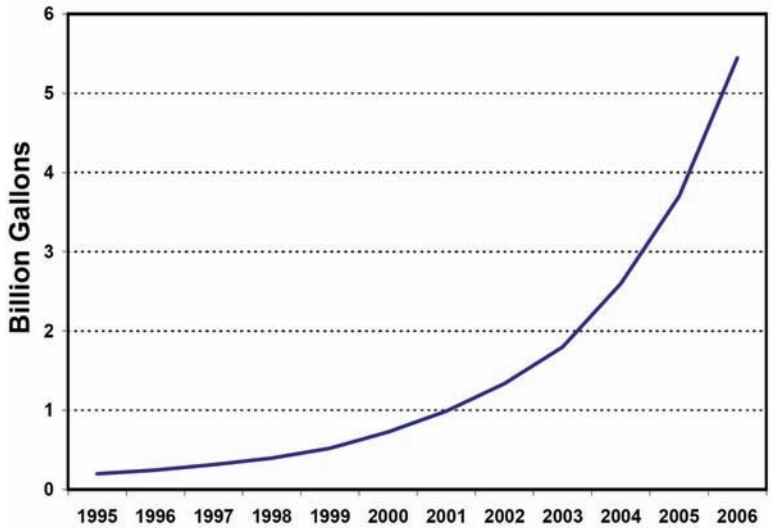
Biodiesel is a fuel that comprises mono-alkyl esters of long-chain fatty acids derived from vegetable oils or animal fats. It offers a biofuel option for diesel vehicles. As discussed in Chapter 13, diesel engines power heavy trucks and equipment. But their use in passenger vehicles is rebounding because of their inherent energy efficiency and improvements made in emissions reductions. Europe has made a strong commitment to diesel cars, and there is likely to be a growing market for clean diesel in the United States.

In fact, like ethanol, biodiesel production has been booming in 2005–2007. Although worldwide biodiesel had only about 8% of the volume production as ethanol in 2005, it grew 67% that year. About 90% of 2005 world biodiesel was in Europe (see Figure 14.18). Why Europe? The European Union (EU) has committed to a renewable fuel standard that 5.75% of its diesel fuel come from biofuels by 2010. Germany leads this effort—its production of 2.0 Mt in 2006 hit its 2010 target four years early. Italy had the next highest capacity at 0.6 Mt. European countries primarily use rapeseed oil as a feedstock.

14.4.1 U.S. Biodiesel Production Capabilities

Production is also growing rapidly in the United States—from 25 Mgal in 2004 to 75 Mgal in 2005 to 250 Mgal in 2006 to an estimated 450 Mgal in 2007. Filling stations selling biodiesel

figure 14.18 **World Biodiesel Capacity, 1995–2006**



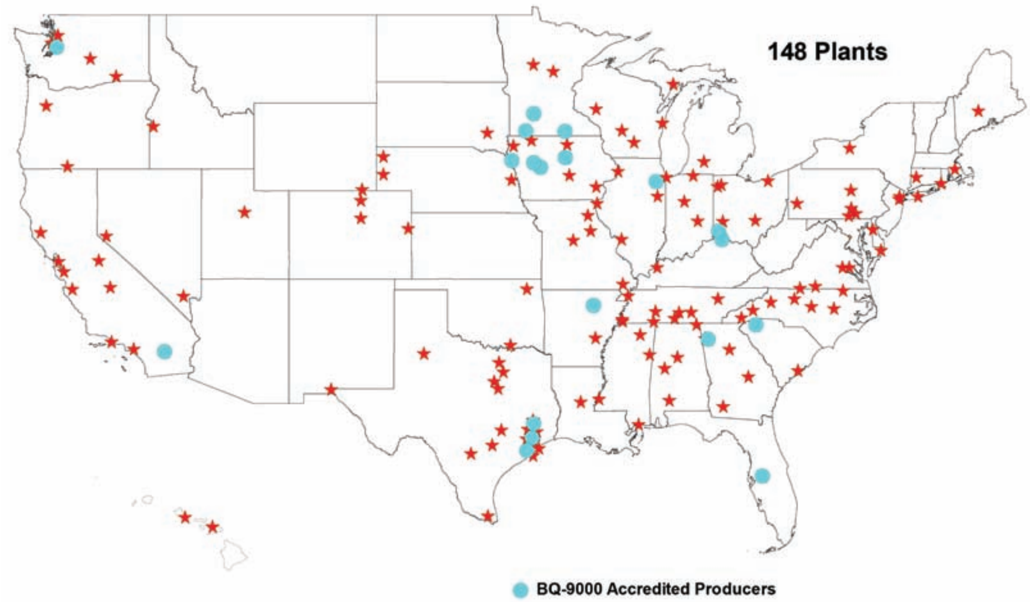
increased from 142 in 2003 to 705 in 2007, with South Carolina leading the nation with 67 (Table 14.2). Other states and communities are encouraging biodiesel development. Minnesota adopted a "blend specific" RFS for requiring all diesel sold in the state to be 2% biodiesel or B-2. It became effective when enough production capacity was developed in the state; when two 30 Mgal/yr facilities were built in 2005, the rule became effective in September 2005. Other states, such as Washington, have adopted "volumetric" RFS like the federal RFS. It has prompted development of production plants. Seattle Biodiesel built a 5 Mgal/yr production plant in downtown Seattle in 2005. Imperium Renewables, parent company of Seattle Biodiesel, is building a 100 Mgal/yr plant in Grays Harbor, Washington.

In the United States, soybean and seed oils are the primary feedstock, although waste vegetable oils are also used. One appeal of biodiesel is that conversion from raw or waste oils is a fairly simple "backyard" technology that can be done at small scale. But one disadvantage is that to be commercial, resulting biodiesel must meet the same strict standard that all diesel fuel must meet, the American Society of Testing and Materials' ASTM D 6751–02. If the product meets this standard it can be used at a range of blends, from B-2 to B-100. Most dealers and manufacturers of diesel engines will honor engine warranties up to B-5, but B-20 is increasingly becoming the blend of choice.

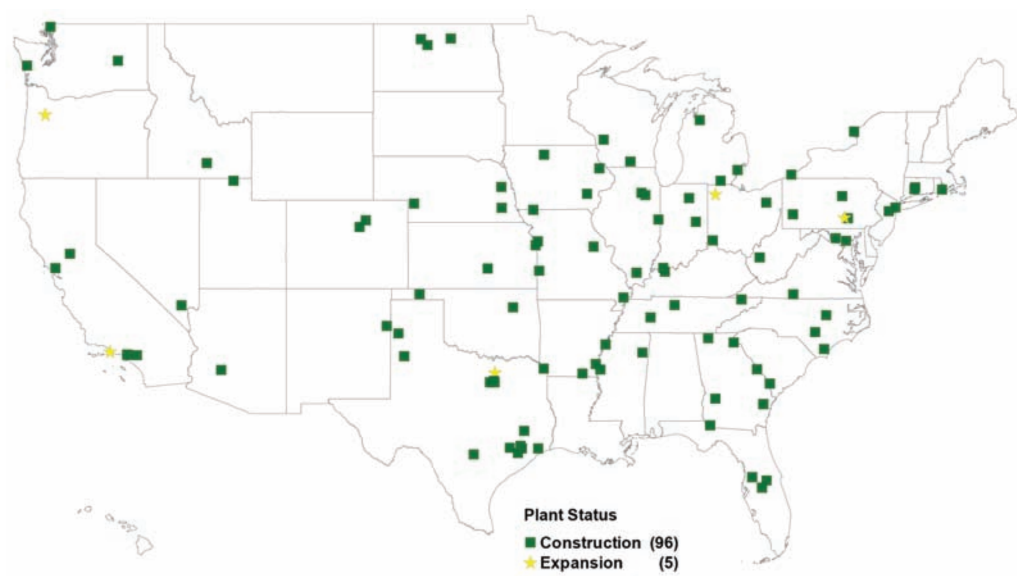
Meeting this standard and dealing with some of the by-products like glycerol, have plagued some small producers. But "backyard" production will not impact our petroleum problem, and only large-scale development will likely have sufficient economies of scale to produce a quality product at competitive prices.

Biodiesel production capacity is growing rapidly in the United States. Figure 14.19 shows the existing production plants and those under construction or expansion in mid-2007. By early 2008, capacity totaled 2240 Mgal/yr. Capacity does not equal production because the plants will not operate at 100% all year. Much of this capacity was just coming on line in 2007, so actual production in 2007 was about 450 Mgal for the year. Nineteen of these plants have BQ-9000 certification, a voluntary and cooperative program of the National Biodiesel Accreditation Board. Capacity under construction or expansion, shown in Figure 14.19(b), totals an additional 1230 Mgal/yr.

figure 14.19 **Existing and New U.S. Biodiesel Production Capacity, 2007**



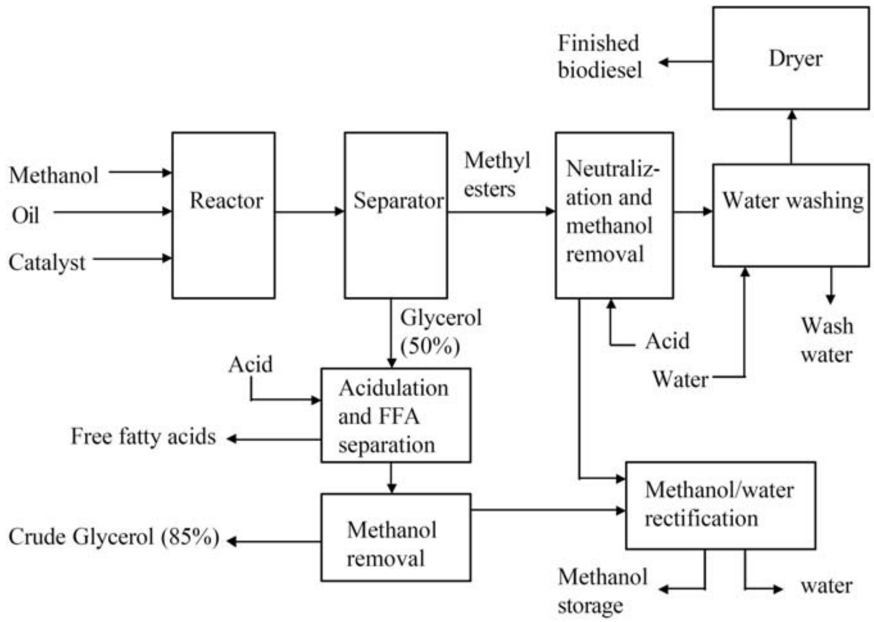
(a) Biodiesel production capacity in June 2007 totaling 1.39 Bgal/yr. BQ-9000 are accredited producers.



(b) Biodiesel production capacity under construction or expansion in 2007 totaling 1.89 Bgal/yr.

Source: NBB, 2007

figure 14.20 Transesterification Process for Producing Biodiesel from Vegetable or Animal Oils



Source: Jon Van Gerpen, Biodiesel Production and Fuel Quality, University of Idaho

14.4.2 Biodiesel Production Technologies

Biodiesel is produced through a process called **alkali-catalyzed transesterification,** illustrated in the schematic in Figure 14.20. Oils along with alcohol (usually methanol) and catalysts are placed into a reactor and then into a separator to divide methyl esters from glycerol. The methyl esters are neutralized and methanol is removed, then they are washed and dried to produce finished biodiesel. The remainder of the process deals with by-products glycerol and methanol, both of which have marketable value if they can be purified. Methanol can be recycled in the process.

The two primary challenges in biodiesel production are meeting the high ASTM D 6751 standard for diesel fuel and converting the potentially hazardous by-products glycerol and methanol into marketable quality. The former requires tight quality control of the methanol removal, water washing, and drying process steps. The latter conversion through methanol and free fatty acid separation is just as important as the production process for commercial effectiveness.

14.4.3 Biodiesel from Algae

Algae is to the future of biodiesel as cellulose is to the future of fuel ethanol. The primary feedstock for existing and planned capacity in the United States is soybean oil, although other

table 14.9 Biodiesel Yield Estimates for Various Sources

Source	Yield (gal/ac)
Corn	15–20
Soybeans	40–50
Safflower	80–90
Sunflower	100–110
Rapeseed	110–130
Palm oil	625–650
Microalgae	5000–15,000

Source: NREL, 1998

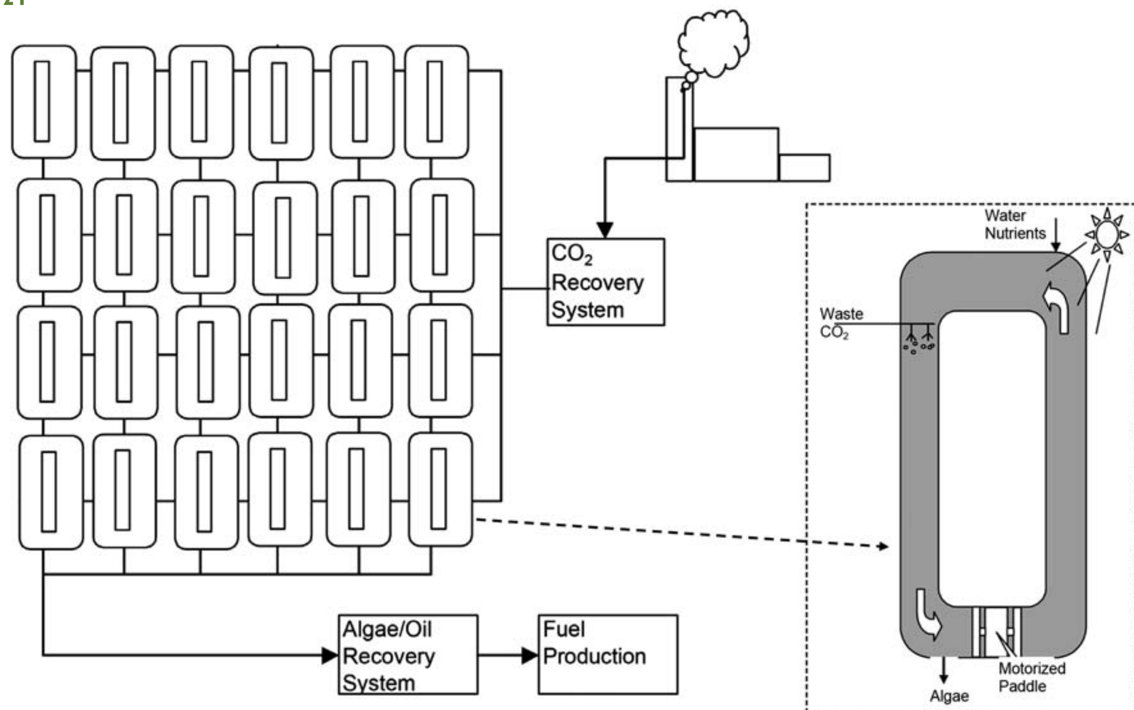
seed oils and some waste oil are used. In Europe, rapeseed oil is the most popular source. These are energy crops that have alternative productive uses, so large-scale biodiesel production from these feedstocks will encounter the same competition with food products as will corn-based ethanol.

Microalgae, including diatoms and green algae, may provide an answer for biodiesel source material. Algae can produce at least thirty times the amount of oil per area of land as terrestrial oil seed crops, because of their abundance; proliferation; high oil content; ideal structure for photosynthesis; and ideal access to nutrients, water, and CO_2 through their aqueous suspension. Table 14.9 gives an estimate of biodiesel yields from various crop seeds (15–650 gal/ac) and microalgae (5000–15,000 gal/ac).

U.S. DOE funded an Aquatic Species Research program at the National Renewable Energy Laboratory from 1978 to 1996. The program funding was small, peaking at $2.5 million in 1984, then declining to closeout in 1996. Although the program ended, it provided basic research for the renewed current interest in algae as a source for biofuels. One concept developed through the program was an algae growth system enhanced by CO_2 capture from fossil fuel power plant emissions. Figure 14.21 shows a conceptual diagram of a series of algae growth lagoons with inputs of water, nutrients, CO_2, and sunlight, and outputs of algae for biofuel production.

This design is now being further developed by GreenFuel Technologies Corp. (GFT), which adapted the concept to the 20 MW cogeneration plant at MIT. The demonstration showed an 82% reduction of CO_2 emissions on sunny days and 50% on cloudy days, and also an 85% reduction in NO_x emissions. The GFT system does not use lagoons, but 3-meter long, 10–20 cm diameter polycarbonate tubes tilted to the sun like evacuated tube solar collectors. Flue gases are introduced at the bottom and bubble up through the algae medium. On a daily basis, 10%–30% of the algae are removed. GFT estimates biodiesel yields of 5000–10,000 gal/ac and comparable yields of ethanol. Others, such as Global Green Solutions, are claiming even higher yields of biodiesel from algae, with a similar design using thin-film membranes developed by Valcent Products. Its demonstration pilot plant was targeted for late 2007.

figure 14.21 Schematic of Algae to Biodiesel Facility using CO_2 Recovery from Fossil Fuel Power Plant



Source: NREL, 1998

14.4.4 Environmental and Life-Cycle Considerations of Biodiesel

Like all biofuels, the overall environmental impacts of biodiesel depend on what raw material is used, what land and production practices are used in growing it, what processes and controls are used to extract oils and convert them to biodiesel, and how the biodiesel is used. Although net energy for biodiesel from seed crops is not as well analyzed as ethanol, it appears to be positive. Like ethanol from corn, the real life-cycle advantages come from GHG emission reduction and petroleum savings. Life-cycle net energy, economic, and environmental benefits are likely to be much greater for biodiesel from algae than from seed crops, just as they are likely to be much greater for ethanol from cellulose than from corn.

Another significant life-cycle advantage of biodiesel and other biofuels is the reduction of CO_2 emissions and most criteria pollutants. When additional public policies for GHG emission reductions (such as a CO_2 cap and trade system) are enacted, they will translate into further economic advantages for biofuels.

Table 14.10 shows that B-20 and especially B-100, have significantly lower emissions of criteria pollutants except NO_x. NO_x continues to cloud the otherwise significant air quality benefits of biodiesel, and research continues to address this and other remaining air quality issues such as black carbon.

table 14.10 Emission Impacts from Biodiesel Compared to Conventional Diesel

	B-100	B-20
Total unburned hydrocarbons	–67%	–20%
Carbon monoxide	–47%	–12%
Particulate matter	–48%	–12%
NO_x	+10%	+2%

Source: EPA, 2002

Agricultural practices for biomass production must minimize impacts on water and soils. For example, in December 2006, the *Wall Street Journal* reported in 2006 that the rush to develop biodiesel from palm oil in Indonesia has created an environmental disaster as huge areas are being burned on Borneo to clear land for the palm oil plantations (Barta and Spencer, 2006).

14.5 Other Biomass Energy and Emerging Biotechnologies

14.5.1 Other Biomass Energy

There are a number of other biomass energy sources. Although they are not directly related to transportation, this is a convenient place in the book to address them. Most of these sources are used for power generation, thermal uses, or both in CHP facilities. The biomass types include wood wastes and residues, municipal wastes, landfill methane recovery, and methane digestion from sewage sludge and agricultural animal wastes (Figure 14.22).

14.5.1.1 Biomass/Wood/Waste Heat and Power Generation

Figure 14.2 showed that 47% of 2004 renewable energy in the United States (or about 3% of total energy) came from biomass. About half of this comes from industrial forest products operations that burn wood residues and pulping liquors for heat and electricity. Of the 1000 wood-fired power plants, about two-thirds are primarily for industrial use and one-third are independent power producers generating electricity for sale.

As several states have adopted Renewable Portfolio Standards (RPS) for which wood-fired power plants qualify, there has been a growing interest in wood-fired electricity generation. In 2006, five such plants were planned in New England. Although such plants provide renewable fuel and GHG emission reduction benefits compared to fossil fuel plants, they are still combustion facilities requiring delivery of bulk solid fuel usually by truck. Local residents have not always embraced these plants in their communities.

Another type of biomass energy facility that has met with local concerns is municipal waste-to-energy plants. These accept raw or processed municipal wastes and burn them similar to old incinerators, except that they have energy recovery for steam heating or power gen-

figure 14.22 **Biomass Sources for Combined Heat and Power**

(a) Wood chip CHP plant

(b) Wood residue

(c) MSW stream

(e) Landfill gas microturbines

(d) Landfill gas recovery

(f) Methane digester at sewage treatment plant

Wood waste and residues and municipal solid waste can be burned in steam boilers for combined heat and power. Landfill gas and methane from sewage sludge or animal waste digestion can be burned in gas or microturbines, reciprocating engines, or Stirling engines for power and heat.

SOURCE: Wisconsin Distributed Energy Collaborative; New Jersey Meadowlands; CB&I, Inc.

eration, and they have modern pollution control. They have an added benefit of reducing the volume of waste to be landfilled. In 2005, 13.6% of U.S. municipal solid waste (MSW) or 33.4 Mdt was combusted for energy recovery in 88 plants, 39 of which are in the northeast and 26 in the south. But the number of waste-to-energy plants, tonnage, and percent of wastes burned are all down since 2000. Table 14.11 shows the MSW generated in the United States and its fate from 1960 to 2005. Combustion with energy recovery peaked in 1990.

table 14.11 U.S. Municipal Solid Waste Generation and Fate, 1960–2005

Activity	1960	1970	1980	1990	2000	2003	2004	2005
Generation (million tons)	88	121	152	205	237	240	247	246
Recovery for recycling	6.4%	6.6%	9.6%	14.2%	22.2%	23.2%	23.1%	23.8%
Recovery for composting	Neg.	Neg.	Neg.	2.0%	6.9%	7.9%	8.3%	8.4%
Total materials recovery	6.4%	6.6%	9.6%	16.2%	29.1%	31.1%	31.4%	32.1%
Combustion with energy recovery	0.0%	0.3%	1.8%	14.5%	14.2%	14.0%	13.8%	13.6%
Discards to landfill other disposal	93.6%	93.1%	88.6%	69.3%	56.7%	54.9%	54.8%	54.3%

Source: U.S. EPA, 2005

14.5.1.2 Landfill Methane Recovery and Methane Digestion

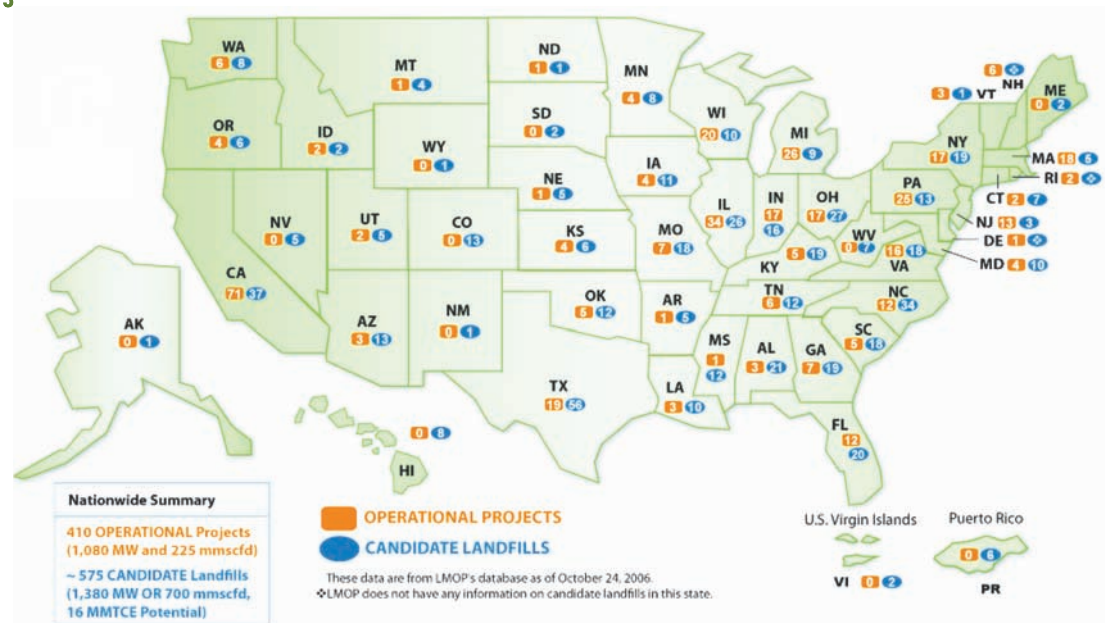
Most municipal wastes are disposed in landfills. Biomass in the waste, mostly paper, decomposes anaerobically (without oxygen) and produces methane (CH_4). This gas is trapped but ultimately seeps into the atmosphere. Many sealed landfills are converted to parks, and leaking methane can be toxic and hazardous to users. To avoid risk, landfills are normally vented to release methane, but methane is a powerful GHG, 23 times more powerful than an equal mass of CO_2. In some landfills the vented methane is flared off, burning the methane to CO_2. Landfill methane recovery, on the other hand, not only captures the methane but uses it to generate heat and power. Using gas turbines, microturbines, or reciprocating or Stirling engines, this gas can be converted to useful power with additional heat recovery.

Landfill gas (LFG) is a growing source of community power. Figure 14.23 shows the status of landfill gas projects in the United States. As of October 2006, there are 410 operational projects with a total 1080 MW capacity capturing 225 million cubic feet per day (mcfd) of methane and generating about 10 billion kWh of electricity. An additional 575 candidate landfills offer a potential for 1380 MW and 700 mcfd capture. The energy provided is good, but the conversion of methane to carbon dioxide is even better.

In a critical assessment of landfill gas (LFG) recovery, the Natural Resources Defense Council (2006) developed the following priorities:

1. **Avoid LFG by avoiding landfills.** The first priority is increased resource reduction and recycling. Biomass—especially paper—is easily recycled or composted. If there is no biomass in landfills, then there will be no LFG.
2. **Burn all LFG that is produced.** Even if we could close all landfills today, they would continue to produce LFG for years to come. Burning LFG in an engine, a turbine, or simply in a flare has tremendous benefits by reducing toxicity and reducing greenhouse

figure 14.23 **Location of Operational and Candidate Landfill Gas Recovery Projects**



California and Illinois are the leading states.

SOURCE: U.S. EPA LMOP, 2006

gases. Over 60% of LFG is generated at landfills with no collection system; and at landfills with collection systems, it is typical for at least 25% of LFG to escape.

3. **Use LFG for energy production.** The balance of benefits favor using LFG for energy.

Methane digestion. Usable methane can also be produced from organic wastes through anaerobic digestion processes. Although digestion has been used to stabilize sewage and animal wastes for decades in the United States and abroad, it has not been developed to its potential for usable energy production. Opportunities exist for additional methane digestion of municipal sewage sludges and especially concentrated animal facilities such as feedlots and poultry operations.

However, methane digestion involves a complex biological process, and a 63% failure rate of farm digesters installed in the 1970s has discouraged new farm applications. In addition to energy production, they also reduce odors and produce a more stable by-product, so as the costs of the conventional disposal methods increase for space or environmental reasons, and as fuel costs rise, methane digestion may increase in use for animal wastes.

Digestion is a two-stage process. First, acid-forming bacteria break down complex wastes into acids; then methane-forming bacteria convert these acids to methane. The resulting "biogas" is about 65%–70% methane. The process requires the right balance of these different bacteria, the right nutrient balance (carbon to nitrogen ratio), the right composition of waste and water, and the right temperature. The "active" ingredients of the wastes are their content of "volatile solids" (VS).

- Animals typically produce about one-third of their body weight in VS per day.
- Typical methane production is about 3–8 cubic feet per pound VS, higher for chickens and pigs, lowest for cows.

Digestion of municipal sewage sludge has been increasing in recent years. Higher performance systems include High Temperature Thermophilic-Mesophilic Digestion (e.g., Duluth, Minnesota), Separate Acid/Gas Phases (e.g., DuPage County, Illinois), and Extended Solids Retention (e.g., Spokane, Washington). These advanced systems have the advantage of producing Class A by-product sludges suitable for most land applications.

14.5.2 Emerging Biotechnologies for Energy

Photosynthesis in green plants is one of the miracles of life. So is human ingenuity. Advances in biotechnology research may create significant opportunities in capturing the sun's energy and transforming it into useful biomass energy more efficiently to increase energy yields. We have seen that common green algae and diatoms have potentially high yields of oils suitable for conversion to biodiesel, far more than terrestrial crops. Genetic engineering research can optimize algae production enhancing the efficiency of transfer of solar energy to biomass energy. Further advances may even use the photosynthetic process directly to produce hydrogen.

This exciting research aims to use the mechanisms of photosynthesis to extract hydrogen directly from water. As introduced in Chapter 4, the magic of photosynthesis is provided by a number of enzymes and nucleotides, such as ADP and ATP, which transport and accept electrons permitting a wide range of chemical reactions for the miracles of life.

Photobiological water splitting uses the natural enzymatic process of photosynthesis to split hydrogen gas directly from water. It uses bioengineered forms of green algae and cyanobacteria that consume water and produce hydrogen as a by-product. Bench lab experiments have collected hydrogen gas from beakers containing water-splitting algae. The biological process is complex, using an integrated system of hydrogen production with a combination of algae and photosynthetic and anaerobic bacteria. Although current processes are too slow for commercial application, this is a promising area of research.

14.6 Natural Gas and Hydrogen as Transportation Fuels

CNG has been a popular alternative urban transportation fuel (Tables 14.1 and 14.2) and natural gas has served as the energy source for what small amount of hydrogen is currently used. Future options for alternative transportation fuels include both synthetic liquids from natural gas and hydrogen.

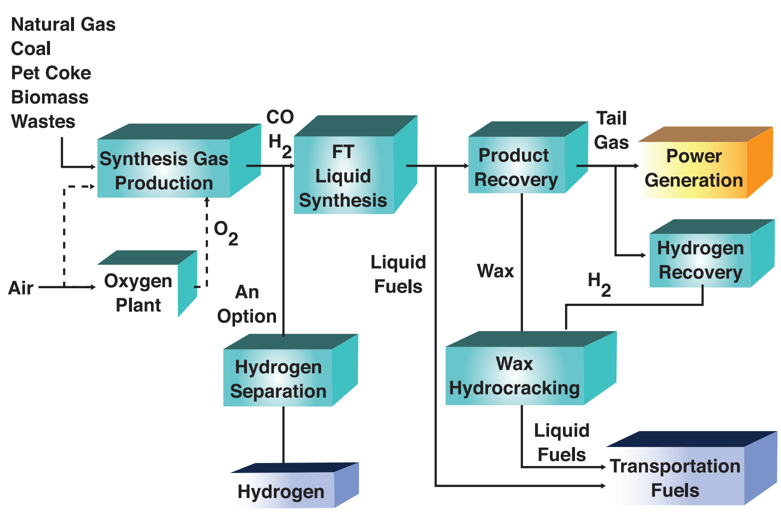
14.6.1 Natural Gas as a Transportation Fuel

Two main options for natural gas are as CNG and natural gas derived synthetic liquid fuel. CNG has been a popular urban fuel for public fleets and buses, but its use is constrained by refueling needs and price uncertainties. As discussed in Chapter 2, natural gas supplies are believed to be greater than oil, and much natural gas is wasted in oil fields around the world for lack of easy transport to markets. Growth of the global market in LNG may help. LNG is simply cold, condensed natural gas (–163°C) that as a liquid occupies 1/600 the volume and can be shipped in tankers. At destination, the LNG is gasified by warming and fed into NG pipelines.

Another alternative is to convert natural gas to liquid (GTL) fuel at normal temperature and pressure so that it can replace gasoline and diesel fuel in transportation vehicles. With higher oil prices, there is renewed interest in GTL conversion. Most current ventures use the well-known Fischer-Tropsch (FT) method developed in the 1920s and used for decades in South Africa by Sasol, which has a capacity of 150,000 bbl/day of liquids from coal and natural gas. Modified versions of the Fischer-Tropsch technology (shown in Figure 14.24) are being developed in other countries.

However, dependency on natural gas for transportation fuel carries with it some of the same problems of petroleum. Although domestic natural gas supplies are greater than oil, they are limited, and future natural gas use in the United States will likely depend more on

figure 14.24 **Schematic of Fischer-Tropsch Technology**



Fischer-Tropsch technology for converting coal, natural gas, or biomass into liquid transportation fuels.

Source: William Harrison, U.S. DOD

imports, now 16% of supply (see Chapter 2). More importantly, natural gas prices follow the volatility of oil prices (see Table 5.4). Finally, natural gas is a source of fossil CO_2 emissions. Although its emissions are 25% less than gasoline, the FT process is only about 66% efficient, and it would exacerbate carbon emissions for transportation fuel. With natural gas feedstock, CO_2 emissions would be 14% more than gasoline; using coal feedstock for FT coal-to-liquids (CTL), emissions would be 100% more than gasoline.

14.6.2 Hydrogen as a Transportation Fuel

During the past five years, hydrogen has been touted as the answer to many of our energy problems—the perfect clean fuel that has multiple applications through direct combustion and conversion to electricity in fuel cells. Fuel cell technology in vehicles provides an opportunity to address petroleum and urban air pollution, and we introduced progress in the development of fuel cells and fuel cell vehicles in Chapters 10 and 13.

However, we know from Chapter 3 (Section 3.3.5) that hydrogen is just a storage medium and an energy source is needed to produce hydrogen. We need to consider life-cycle cost of hydrogen production—carbon-free, oil-free, and secure energy sources are the best options. Hydrogen can be extracted from water using electrolysis, in which electrical energy is used to break water into hydrogen and oxygen at about 70% efficiency from electrical energy to hydrogen energy. Electrolysis using carbon-free renewable wind and solar electricity is promising, but overall efficiency is small and it may be better to use the electricity directly.

Photobiological techniques discussed in the previous section are very exciting. So is **photoelectrochemical water splitting.** In this process, instead of using photosynthesizing algae and bacteria, hydrogen is produced from water using sunlight and specialized semiconductors. Different semiconductor materials work at different wavelengths of light and directly dissociate water molecules into hydrogen and oxygen. More research is needed to find the right materials and to collect the separated hydrogen.

But we are a long way from perfecting such a process, and until we do we are left with existing technologies of electrolysis or reforming hydrogen from natural gas or other fossil fuels, the most common method today. Reformation extracts hydrogen from natural gas at about 60% efficiency. Figure 13.22 showed a Honda prototype Home Energy Station that reforms natural gas to hydrogen, which can then be used in a fuel cell vehicle and a stationary home fuel cell. This looks pretty cool, but we saw in our well-to-wheel (WTW) assessment in Chapter 13 that reformed hydrogen in a fuel cell vehicle has 25% more energy use than a Prius hybrid without any reduction in CO_2 emissions over a hybrid (Figures 13.27 and 13.28).

Our WTW assessment also showed that the WTT efficiency of hydrogen electrolysis using fossil fuel steam-generated power is only 20%–30% depending on the type of generation. WTW energy use of fossil-steam electrolysis hydrogen fuel cell vehicles was by far the highest of all of the fuel-vehicle options, 22%–75% greater than a conventional gasoline vehicle depending on the type of generation. The hydrogen fuel cell vehicle using grid-average power for electrolysis also had the highest CO_2 emissions, 42% greater than the conventional gasoline car.

In addition to these life-cycle energy, economic, and carbon issues of hydrogen, there are technical and economic issues of storage, transport, and delivery of hydrogen to use, that pose significant barriers to what many have referred to as the "hydrogen economy." As far as vehicles are concerned, flex-fuel, plug-in hybrid electric vehicles may offer an easier, more cost-effective, and more energy efficient option than hydrogen fuel cell vehicles not only for the short term, but also for the long term.

14.7 Summary

In our quest to reduce oil use, carbon emissions, and energy demand growth, we must address transportation energy. Transportation consumes 68% of the oil and accounts for 32% of the carbon emissions in the United States today. More than 80% of that oil and carbon is attributable to highway vehicles, and three-fourths of that is from light cars, SUVs, and pickups. In Chapter 13, we introduced three approaches in our quest:

1. Improved vehicle efficiency through new designs and technologies
2. Alternative fuels to displace oil and reduce emissions
3. Reduction in vehicle miles traveled through better land use planning and increased use of commuter transit and other efficient transportation modes

Chapter 13 focused on vehicle efficiency and technology and Chapter 15 addresses vehicle miles traveled. This chapter has explored alternative fuels, especially biofuels. Electric and plug-in hybrid vehicles discussed in Chapter 13 may increase the use of electricity as an alternative "fuel." We saw that electric and plug-in hybrid vehicles can offer high performance, zero urban air emissions, and affordable per-mile costs, especially with overnight, off-peak battery charging. Figure 10.5 showed that if 40% of California vehicles were electric or plug-in hybrid, they could all be charged overnight with currently unused off-peak capacity. Advances in lightweight battery technology are likely to reduce cost and grow this market.

Biofuels, especially fuel ethanol produced from cellulosic crop residues such as corn stover, and perennial grasses such as switchgrass, may provide significant displacement of gasoline and reduction of GHG emissions. Biodiesel also has promise, but like ethanol, increased biodiesel volume depends on non-food biomass sources like microalgae. Recent studies by U.S. DOE, USDA, ORNL, and others estimate a domestic potential to grow 1.3 Bdt of biomass for energy, enough to displace 30% of our petroleum consumption and 60% of our gasoline consumption by 2030. This could be done without impacting domestic and export needs for food and fiber, while maintaining environmental land conservation and revitalizing rural economies.

The best bet for rapid expansion of biofuels is increasing production and marketing of E85, the blend of 85% ethanol and 15% gasoline. This requires

- Large development of biorefinery capacity
- Gearing up of production and recovery of cellulosic crop wastes and grasses

- Advances and cost reduction in enzymatic hydrolysis of cellulose
- Manufacture of more flex-fuel vehicles
- Increased availability of E85 fueling pumps at filling stations

None of these actions is difficult and the good news is that a coalition of diverse interests, including private investors, energy, and automobile companies, state and federal policy makers, and civil society organizations, are beginning to speak in one voice for these actions. RFS and other policies at the federal level and in several states help set the stage for significant private investment, the critical ingredient for rapid deployment.

The U.S. national RFS set by the 2005 Energy Policy Act of 7.5 Bgal of biofuels by 2012 was too modest, and in 2007 Congress changed it to 35 Bgal/yr by 2022. This is similar to President Bush's goal of "20 in 10," for a 20% biofuel contribution to vehicle fuel in ten years or by 2017. This would amount to about 35 Bgal of biofuels. The more ambitious "25 × '25" goal, endorsed by half of the states and resolutions in Congress, calls for 25% of transportation fuel from renewables by 2025, amounting to about 85 Bgal. And Vinod Khosla's vision of 150 Bgal/yr by 2031 takes the cake. Still this vision equals the production from ORNL's estimated biomass fuel potential of 1.3 Bdt per year.

Khosla (2006a) offers three simple policy recommendations to accelerate the movement toward this vision.

1. Require E85 distribution at 10% of all gas stations owned by those with more than fifty stations in the country.
2. Require 70% of all vehicles sold in the United States to be FFV within five years. Supply them all with yellow gas caps and give those caps to all who currently have FFV so they all know they can fill up at E85.
3. Establish a contingency tax on oil if it falls below $40/bbl to assure that will be the floor price. This assurance that oil will not undercut biofuels will spur needed investment. The tax revenues could be used to reduce oil price if it gets above $60 or $80/bbl.