USDA
United States
Department
of Agriculture

BIO-01-01
May 2010

Outlook

Contents

Approved by USDA's
World Agricultural
Outlook Board

A Report from the Economic Research Service

www.ers.usda.gov

Next-Generation Biofuels

Near-Term Challenges and Implications for Agriculture

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Abstract

Next-generation U.S. biofuel capacity should reach about 88 million gallons in 2010, thanks in large measure to one plant becoming commercially operational in 2010, using noncellulosic animal fat to produce green diesel. U.S. production capacity for cellulosic biofuels is estimated to be 10 million gallons for 2010, much less than the 100 million gallons originally mandated for use by the 2007 Energy Independence and Security Act. In early 2010, the Environmental Protection Agency lowered the cellulosic biofuel mandate to 6.5 million gallons, more in line with production prospects. Even so, expansion of next-generation fuels will have to be rapid to meet subsequent annual mandates and the longer term goal of 16 billion gallons for cellulosic biofuel use by 2022. Near-term sector challenges include reducing high capital and production costs, acquiring financial resources for precommercial development, and developing new biomass supply arrangements, many of which will be with U.S. farmers. Overcoming the constraints of ethanol's current 10-percent blending limit with gasoline, or expanding E85 markets, would improve prospects for cellulosic ethanol. An alternative is production of green gasoline and green diesel, biobased fuels equivalent to fossil fuels that could be used in unlimited volumes with existing vehicles and in the existing fuel distribution system.

Keywords: Biofuels, bioenergy, cellulosic ethanol, next-generation biofuels, feedstocks, petroleum-equivalent fuels

Acknowledgments

Thanks to Janet Perry, Tom Capehart, John Dyck, and Paul Westcott, USDA/ERS, for their helpful comments. Thanks also to Mary Blanchard (Virent Energy), Clark Garland and Samuel Jackson (Univ. of Tennessee), Tom Elam (Farm Econ), Tom Foust (DOE), Bill Hagy (USDA/Rural Development), Andrew McAloon (USDA/Agricultural Research Service), Matt Merritt (POET), Carl Pray (Rutgers University), Robert Rapier (R-Squared Energy Blog), Charles Rock (Rollins College), Hosein Shapouri (USDA/Office of Energy and New Uses), and David Woodburn (formerly of ThinkEquity). Their input significantly enhanced the quality of the report. Thanks also to Priscilla Smith for editing and Cynthia Ray for designing the report and to David Nulph and Vince Breneman for developing the map.

Introduction

Will “next-generation” biofuel production rise enough to reach current legislative mandates? What feedstocks and technologies are envisioned for next-generation biofuel production? How costly will such production be? How will investment be financed and what prospects do investors see for cost reduction? What will the role of agriculture be in supplying feedstocks for production of next-generation biofuels?

These questions can be addressed in part by examining the published plans for next-generation biofuel projects. Information that is publicly available provides insights into the scope and trends of next-generation biofuel developments that are in progress or soon will be launched.

The information, drawn from public statements by corporations and governments and from press reports, could miss projects that have a relatively low public profile or that have not been publicly revealed. In most cases, it is assumed that major investments come into the public record in one way or another. Since most of the estimates and projections are based on the published expectations of firms that hope to profit from them, the data are likely to give an optimistic picture of the near future. However, aggregating these expectations is still of interest, providing insights into the potential for future output and costs of next-generation initiatives under the most favorable conditions.

Next-generation biofuels refer to biofuels made using advanced technologies that greatly expand the potential to use widely available biomass, including woody biomass and wood waste; crop residues; dedicated energy crops such as switchgrass, energy cane, and biomass sorghum; municipal solid waste; and algae. Some next-generation biofuels, however, such as biobutanol and green gasoline and green diesel may use traditional feedstocks such as sugar beets, corn, sugarcane, animal fats, and vegetable oils. (*ScienceDaily*, 2008).

Rising oil prices through the past decade, along with strong public-sector support, significant venture capital interest, joint arrangements with large multinational companies, and affiliations with universities, have spurred the creation of several dozen next-generation biofuel companies in the United States. Public-sector support for next-generation biofuels is driven by:

- national interests in reducing the economy’s dependence on imported petroleum
- minimizing the price impacts on food crops
- mitigating greenhouse gas emissions, and
- enhancing rural employment opportunities.

The focus of this report is on the outlook for production of next-generation biofuels, key near-term challenges for the sector, and the implications for feedstock supply from U.S. agriculture.

Short-Term Outlook for Next-Generation Biofuel Production

Total production capacity for next-generation biofuels, including cellulosic biofuel, biobutanol, and biobased petroleum equivalents, is expected to be about 88 million gallons per year (a large share from one company, Dynamic Fuels) by the end of 2010, less than the average capacity of a single new corn ethanol plant (fig. 1). Total sector capacity is expected to surpass 350 million gallons by 2012.

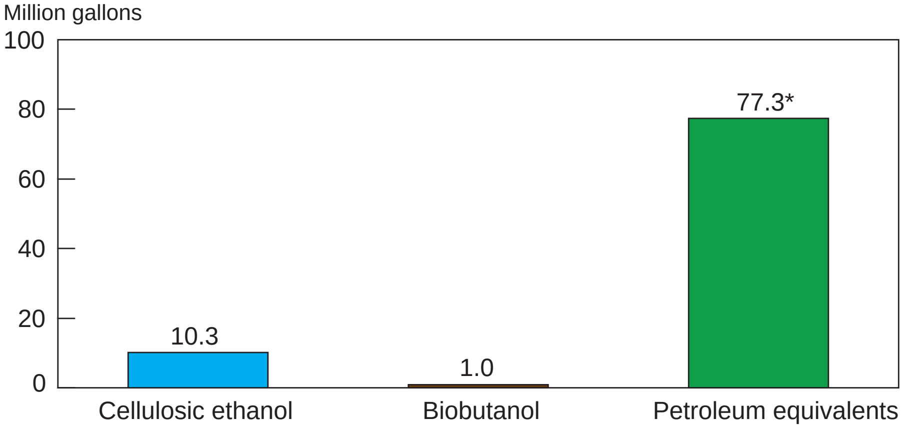
In early 2010, the EPA announced that the cellulosic biofuel mandate for 2010, the most significant next-generation category in the 2007 Energy Independence and Security Act (EISA), would be greatly reduced from 100 million gallons as specified in EISA, to 6.5 million gallons. There were no changes to mandated levels for cellulosic biofuel use in subsequent years. Based on company press releases and other reports,[1] ERS estimates that production capacity for cellulosic biofuel, primarily ethanol, may be somewhat higher, about 10 million gallons, with capacity expanding to over 200 million gallons by 2012 (fig. 2) (table 1). Production likely will be less than the capacity estimates because of the short-term prevalence of pilot and demonstration facilities that are not operated on a continuous basis.

The EISA establishes ambitious goals to more than triple overall U.S. biofuel use to 36 billion gallons by 2022, with cellulosic biofuels making up 16 billion gallons and on a trajectory to surpass corn-based ethanol use (fig. 3).

There are about 30 next-generation companies in the United States developing biochemical, thermochemical, and other approaches, and experimenting with a variety of feedstocks, some of which are directly linked to agriculture (see table 1).

Figure 1

Next-generation biofuel production capacity, 2010



*Dynamic Fuels, with a commercial plant expected to be operational in 2010, accounts for 75 million of the total. That plant will use animal fat to produce biobased fuel.

Source: USDA, Economic Research Service (table 1, pp. 4-5).

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[1] There are no publicly available production surveys of the next-generation biofuel sector. Production estimates in this report are based on company press releases and various reports. Because of the lack of transparency and the high degree of uncertainty about the commercialization of next-generation biofuels, production-capacity estimates must be reviewed and updated frequently as the sector develops.

Table 1

Selected companies developing next-generation biofuels in the United States

Company	Plant location	Plant type	Technology	Biofuel	Production capacity[1]					Biomass
					2009	2010	2011	2012	>2012	
					Million gallons per year					
Abengoa Bioenergy	York, NE	Pilot	Bio	Ethanol	0.02	0.02	0.02	0.02	0.02	Ag residue
Abengoa Bioenergy	Hugoton, KS	Commercial	Bio	Ethanol				11.6	11.6	Ag residue/ energy crops
AE Biofuels	Butte, MT	Demo	Bio	Ethanol	0.15	0.15	0.15	0.15	0.15	Ag residue
AE Biofuels	Keyes, CA	Commerical	Bio	Ethanol			5	10	10	Ag residue
Amyris	Emeryville, CA	Pilot	Bioengineered	Petroleum equivalents	2	2	2	2	2	Crops
Amyris	Campinas, Brazil	Pilot	Bioengineered	Petroleum equivalents	/2	/2	/2	/2	/2	Crops
Amyris	Campinas, Brazil	Commercial	Bioengineered	Petroleum equivalents					/2	Crops
BlueFire Ethanol	Lancaster, CA	Commercial	Bio	Ethanol			3.9	3.9	3.9	MSW[3]
BlueFire Ethanol	Fulton, MS	Commercial	Bio	Ethanol					19	Multiple
Cello Energy	Bay Minette, AL	Commercial	Cat	Petroleum equivalents		/4	/4	/4	/4	Multiple
Central Minnesota Cellulosic Ethanol Partners	Little Falls, MN	Commercial	Bio	Ethanol					10	Wood waste
ClearFuels Technology	Kauai, HI	Pilot	Thermo	Ethanol			1.5	1.5	1.5	Ag residue
ClearFuels Technology	Collinwood, TN	Commercial	Thermo	Petroleum equivalents					16	Wood waste
Cobalt Biofuels	Mountain View, CA	Pilot	Bio	Biobutanol		0.035	0.035	0.035	0.035	Multiple
Cobalt Biofuels	Mountain View, CA	Demo	Bio	Biobutanol			1.5	1.5	1.5	Multiple
Coskata	Madison, PA	Demo	Hybrid: Bio and thermo	Ethanol	0.04	0.04	0.04	0.04	0.04	Multiple
Coskata	Southeast	Commercial	Hybrid: Bio and thermo	Ethanol				50	50	Multiple
DuPont Danisco	Vonore, TN	Pilot	Bio	Ethanol	0.25	0.25	0.25	0.25	0.25	Ag residue/ energy crops
Dynamic Fuels	Geismar, LA	Commercial	Hydro	Petroleum equivalents		75	75	75	75	Animal fat, veg. and other oils
Enerkem	Pontotoc, MS	Commercial	Thermo	Ethanol				10	20	Multiple
Fiberight	Blairstown, IA	Demo	Bio	Ethanol		2	2	2	8.6	MSW[3]
Flambeau River	Park Falls, WI	Demo	Thermo	Petroleum equivalents					8	Wood waste
Fulcrum Bioenergy	Storey County, NV	Demo	Thermo	Ethanol				10.5	10.5	MSW[3]
Gevo	St. Joseph, MO	Demo	Bio	Biobutanol	1	1	1	1	1	Crops
Gevo	Various locations	Commercial	Bio	Biobutanol			50	50	50	Crops
Gulf Coast Energy	Livingston, AL	Demo	Thermo	Ethanol	0.2	0.2	0.2	0.2	0.2	Wood waste
ICM	St. Joseph, MO	Pilot	Bio	Ethanol			0.5	0.5	0.5	Ag residue/ energy crops

continued—

Table 1

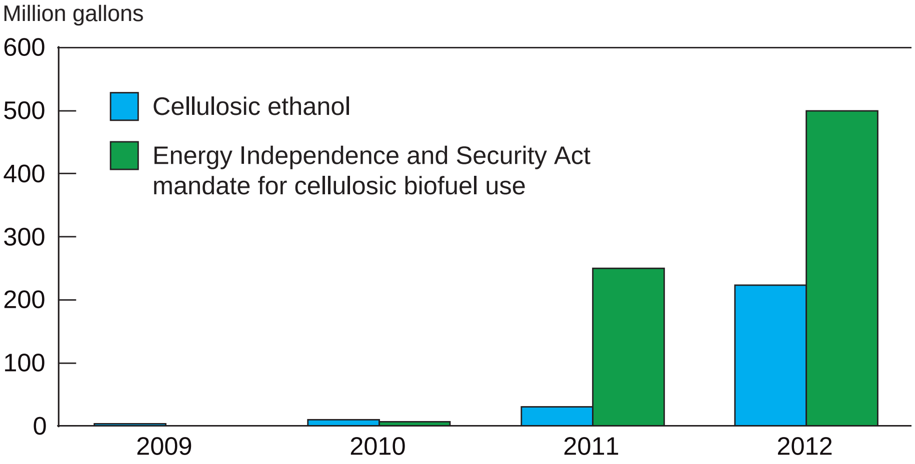
Selected companies developing next-generation biofuels in the United States—continued

Company	Plant location	Plant type	Tech-nology	Biofuel	Production capacity[1]					Biomass
					2009	2010	2011	2012	>2012	
					Million gallons per year					
Inbicon	Spiritwood, ND	Commercial	Bio	Ethanol					20	Ag residue
INEOS Bio	Fayetteville, AR	Pilot	Thermo	Ethanol	0.04	0.04	0.04	0.04	0.04	MSW[3]
INEOS Bio-New Planet Energy	Florida	Commercial	Thermo	Ethanol			8	8	8	Multiple/ Non ag
LS9, Inc.	San Francisco, CA	Pilot	Bioengineered	Petroleum equivalents			Lab scale			Multiple
LS9, Inc.	Okeechobee, FL	Demo	Bioengineered	Petroleum equivalents			0.05	0.05	0.1	Multiple
Mascoma	Rome, NY	Demo	Bio	Ethanol	0.2	0.2	0.2	0.2	0.2	Wood waste
Mascoma (Frontier Renewable Resources)	Kinross, MI	Commercial	Bio	Ethanol				20	20	Wood waste
Ohio River Clean Fuels/ Baard	Wellsville, OH	Commercial	Thermo	Petroleum equivalents					17	Multiple
Pacific Ethanol	Boardman, OR	Demo	Bio	Ethanol					2.7	Multiple
POET	Scotland, SD	Pilot	Bio	Ethanol	0.02	0.02	0.02	0.02	0.02	Ag residue
POET	Emmetsburg, IA	Commercial	Bio	Ethanol			25	25	25	Ag residue
Qteros	Springfield, MA	Pilot	Bio	Ethanol	Small pilot under construction					Multiple
Range Fuels	Soperton, GA	Commercial	Thermo	Methanol, ethanol		4	4	30	30	Wood waste
Rentech	Commerce City, CO	Demo	Thermo	Petroleum equivalents	0.15	0.15	0.15	0.15	0.15	Multiple
Rentech	Rialto, CA	Demo	Thermo	Petroleum equivalents				9.2	9.2	Multiple
Terrabon	Bryan, TX	Pilot	Bio	Petroleum equivalents	0.11	0.11	0.11	0.11	0.11	Multiple
Verenium	Jennings, LA	Pilot	Bio	Ethanol	0.05	0.05	0.05	0.05	0.05	Ag residue
Verenium	Jennings, LA	Demo	Bio	Ethanol	1.4	1.4	1.4	1.4	1.4	Ag residue
Verenium	Highlands County, FL	Commercial	Bio	Ethanol				36	36	Energy crops
Virent	Madison, WI	Demo	Bioengineered	Petroleum equivalents		0.01	0.01	0.01	0.01	Crops
Western Biomass Energy/KL Energy	Upton, WY	Demo	Bio	Ethanol	1.5	1.5	1.5	1.5	1.5	Wood waste
ZeaChem	Boardman, OR	Demo	Hybrid: Bio and thermo	Ethanol		0.25	0.25	0.25	0.25	Poplars
					Million gallons per year					
Cellulosic biofuel (1)					3.9	10.1	29.0	223.1	291.4	
Mandate for cellulosic biofuels (2007 EISA)						[5]6.5	250	500	1,000	
Biobutanol (2)					1.0	1.0	52.5	52.5	52.5	
Petroleum equivalent (3)					2.3	77.3	77.3	86.5	127.6	
Total next-generation (1)+(2)+(3)					7.1	88.4	158.9	362.2	471.5	

Bio=biochemical processes; Thermo=thermochemical processes; Cat=catalytic depolymerization; Hydro=hydroprocessing technology (see appendix for descriptions). [1]The numbers in this table represent "production capacity," not "production." Actual production from these plants is likely to be less in the short run since many are pilot or demonstration plants not operated on a continuous basis. Numbers are volumetric and not adjusted for energy content. [2]Production in Brazil; capacity of demonstration plant is 10,000 gallons per year; commercial output from various plants could be as much as 200 million gallons/year after 2012. [3]MSW = municipal solid waste. [4]Limited information about feedstock used; capacity has been estimated at 20 million gallons per year. [5]Mandate for cellulosic biofuel reduced by EPA from 100 million gallons per year (specified in 2007 EISA), to 6.5 million gallons in February 2010. Sources: USDA, Economic Research Service analysis of data from U.S. Environmental Protection Agency, ThinkEquity, company websites (names as listed above).

Figure 2

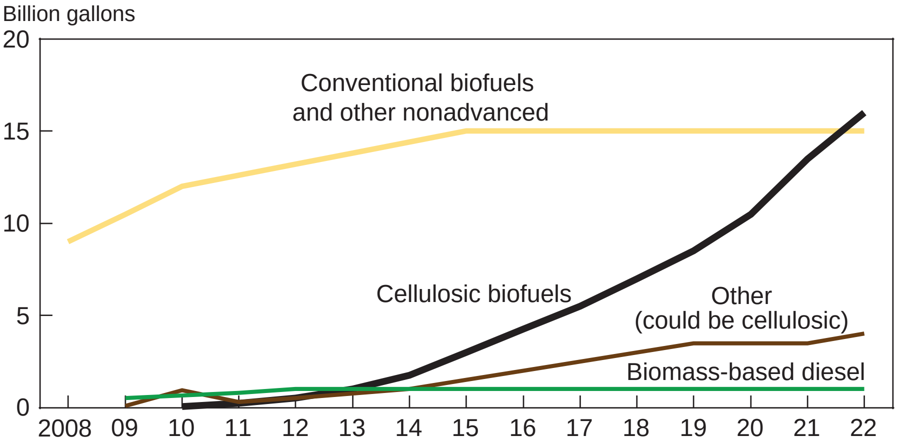
Cellulosic ethanol production capacity in the United States



Source: USDA, Economic Research Service (table 1, pp. 4-5).

Figure 3

Rapid rise in use of cellulosic biofuel mandated by Energy Independence and Security Act



Source: U.S. Environmental Protection Agency. *Regulation of Fuels and Fuel Additives: Changes to Renewable Fuel Standard Program: Final Rule*. February 2010.

Range Fuels and Dynamic Fuels are expected to complete the first commercial next-generation biofuel plants in 2010. Range's plant in Soperton, GA, will use pine-tree waste as the feedstock. According to the EPA, however, the plant's initial capacity has been reduced from 10 million to 4 million gallons per year and initial output will be methanol. The company's ethanol production is expected to commence at a later stage of development. Dynamic Fuel's plant in Geismar, LA, is expected to start commercial operations in the second half of 2010, using animal fat as the feedstock and producing a biobased diesel fuel. POET, which has a pilot plant operational in Scotland, SD, may have the first commercial plant to produce cellulosic ethanol. The facility will be colocated with one of POET's existing corn ethanol plants in Emmetsburg, IA, and is scheduled to be operational in late 2011 or early 2012, using corn cobs as the feedstock. Most other companies have small pilot or demonstration plants, with average estimated production capacity of less than 1 million gallons in 2010, but with future plans to expand.

There are more than two dozen other next-generation companies in Europe, Canada, Brazil, China, and other countries at various stages of development. And more than two dozen companies in the United States are developing approaches to growing and converting algae to fuel (see box, “Algae’s High Potential Yield Per Acre Interests U.S. Biofuel Producers”).

Biochemical and Thermochemical Are Leading Conversion Processes

Next-generation companies are developing a variety of biochemical and thermochemical pathways to convert biomass to fuel. For 2009-10, including pilot and demonstration plants in operation as well as planned operations for 2010, biochemical approaches are most common (table 2). Those companies using or planning to use biochemical processes include Verenium, Mascoma, Abengoa, and POET. Those using thermochemical approaches include Range Fuel, Rentech, and INEOS Bio. Coskata and ZeaChem are combining biochemical and thermochemical processes. LS9, Amyris, and Virent are companies using other approaches to produce biobased petroleum-equivalent fuels.

There may be a shift in favored technologies underway. Several companies planning to be operational with some of the larger plants in the next several

Algae’s High Potential Yield Per Acre Interests U.S. Biofuel Producers

More than 30 U.S. companies currently are experimenting with different approaches to producing algae-based fuels. Their interest in algae as a feedstock is driven by algae’s high potential yield per acre. Some companies grow algae in photo-bioreactors and others in open ponds, with yields potentially greater than 5,000 gallons per acre, by far the greatest potential of any feedstock for conversion to biofuels. Algae can be cultivated on marginal land that is unsuitable for growing crops or raising livestock, but also can compete with food-producing resources (for example, converting catfish ponds to algae propagation). Although the majority of algae-to-biofuel companies are focusing on producing algae oil for traditional biodiesel production, some companies are using algae to produce ethanol (Algenol), or petroleum-equivalent fuels (UOP and Sapphire).

However, production cost estimates (net of capital costs) for growing and converting algae to fuel are significantly higher than for first- and next-generation biofuels, ranging from $9 per gallon to $35 per gallon, depending on the production technology (British Columbia Innovation Council, 2009). This compares with less than $3 per gallon for cellulosic ethanol. Except for subsidized military uses, the market for algae-based fuels will be limited until production costs are greatly reduced.

Table 2

Next-generation biofuel plants by conversion technology, 2010

Technology	Cellulosic ethanol	Biobutanol	Petroleum equivalent	Total
	Number of plants			
Biochemical	9	2		11
Thermochemical	3		2	5
Hybrid	2			2
Other			4	4
Total	14	2	6	22

Includes pilot, demonstration, and commercial plants.

Source: USDA, Economic Research Service (table 1, pp. 4-5).

years plan to use thermochemical approaches or other processes that produce biobased petroleum-equivalent fuels.

About 50 Percent of Next-Generation Companies Will Use Feedstock From Agriculture

Based on company information, about 50 percent of next-generation plants in 2009-10 likely will use exclusively agricultural biomass (table 3):

- crops, vegetable oils, and animal fats, typically used for first-generation biofuels
- crop residues
- energy crops

The proportion may be higher if some companies that report capacity to use multiple feedstocks actually use agricultural biomass. About 20 percent of the companies report their use or intention to use forestry products as feedstocks.

The overall impact from the expansion of next-generation biofuels on U.S. agriculture initially will be small because fuel production will be very limited, requiring only modest amounts of biomass from all sources in the next several years. Some companies will exploit already existing streams of forestry waste and municipal solid waste. Other companies are in the process of developing supply arrangements for agricultural biomass (particularly crop residues and energy crops) (fig. 4). Eventually agriculture could play a significant role as next-generation biofuel production expands. Biomass inventory studies show that of all potential sources of biomass in the United States, agricultural biomass is the most significant. This is reflected by a number of companies planning significant biofuel production in 2011-12 from agricultural biomass: POET plans to produce 25 million gallons from corn cobs starting in 2011 or 2012; Abengoa, 11.6 million gallons from corn stover, wheat straw, and switchgrass in 2012; and Verenium, 36 million gallons from energy grasses in 2012. Other companies developing technologies for producing petroleum-equivalent fuels and biobutanol may use first-generation feedstocks, such as sugarcane, sugarbeets, corn, vegetable oils, and animal fats.

Table 3

Next-generation biofuel plants by feedstock used, 2010

	Cellulosic ethanol	Biobutanol	Petroleum equivalent	Total	Capacity
	Number of plants[1]				*Million gal/year*
Ag residue	3			3	1.6
Ag residue/energy crops	2			2	0.3
Animal fat, vegetable oil			1	1	75
Crops		1	2	3	3
Energy crops	1		1	2	0.2
Ag related	6	1	4	11	80.1
MSW[2]	2			2	2
Multiple[3]	1	1	2	4	0.2
SRWC[4]	1			1	0.3
Wood waste	4			4	5.9
Total	14	2	6	22	88.5

[1] Pilot, demonstration, and commercial plants. [2] MSW = municipal solid waste.

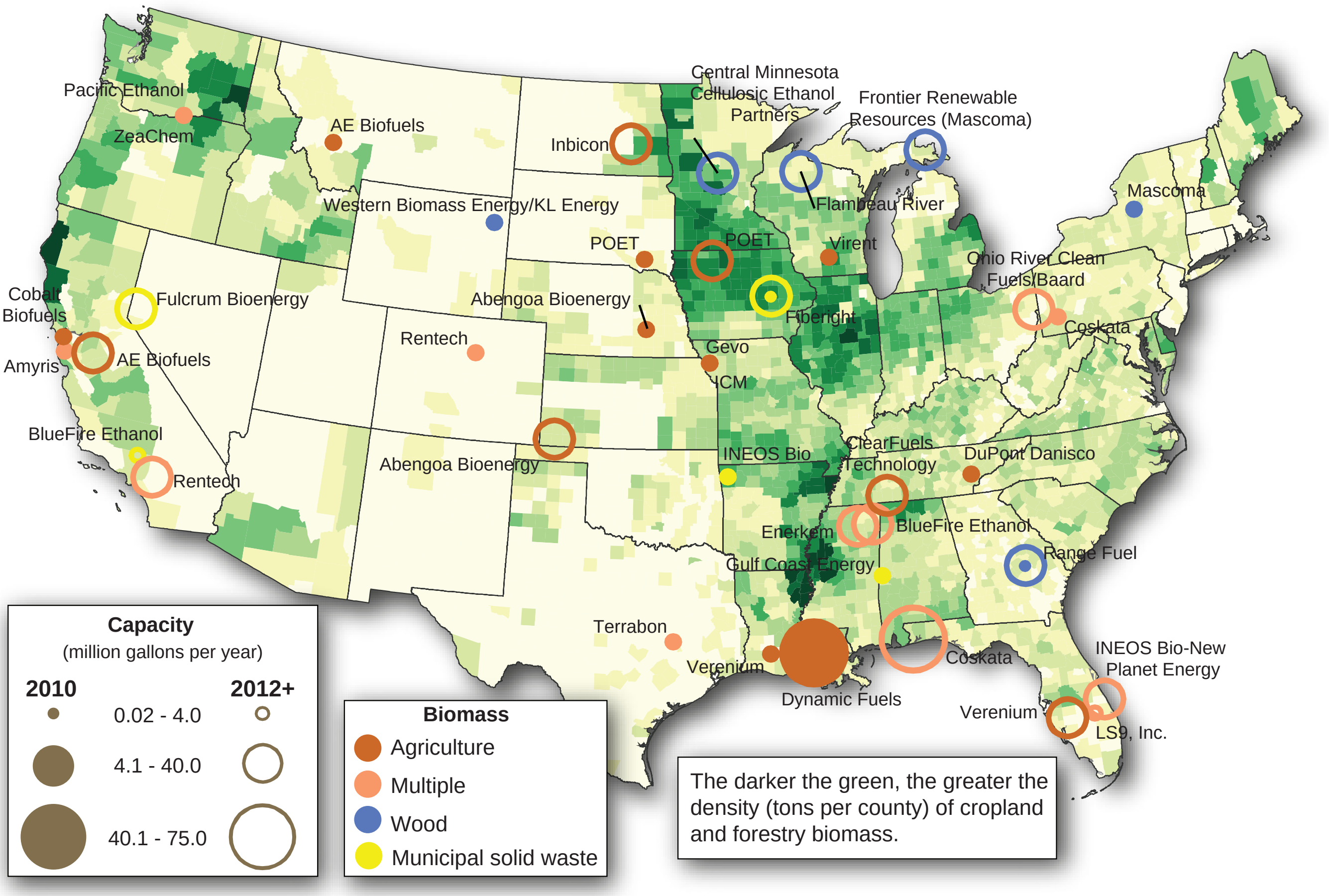
[3] Plant is capable of using a range of feedstock, including at least 2 categories of biomass.

[4] SRWC = short rotation woody crops.

Source: USDA, Economic Research Service (table 1, pp. 4-5).

Figure 4

Next-generation biofuel plants located across the Nation near biomass supplies



Source: USDA, Economic Research Service (table 1, pp. 4-5); biomass resource map from Oak Ridge National Laboratory (Biomass Research and Development Initiative, December 2008, p. 79).

Key Challenges Facing Next-Generation Biofuels

The future of next-generation biofuels will hinge on success in addressing the following challenges:

- reducing high production and capital costs
- securing financial support during precommercial development
- establishing feedstock supply arrangements
- overcoming blend wall constraints

Reducing High Production and Capital Costs

High production and initial construction costs for untested technologies and processes on a large scale increase investment risk and affect the willingness of investors to underwrite projects.

Estimated production and capital costs for next-generation biofuel production are significantly higher than for first-generation biofuels. These costs are expected to decline as companies scale up production. Government programs to subsidize feedstock delivery and a company's choice of feedstock and operational structure may also help to lower production costs.

In 2007, USDA estimated cellulosic ethanol production costs at $2.65 per gallon, compared to $1.65 for corn-based ethanol. In this estimate, conversion and capital costs for cellulosic ethanol were significantly higher than for corn-based ethanol (fig. 5) (Collins, 2007). POET recently reported it had lowered production costs for cellulosic ethanol, including capital expenses, from $4.13 to $2.35 per gallon in a year as of November 2009 at its South Dakota pilot plant.[3] Novozymes, the world's leading producer of enzymes, recently estimated that the cost of enzymes for cellulosic ethanol production had been reduced significantly in the last 2 years to about 50 cents per gallon, reducing total production costs in the near term to about $2 per gallon.[4]

These production cost trends are in line with Government targets for the industry. The 2008 National Biofuels Action Plan[5] set target costs for cellulosic ethanol at about $2 per gallon for 2009. The U.S. Energy Department set in 2006 a goal of reducing production costs for next-generation biofuels to about $1.00 per gallon by 2012 (Karsner, 2006).

A key area of uncertainty is the cost of biomass, which needs to be relatively low to offset higher conversion and capital costs relative to first-generation biofuel production. According to a 2008 report by the Biomass Research and Development Board,[6] farmgate prices of $40 to $45 per dry ton would be sufficient to secure feedstocks for U.S. production of 12 to 16 billion gallons of cellulosic ethanol. These biomass price assumptions are consistent with $40- to $60- per-ton prices POET reportedly intends to pay suppliers for delivery of corn cobs to its cellulosic plant in Iowa. But the range of prices may underestimate the cost of increasing biomass yields on marginal lands and the incentives required for harvesting, gathering, and delivering bulky material to the biorefinery. Corn cobs, for example, are two to four times

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[3] POET company website. Available at: http://www.poet.com/news/showRelease.asp?id=181.

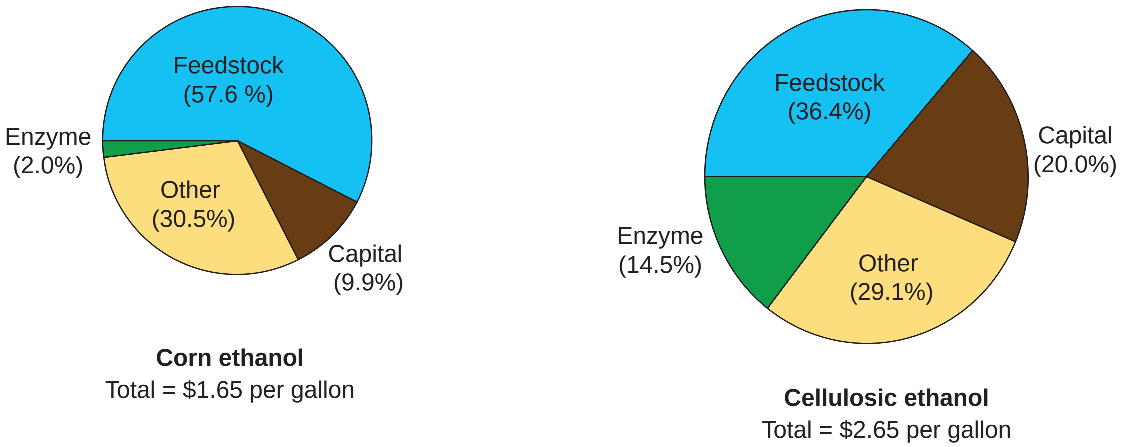
[4] "Novozymes, Genencor Unveil New Enzymes for Cellulosic Ethanol," SustainableBusiness.com. February 17, 2010.

[5] Biomass Research and Development Initiative, October 2008.

[6] Biomass Research and Development Initiative, December 2008.

Figure 5

Comparing corn and cellulosic ethanol production costs



Source: Keith Collins, Chief Economist, USDA. *The New World of Biofuels: Implications for Agriculture*. Presentation at Energy Information Administration (EIA) Energy Outlook, Modeling, and Data Conference, March 28, 2007.

more expensive to transport than corn kernels on a tonnage basis because they are much more bulky (Hudson, 2009). Also, dedicated energy crops would need to compete with the lowest value crop such as hay which has had a price exceeding $100 per ton since 2007 (NASS, 2007). The new Biomass Crop Assistance Program in the 2008 Farm Act will help to boost farmer incentives by as much as $45 per ton and thus lower feedstock costs for biorefineries.

Capital-investment costs for cellulosic ethanol are estimated to be more than three or four times those for corn ethanol plants. It must be kept in mind that these are estimates, and that there are no actual cost data for commercial operations since none are yet operational. DOE’s Energy Information Administration estimated in 2004 that capital investment costs for biomass-to-liquid facilities ranged from $650 million to $900 million for a 100-million-gallon capacity plant, compared with $65 million to $195 million for a similar size biodiesel plant and $130 million to $230 million for a similar size corn ethanol plant (U.S. Department of Energy, 2006). According to a more recent analysis using normalized data for 2007, to produce 100 million gallons, projected total project-investment costs for biochemical conversion were $320 million and for thermochemical conversion $340 million (Foust et al., 2009). While this and another analysis conclude that there was no clear difference in capital-investment costs or operating costs for either the thermochemical or biochemical approaches, (Wright and Brown, 2007) they do allude to a downward trend in overall capital costs relative to earlier DOE estimates. This likely occurred despite significant increases in nonlabor costs since 2003 because of a variety of market changes leading to higher material and energy costs (Foust et al., 2009).

Company estimates are mostly consistent with the DOE estimates. Canada’s Iogen Corporation estimated in 2006 that a cellulosic plant with the capacity of 50 million gallons per year would cost about $300 million. By comparison, a corn ethanol plant with the same capacity could be built for about $65 million (U.S. Department of Energy, 2006). Abengoa Bioenergy announced in 2007 that its hybrid plant in Hugoton, KS, that will produce 85 million gallons per year of corn ethanol and 11.6 million gallons of cellulosic ethanol, would cost $400 million (*Environment News Service*, 2007). Coskata estimated in 2008 that a 100-million-gallon capacity per year cellulosic plant would cost $300 million, later updating the estimate to $400 million (Ring, December 2008).

The way a company structures its operation may also help to reduce costs by taking advantage of existing residue waste streams and/or combining advanced cellulosic ethanol production with corn ethanol production. Three of the four plants (Bluefire, POET, and Range) supported by 2007 DOE grants and expected to have commercial operations relatively early are focused on residues (municipal solid waste, cobs and wood waste), while one (Abengoa) is focused on a number of potential feedstocks, including switchgrass and agricultural residues, such as corn stover and wheat straw. Two of the four plants (POET and Abengoa) are building operations that combine cellulosic and corn ethanol production in close proximity.

Securing Financial Support During Precommercial Development

Next-generation biofuel companies are using a variety of strategies to overcome high initial capital-investment costs and to sustain themselves during precommercial development. These strategies include the use of venture capital, Government grants and loan guarantees, alliances with large U.S. and multinational companies, ties with academic institutions to benefit from access to intellectual capital, and combinations of these strategies.

Venture capital: Venture-capital investment worldwide in clean-technology (solar, biofuels, vehicle technology, and wind companies) rose in 2002-08, totaling $8.5 billion in 2008, (Covel, 2009) with solar accounting for almost 40 percent of the total, followed by biofuels at about 10 percent. U.S. companies accounted for more than two-thirds of the global total (*SustainableBusiness.com News*, 2009). Leading biofuel companies receiving venture capital in 2008 were Range Fuels ($166 million), Sapphire ($100 million), Amyris ($90 million), Mascoma ($61 million), Solazyme ($45.4 million), and Coskata ($40 million) (Lane, 2009).

In 2009, overall clean-technology venture capital declined by one-third from the effects of the global recession. Because of strong Government support for clean technologies, not as much of a decline occurred as in other venture-capital sectors. Within the biofuel sector, venture capital has shifted away from traditional corn-based production to next-generation biofuels and algal biodiesel.

Public-sector support: Venture capital support for next-generation projects was bolstered by a major infusion of public-sector support in December 2009 when DOE announced $564 million in grants to 19 next-generation companies. These grants were part of the Federal stimulus program (American Recovery and Reinvestment Act of 2009) and were divided about equally in number among companies developing cellulosic ethanol and those developing biobased petroleum substitutes, closely akin to fossil fuels. USDA also extended three major loan guarantees in 2009-10, two for next-generation biofuel companies: one for $80 million to Range Fuels and another for $54.5 million to Sapphire Energy.

The Federal Government committed a total of more than $2 billion to next-generation biofuels in 2007-09 in direct private-sector support, university research and development, including biomass development projects. The largest grants[7] previous to the December 2009 ones were also made by DOE in 2007 and allocated to six companies: Abengoa Bioenergy (Hugoton, KS; $76 million), Range Fuels (Soperton, GA; $76 million), BlueFire Ethanol (Lancaster, CA; $40 million), POET (Emmetsburg, IA; $80 million), Alico (La Belle, FL; $33 million), and Iogen (Shelley, ID; $80 million). The last two dropped out of the program.

A number of States also have provided financial support to specific next-generation companies, including Michigan's support ($23.5 million grant from the State and $26 from the U.S. DOE) for Mascoma's plant in Kinross, MI; Iowa's support for POET's Emmetsburg, IA, plant ($14.8 million in funding from the Iowa Power Fund and a $5.3-million grant from the Iowa Department of Economic Development); and the State of Tennessee's support to build and operate DuPont-Danisco's pilot plant in Vonore, TN ($70.5 million). Other States, including New York, Florida, Colorado, and California, are providing support for projects in their jurisdictions.

Partnerships with corporations: Another strategy is for biofuel companies to partner with large corporations in the energy, automotive, forestry, and seed product industries. These arrangements augment a small company's financial resources and provide opportunities to gain access to engineering and marketing know-how, and some cases, conversion technologies. For the large companies, these partnership or arrangements may provide an opportunity to vertically integrate or diversify their businesses.

BP, Shell, Chevron, and Valero have partnered with next-generation biofuel companies as well as institutions engaged in biofuel research. BP has relationships with Verenium to work on a prospective commercial plant in Florida and in other locations in the southern United States. In addition to first-generation facilities in Brazil, BP is also partnering with U.S. startup Qteros in Massachusetts and is working with DuPont and Associated British Foods to develop biobutanol in the United Kingdom. BP is investing $500 million in a 10-year program (started in 2007) in the Energy Bioscience Institute with the University of California (Berkeley), University of Illinois and the Lawrence Berkeley Labs to focus on biotechnology applications to energy, including development of next-generation biofuels.

Shell Oil Co. is a partner with Canada's Iogen, one of the world's first cellulosic companies. Shell raised its equity share in the company to 50 percent in 2008 (Burnham, 2009). Shell also has collaborative arrangements with Virent in Wisconsin; agreements with researchers at academic institutions around the world; a joint venture with Cosan, Brazil's largest sugarcane producer; and an agreement with Codexis, a California company developing enzymes to lower next-generation biofuel production costs.

Chevron has a partnership with Solazyme (a California company working on the production of algal oil) and a number of academic institutions as well

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[7] The grants were awarded under Section 932 of the Energy Policy Act of 2005, which authorized the U.S. Department of Energy to fund commercial demonstration of advanced biorefineries that use cellulosic feedstock to coproduce ethanol, bioproducts, heat and power. Awards were capped at 40 percent of the total project cost, up to a maximum of $80 million. By investing in these facilities, DOE is sharing the risk of financing first-of-a-kind technology and providing crucial funding at a difficult stage in the development process.

as a joint venture (Catchlight Energy) with Weyerhaeueser, a wood products company, to produce cellulosic and other biobased fuels.

In 2009, Exxon Mobil announced a partnership with Synthetic Genomics, a company developing strains of algae for producing petroleum-like products.

Valero, the leading U.S. oil refiner, expanded its biofuel interests by purchasing corn ethanol facilities in 2009 from bankrupt VeraSun[8] to add to interests in next-generation startups: Qteros (Massachusetts-based company working on converting woody biomass and fast-growing grasses to cellulosic ethanol), ZeaChem (Oregon-based plant working on converting poplar trees to cellulosic ethanol), Terrabon (Texas-based company working on converting sorghum to petroluem-equivalent fuel) and Solix (Colorado-based company working on growing algae for conversion to biofuels).

Coskata, a next-generation startup headquartered in Illinois, has partnered with General Motors as well as with the U.S. Sugar Corporation and is exploring business relationships with Australian and Chinese interests. General Motors also has invested in Mascoma, with a demonstration plant now operational in New York State, and plans to build a larger plant in upper peninsula Michigan. Canadian startup Lignol signed a memorandum of understanding in 2008 with Weyerhaeuser to explore development of commercial applications of Lignol's biorefining technology and to evaluate the development of a commercial-scale biorefinery plant at or near a Weyerhaeuser mill site.

Danish-owned Novozymes, the world's leading producer of industrial enzymes, has partnerships with next-generation companies POET, KL Energy, ICM, Inc., and Inbicon. Novozymes has received research support from the U.S. Department of Energy and has its own researchers in California, North Carolina, Denmark, Brazil, and China as well as partnerships with Cornell University, Pacific Northwest National Laboratory, the DOE's National Renewable Energy Laboratory and France's National Center for Scientific Research.[9] Novozymes is developing enzyme production facilities in Nebraska, first for corn ethanol and then for cellulosic production (a $200-million investment, scheduled to be operational in 2011), and in China. In some countries, large state-run companies like Petrobras in Brazil and the China National Cereals, Oil and Foodstuff Corporation (COFCO) in China are spearheading development of next-generation biofuels. Petrobras, through its Center for Research and Development, is operating a next-generation pilot plant using sugarcane bagasse (fibrous residue after cane is crushed) as the feedstock and plans to commercialize production by 2015. COFCO is collaborating with Sinopec and Novozymes to develop large-scale production of cellulosic ethanol (*Green Car Congress*, 2009). Since 2006, COFCO has been producing 1.7 million gallons of cellulosic ethanol per year[10] from corn stover, wheat straw, grasses and other organic material (STT Pressi.com, 2006; USDA/FAS, 2006) at a demonstration plant in Zhaodong, Heilongjiang province, alongside a traditional ethanol facility.

Partnerships with universities: Some of these technology-intensive enterprises are closely associated with universities: three examples are Qteros (University of Massachusetts), Mascoma (Dartmouth College, New Hampshire), and Virent (University of Wisconsin).

[8] "Valero wins bid to buy VeraSun plants," *F.O. Licht's World Ethanol & Biofuels Report*. March 25, 2009.

[9] "The Forefront of Enzyme Production," *Ethanol Producer Magazine*. June 2009.

[10] "China's COFCO eyes cellulosic ethanol progress." *F.O. Licht's World Ethanol & Biofuels Report*. March 27, 2007.

In the case of Qteros, the connection is with the University of Massachusetts where the company's chief scientist is also a microbiology professor. In 2005, her lab discovered the capability of a microbe (*Clostridium phytofermentans*) to consume a variety of plant material, including woody biomass and fast-growing grasses, and convert them directly into ethanol, potentially a step-reducing and cost-lowering discovery (Kho, 2008).

One of Mascoma's founders is a Dartmouth College engineering professor who has been developing technologies that reduce the number of steps and increase the speed of cellulosic-to-ethanol conversion.

Virent's founder invented its BioForming technology at the University of Wisconsin where he was a chemical engineer before leaving in 2001. That process converts plant sugars into a variety of hydrocarbon molecules identical in structure to petroleum-based fuels.

Several other next-generation companies have university connections: INEOS (University of Arkansas), DuPont-Danisco (University of Tennessee), CleanTech Biofuels (University of California, Berkeley), Solix (University of Colorado), Verenium (University of Florida), and Zymetis (University of Maryland) among others.

Establishing Feedstock Supply Arrangements

Another challenge facing the next-generation biofuel sector is the development of arrangements to assure a steady year-round supply of biomass to the biorefinery. Access to low-cost feedstock is critical to the commercial prospects of next-generation companies, particularly given their high capital and conversion costs. Feedstock accounts for more than one-third of estimated cellulosic ethanol production costs. When fully commercialized, companies will require vast amounts of bulky material to be delivered and stored at the processing plant. Biomass producers will need incentives to commit to sustained production of new feedstocks.

From a broad perspective, the United States has the potential to produce a significant volume of biomass on a sustainable basis, enough to produce about 60 billion gallons of gasoline equivalent, or about a third of current U.S. fossil fuel transportation demand (140 billion gallons of gasoline demand and 40 billion gallons of diesel demand) (Sandia Labs and General Motors, 2009; and U.S. DOE and USDA, 2005). Other reports (Biomass Research and Development Initiative, December 2008; and EPA, 2009) conclude that EISA mandates for cellulosic biofuel can be met, primarily with domestic crop residues, forestry biomass, and energy crops.

But physical potential does not translate into economic availability. In some cases companies are planning to exploit existing waste streams of MSW and wood products. But in other cases, supply arrangements for new feedstocks need to be developed. Companies are working with local biomass producers to develop feedstock supplies for their pilot or demonstration plants to lay the groundwork for larger commercial operations. Here are a few examples:

- POET is working with regional corn producers to supply cobs in addition to grain in anticipation of graduating from its pilot-scale cellulosic plant in Scotland, SD, to its commercial combined-corn-and-cellulosic facility scheduled for operation in late 2011 or early 2012 in Emmetsburg, IA. The company is working with a number of equipment manufacturers to facilitate the simultaneous harvesting of grain and cobs. It is also working with local farmers and expects to pay producers $40 to $60 per ton for their cobs.

- ZeaChem, with a demonstration cellulosic plant planned for operation in 2010 in Boardman, OR, is working with GreenWood Resources, Inc., to supply poplar trees to support the company's initial 250,000 gallon per year output. It takes about 40 acres of hybrid poplars to produce this amount. Since poplars take 6 years to mature, it will take about 240 acres to sustain ZeaChem's initial level of production.[11]
- The Noble Foundation is partnering with the Oklahoma Bioenergy Center to plant and conduct research on 1,000 acres of switchgrass in anticipation of the completion of a cellulosic plant in 2011 by Abengoa Bioenergy in Hugoton, KS.[12]
- The State of Tennessee, through the University of Tennessee, is providing 60 farmers with subsidies and other assistance to help meet feedstock demand at the DuPont-Danisco pilot plant in Vonore, TN.[13] About 7,000 acres of switchgrass are expected to be in production by the end of 2010.
- The Verenium-BP joint venture in Highland County, FL, signed a long-term lease for 20,000 nearby acres to supply energy cane[14] and forage sorghum to the planned 36-million-gallon-per-year cellulosic ethanol plant.[15]

Overcoming Blend Wall Constraints

EISA and the 2008 Farm Act provide substantial support for next-generation biofuels (see box, "U.S. Policies Support Next-Generation Biofuels"). But there is a technical standard that has a more immediate effect on the outlook for both corn and cellulosic ethanol. This is the "blend wall" that limits the share of ethanol that can be blended in gasoline. Car manufacturer warranties and extended warranties for non-flex-fuel vehicles cover an ethanol share in gasoline no more than 10 percent on a volumetric basis because of the potential for higher blends to damage the engine and other components.

Ethanol use across the United States was about 10.8 billion gallons in 2009. Since 2009 gasoline demand was 138 billion gallons, the ethanol share in gasoline was about 7.8 percent. Under EISA, the maximum amount of corn ethanol use that can count toward the Renewable Fuel Standard in 2015-22 is 15 billion gallons. If gasoline consumption remains constant at 138 billion gallons, as some industry analysts predict, corn ethanol's share could exceed 10 percent, leaving little opportunity for cellulosic ethanol to compete with corn ethanol for the blended gasoline market.

Reaching the 2022 targets in EISA for cellulosic and corn-based ethanol will require raising the 10-percent blend standard for regular vehicles and/or expanding the use of the gasoline substitute, E85.[16] In 2009, the EPA deferred until mid-2010 a decision to raise the 10-percent standard to 15 percent, at least possibly for newer vehicles manufactured after 2000. Expanding the use of E85 will require development of an infrastructure to

[11] ZeaChem website: http://www.zeachem.com/press/pressrelease01.php

[12] "Oklahoma switchgrass project gets extra funding." *F.O. Licht's World Ethanol & Biofuels Report*. Tuesday November 11, 2008.

[13] "Tennessee farmers sign up for cellulosic switchgrass funding." *F.O. Licht's World Ethanol & Biofuels Report*. June 22, 2009.

[14] Energy cane is a relative of sugarcane but is lower in sugar and higher in fiber. The high fiber content allows the plant to grow taller, increasing per-acre yield.

[15] http://www.vercipia.com/pdfs/Highlands_FactSheet.pdf

[16] "Currently, high-percentage blends account for well under 1 percent of the overall U.S. market for fuel ethanol. Expanded use of high-percentage blends is necessary if total ethanol use is to grow beyond the level of 12 to 15 billion gallons per year that would saturate the market for low-percentage blends." –Testimony of Dr. Howard Gruenspecht, Acting Administrator, U.S. Energy Information Administration before the Subcommittee on General Farm Commodities and Risk Management, Committee on Agriculture, U.S. House of Representatives. April 1, 2009.

distribute and dispense E85 and expanded manufacture of vehicles capable of using it. Currently, there are only 9 million of about 235 million cars and other light vehicles in the United States that are E85 capable and 2,200 of the Nation's 160,000 gas stations are set up to dispense E85.[17]

Given the limited market for ethanol as a gasoline additive (due to the E10 "blend wall") and as a gasoline substitute (because of slow development of the E85 market), developers and investors may turn away from cellulosic ethanol in favor of production of another class of next-generation biofuels, petroleum substitute fuels. These so-called "drop in" fuels can be used as gasoline or diesel substitutes in current vehicles without limit and distributed seamlessly in the existing transportation fuel infrastructure.

[17] Paul Westcott. "Full Throttle U.S. Ethanol Expansion Faces Challenges Down the Road," *Amber Waves*. September 2009.

U.S. Policies and Programs Support Next-Generation Biofuels

The development and production of next-generation biofuels in the United States are supported by a variety of policies, including some originally designed to support first-generation biofuels: corn-based ethanol and soy and recycled vegetable and animal fat biodiesel.

The following policies and programs are designed to provide broad support for next-generation biofuel producers. Other programs discussed in the text relate to direct support for specific bioenergy companies.

Renewable Fuel Standard Mandates Increased Use

The most significant of the broad market policies is the consumption mandate or renewable fuel standard (RFS2) enacted in the 2007 Energy Independence and Security Act (EISA). It is referred to as RFS2 because it supersedes the RFS in the 2005 Energy Policy Act (EPACT). RFS2 specifies annual mandates for expanded use of conventional (ethanol primarily from corn starch) and advanced biofuels (from cellulosic, biomass-based diesel, and other sources) through 2022. The law provides waivers that allow the EPA administrator to adjust the annual mandated amounts because of adverse economic or environmental impacts, or if there is insufficient production.

The various categories of biofuels are generally defined by their environmental impact; that is, the reduction in life-cycle greenhouse gas (GHG) emissions relative to fossil fuel. EISA defines renewable biofuels as those that reduce life-cycle GHG emissions by at least 20 percent relative to fossil fuel; advanced biofuels by at least 50 percent, including biomass-based diesel; and cellulosic biofuels by at least 60 percent.

Tax Credits and Border Protection

There is a tax credit of $1.01 per gallon for cellulosic ethanol (2009-12), more than double the 45 cents per gallon for first-generation ethanol. Cellulosic ethanol benefits from the same border protection as first-generation ethanol: 2.5-percent ad valorem and 54-cents-per-gallon surcharges (which are waived for imports from Caribbean Basin Initiative countries that meet certain conditions regarding local content).

U.S. Farm Act Provides R&D Support and Loan Guarantees

The 2008 Farm Act provides more funding for research and development on conversion technologies and biomass and assistance to producers for eligible second-generation feedstocks. The Biomass Crop Assistance Program provides assistance up to $45 per dry ton for eligible biomass. The assistance is directed at the establishment and production of new feedstocks for biofuels. The subsidy significantly increases incentives to produce, harvest, collect, and deliver bulky low-value biomass products to biorefineries and other conversion facilities. This, in turn, will help to lower feedstock costs and facilitate timely availability of supply to biorefineries.

USDA also provides loan guarantees to support development of innovative conversion processes for cellulosic biofuel. EISA provides a 50-percent-depreciation deduction for eligible cellulosic biofuel plants in the first year of operation through 2012.

USDA and DOE Support Basic and Applied Research

Finally, USDA and DOE are committed to basic and applied research through their national networks of laboratories and experiment stations. DOE has also funneled significant resources into the creation of three Bioenergy Research Centers, led by the Oak Ridge National Laboratory in Oak Ridge, TN; the Universitiy of Wisconsin in Madison, WI; and the Lawrence Berkeley National Laboratory in Berkeley, CA. Significant resources are allocated through DOE labs, including the National Renewable Energy Laboratory in Colorado. Public-research funds target efforts to lower the costs of production of next-generation biofuels through increasing biomass yields (tons per acre), conversion yields (gallons per ton), and speed of conversion; finding new uses for co-products, better understanding of optimal removal rates for agricultural residues, as well as addressing economic and environmental issues.

Next-Generation Biofuels Poised to Expand

The next-generation biofuel sector in the United States is slowly emerging. It now consists of several dozen companies, many with small pilot or demonstration plants, which have plans to scale up production in the next several years. High oil prices and strong public-sector and venture-capital support are the industry drivers. Public-sector support is driven by multiple national interests: reducing the economy's dependence on imported petroleum, minimizing the price impacts on food crops, mitigating greenhouse gas emissions, and enhancing rural employment opportunities.

Based on company reports and other sources of information, total production capacity for next-generation biofuels, including cellulosic biofuel, biobutanol, and biobased petroleum equivalents, will be about 88 million gallons in 2010, expanding to more than 350 million gallons by 2012. Production capacity for cellulosic biofuel, the most significant category for next-generation biofuels under the 2007 Energy Independence and Security Act, is estimated at about 10 million gallons, much less than the 100 million gallons originally mandated for 2010 in the 2007 Energy Independence and Security Act. In early 2010, EPA lowered the mandate only for 2010 to 6.5 million gallons, more in line with ERS' capacity estimate. U.S. production capacity will have to accelerate to meet subsequent annual mandates and the long-term mandate of 16 billion gallons for cellulosic biofuel use by 2022.

Near-term challenges facing the next-generation biofuel sector include reducing high capital-investment and production costs, acquiring sufficient financial resources for precommercial development, and developing new feedstock supply arrangements. Success has been achieved in the last decade in reducing costs as reported by individual companies and by DOE analyses. Private financial resources supporting the sector may have slowed their increase in 2009 as the recession reduced energy demand and investor interest in alternative fuels. Public-sector resources helped to bolster private resources through the Federal stimulus bill (American Recovery and Reinvestment Act of 2009) and other Government programs for next-generation projects.

The role for agriculture could be substantial as the next-generation sector expands. Biomass inventory studies conclude that agricultural biomass is the most plentiful potential feedstock relative to other sources, including forestry products and municipal solid waste. So far, the role for agriculture is small because next-generation biofuel production is very limited. A key challenge will be the development of supply arrangements for agricultural residues, energy crops, and other feedstocks. These arrangements are beginning to develop. The use of existing streams of biomass, such as wood waste and municipal solid waste, may provide some early advantages for nonagricultural biomass until supply arrangements for agricultural residues and dedicated energy crops are developed.

Another important issue will be managing risk. The capital-investment and production costs of next-generation biofuel currently are high. It is an emerging sector and untested in the market. Two commercial plants are expected to be operational in 2010. Once up and running, companies will depend on the delivery of large quantities of biomass, subject in some cases to the vagaries of weather. They will have to deal with the limited market for ethanol as a gasoline additive as the E10 “blend wall” is approached and as a gasoline substitute as the market for E85 slowly develops. Given these elements of risk and uncertainty, investors in new operations will strive for maximum flexibility in terms of the kinds of feedstock they are capable of processing and for the kinds of biofuels that are least affected by constraints in the ethanol market. Developing the capacity to use multiple feedstocks and to produce biobased fuels that are equivalent to fossil fuels that can be used in current vehicles without limit and distributed seamlessly in the existing transportation sector may become the least risky business model to pursue.

Acronyms

BP—British Petroleum

CO—Carbon monoxide

CO_2—Carbon dioxide

DOE—U.S. Department of Energy

E10—Blend of 10-percent ethanol and 90-percent gasoline.

E85—Blend of 85-percent ethanol and 15-percent gasoline.

EIA—Energy Information Administration, Department of Energy

EISA—Energy Independence and Security Act of 2007

EPA—U.S. Environmental Protection Agency

EPACT—Energy Policy Act of 2005

GHG—Greenhouse gas

H_2—Hydrogen

MSW—Municipal solid waste

NREL—National Renewable Energy Lab of the Department of Energy

RFS—Renewable Fuel Standard defined in Energy Policy Act of 2005

RFS2—Renewable Fuel Standard defined in Energy Independence and Security Act of 2007

SRWC—Short-rotation woody crop

USDA—U.S. Department of Agriculture

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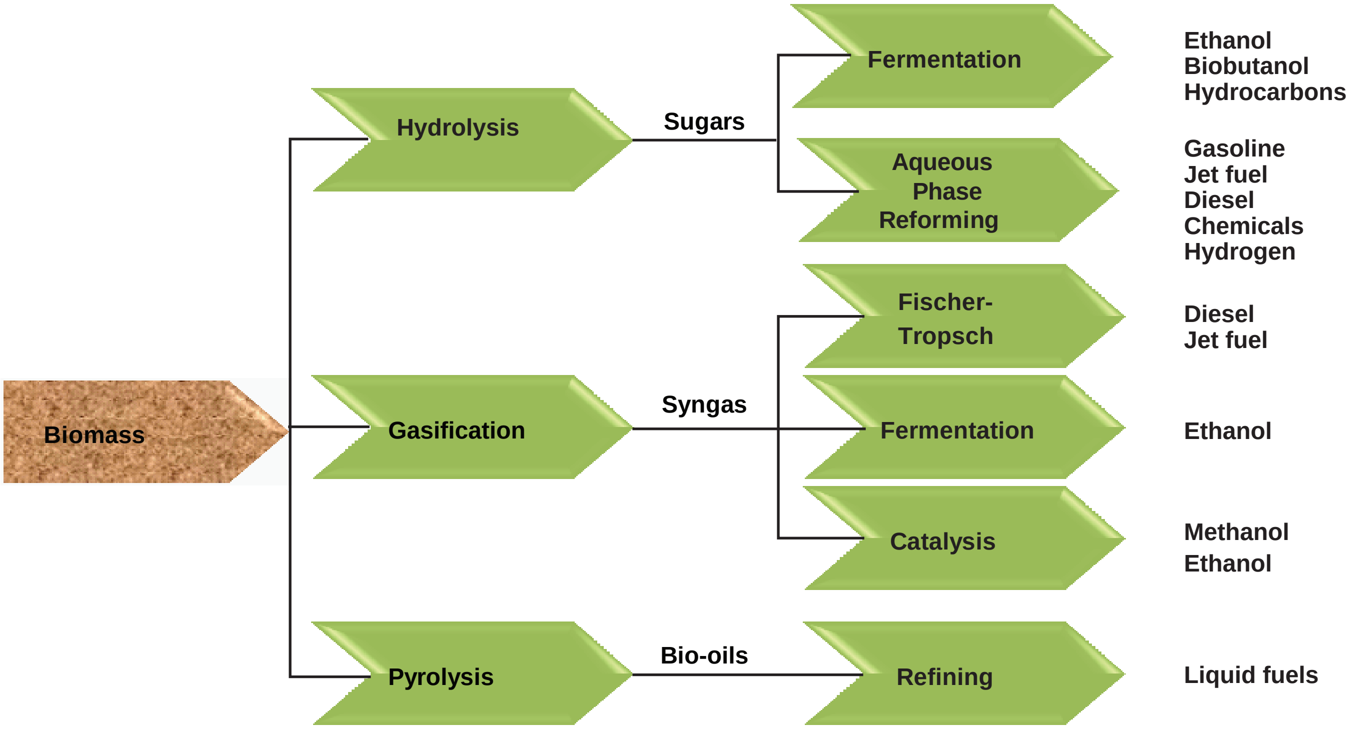
Appendix: Biochemical, Thermochemical Processes and Algae Feedstock Development Characterize Next-Generation Biofuels

There are three significant conversion pathways for producing next-generation biofuels: one biochemical—hydrolysis, and two thermochemical—gasification and pyrolysis. Each pathway involves the breaking down of biomass into intermediate compounds—sugars, syngas and bio oil—and then converting them into various fuels, primarily ethanol, but also biobutanol, and petroleum-equivalent fuels. (See box, "Pathways to Renewable Fuels"). In some cases, a hybrid approach is used, combining both biochemical and thermochemical processes. While most next-generation companies are using or planning to use nonfood feedstocks, there are some that may use first-generation feedstocks, such as corn, sugar cane and sugar beets, for production of biobutanol and petroleum-equivalent fuels. The primary development focus for algae-based fuels is reducing the production costs of the algae feedstock.

Biochemical pathways

Hydrolysis:[1] In this process, the biomass is physically or chemically pretreated to open up the structure and to separate the sugar-containing components, cellulose (6-carbon sugar) and hemicellulose (5-carbon), from the nonsugar lignin, the tough substance that gives rigidity to plant material. This makes two-thirds of the biomass, the cellulose and hemicellulose,

Pathways to renewable fuels



Source: Virent, 2010.

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[1] Hydrolysis is the decomposition of a compound by reaction with water (American Heritage Dictionary).

more accessible for further chemical or biological treatment. Enzymatic or acid hydrolysis is then used to break down the cellulose into simple sugars. Companies are experimenting with different combinations of pretreatments, enzymes and acids to reduce processing costs. The sugars are fermented using yeast or bacteria to produce a dilute solution of ethanol that is then distilled to fuel-grade quality (95 percent or more ethanol), similar to the first-generation process.

> *Biobutanol*: Like ethanol, biobutanol is a product of fermentation but has a higher energy content. Microbes are genetically modified to produce an alcohol with a longer hydrocarbon chain (four versus two carbons) than ethanol, raising its energy content above that of ethanol and closer to gasoline (90 versus 67 percent). Being more similar to gasoline, biobutanol can be more easily blended with gasoline and transported by pipeline than ethanol.

Bioengineered: One process under this category converts sugars (from either cellulosic sources or first-generation feedstocks like sugarcane and corn) using catalysts to produce hydrocarbons. Another replaces natural genes with synthetic ones in microorganisms that convert sugars, not into alcohols, but directly into diesel, gasoline, or jet fuel. One company is developing genetically engineered algae to convert CO_2 directly into oil. The oil has similar structure to petroleum and can be refined into gasoline, diesel, and jet fuel.

Thermochemical pathways

Gasification: Biomass is heated to a high temperature (about 800 degrees C) with limited oxygen. The biomass breaks down into carbon monoxide (CO), hydrogen (H_2) and carbon dioxide (CO_2). CO and H_2 are combined to form synthesis gas, or syngas, which is cleaned, cooled, and either metabolized by bacteria and converted to ethanol or used as a feedstock for Fischer-Tropsch synthesis,[2] in which the syngas undergoes a catalytic reaction to produce liquid hydrocarbons of various types.

Pyrolysis: Biomass is heated to a lower temperature in the absence of oxygen to produce bio oil, biochar (like charcoal), and pyrolysis vapors. The bio oil is then refined to produce various petroleum-equivalent fuels.

Algae propagation and conversion

U.S. and foreign companies are developing ways to propagate special strains of algae in enclosed bioreactors (tubes, plastic bags, flat tanks) or in large open ponds. Algae have a potentially very high biofuel yield per acre (more than 5,000 gallons per acre). The algae are fed carbon dioxide (CO_2), in some cases from nearby heavy CO_2 emitters like coal-powered plants, cement kilns, or breweries. The algae are separated from the water by centrifuge or other means and the oil is extracted using a solvent. The oil is then processed into biodiesel, using first-generation technology.

Others

Hydroprocessing technology is used to convert animal fats and vegetable oils into a petroleum-equivalent fuel very similar to diesel. Catalytic depolymerization involves the breaking down of feedstock molecules more directly into biomass-based diesel.

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[2] Fischer Tropsch is a process developed by German scientists Franz Fischer and Hans Tropsch in the 1920s to convert coal to liquid fuel.